TRIANGLE UNIVERSITIES NUCLEAR LABORATORY ANNUAL REPORT - TUNL XIX

1 JANUARY 1980 - 31 DECEMBER 1980

MASTER

Duke University
University of North Carolina at Chapel Hill
North Carolina State University at Raleigh

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TRIANGLE UNIVERSITIES NUCLEAR LABORATORY

Duke University
University of North Carolina at Chapel Hill
North Carolina State University at Raleigh

Duke Station, Durham, North Carolina 27706

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TRIANGLE UNIVERSITIES NUCLEAR LABORATORY

PREFACE

Triangle Universities Nuclear Laboratory is operated as a cooperative research facility by Duke University, the University of North Carolina at Chapel Hill, and North Carolina State University at Raleigh. It is supported by the U. S. Department of Energy and by the three universities. This progress report of laboratory activities for the year 1980 was prepared for submission to the U. S. Department of Energy.

The varied research programs described in this report reflect a decision by TUNL to devote its major resources to the study of the multiple facets of nuclear structure which can be probed through light ion induced nuclear reactions. With the advantage of a large permanent research staff, made possible by the enthusiastic commitments of the three universities to the laboratory's future, sufficient manpower and expertise are available at TUNL to exploit many different experimental approaches to the unsolved questions of nuclear structure. The flexibility of our experimental groups ensures that a success in one area quickly exerts a beneficial impact in many different but allied efforts.

At TUNL particular emphasis has evolved for programs studying interactions induced by polarized protons, deuterons, and neutrons. We also continue our historic major commitment to the study of the statistical properties of nuclear structure revealed by elastic and inelastic scattering experiments using ultra high resolution beams. A third major laboratory commitment involves measurements of fast neutron cross sections required by the Department of Energy's program to produce controlled thermonuclear fusion.

The major accelerator facilities of the laboratory include a model FN tandem Van de Graaff accelerator and a 15 MeV fixed energy negative ion cyclotron injector. These accelerators coupled together, constituted the world's first Cyclo-Graaff. A plan view of the Cyclo-Graaff laboratory is shown on the following page. The laboratory has two additional single ended Van de Graaff accelerators with terminal energies of 4 MV and 3 MV, respectively. The latter accelerator, with its associated equipment, is an exceptional facility which provides intense beams of very high energy resolution. The 4 MV accelerator, which was the second Van de Graaff accelerator produced by High Voltage Engineering Corporation, is now enjoying renewed research usefulness in a program funded by the National Science Foundation for the study of plant processes utilizing Carbon 11 as a tracer.

We believe the work detailed in the following pages confirms that 1980 was a productive year at TUNL.

Blank

Cyclo-Graaff Laboratory

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A. NEUTRON CROSS SECTION EXPERIMENTS

1. Neutron Cross Section Studies - An Overview

(A. Beyerle, J. Dave, S. G. Glendinning,*
C. R. Gould, C. Howell, Sadiq El Kadi,
C. E. Nelson,** R. Pedroni, F. O. Purser,
L. W. Seagondollar, P. Thambidurai, R. L.
Walter, G. Tungate, H. Pfutzner)

TUNL has been involved in a major program of neutron elastic and inelastic scattering cross section measurements since 1975. The work was initiated to support the high-priority and long-range nuclear data needs of the U.S. fusion energy program and the main thrust of the program has been directed towards satisfying these needs. The information gained is also of basic interest, however, and is relevant to optical model parametrizations of nucleon scattering, studies of isospin dependence in nucleon scattering, nuclear level density parameters and pre-equilibrium emission processes.

The focus of the early work was on measurements of elastic and inelastic scattering cross sections for 1-p shell nuclei. More recently the emphasis has shifted to heavier nuclei, and the program now concentrates on neutron emission spectra measurements in addition to the continuing elastic scattering studies.

The status of the TUNL neutron scattering program has been reviewed at two recent conferences, namely, the Symposium on Neutron Cross Sections from 10 to 50 MeV at Brookhaven, [1] and the Conference on the Application of Accelerators in Research and Industry at Denton, Texas. [2]

REFERENCES (Section A1)

- * G.E., Wilmington, N. C.
- ** Department of Radiology, Duke University Medical Center
- 1. R. L. Walter and C. R. Gould BNL-NCS-51245 (July 1980)
p. 259
- 2. C. R. Gould IEEE Trans. on Nucl. Sci. (to be published)

2. Summary of Recent Facility Changes

Improvements have been made in the electro-mechanical system that is used to position our scattering samples remotely (see TUNL XVII, 1978). The action of the stepping motor which moves the fine steel cable supporting the samples introduced longitudinal pulses into the cable. These pulses caused transverse vibrations of the cable and of the samples while they were being moved. The vibrations have been almost

completely eliminated by the installation of a rubber coupling between the stepping motor and the cable-driving drum. Also, we have changed the method of coupling sample "modules" into the cable system. Each is mounted on a six-inch length of 0.016" diameter steel cable and as many as four are mounted together. Previously, one end of the six-inch cable terminated in a 0-80 male screw and the other end terminated in a 0-80 internally threaded sleeve. Fastening these small couplings was tedious and sometimes personnel did not get mating parts together properly. Now, 2-56 male screws terminate each end of the module cable. Adjoining modules are coupled by means of 1/4" long, 1/8" square brass couplers that have 2-56 threaded holes along their long axes. Fabrication of couplings is easier and fumbling problems are virtually eliminated.

The time-of-flight of neutrons in our system is measured by the time between a "start" signal created by the detector photomultiplier and a "stop" signal obtained by a delayed signal from a capacitive pickoff. Protons or deuterons go through the pickoff just before entering our tritium or deuterium gas targets. Observation of the amplified pickoff signal often showed unexplained time jitter that complicated proper adjustment of pulsing equipment. Also, the amplitude of the signal-to-noise ratio was borderline for reliable pickoff. During the past year, these problems have been eliminated by the replacement of the old preamplifier by two Hewlett Packard 108555A preamplifiers (connected in series) and connecting them directly to the pickoff. These units have a low-frequency cut-off at about 2 MHz and the time jitter has disappeared and the amplified signal now rides well above the electronic noise.

The radial position of both our "4-meter" and "6-meter" detectors, with their massive shields, can be changed by rolling on solid aluminum "wheels" (each wheel is about 6" diameter and 6" long). These wheels roll on the tops of milled-flat I-beams that are part of the rugged angular carts that pivot to different scattering angles. In order that the wheels do not wander as they are rolled back and forth, a 45 degrees flange on each wheel protruded inside the I-beams. Reproducibility of path checks showed the degree of wander was excessive. The flanges have been removed and a one-inch wide semicircular cross section groove has been cut in the wheels on one side of each detector. One-inch wide half-oval cross section brass strips have been bolted to the top of the corresponding I-beams on each detector cart. Reproducibility of tracking has been improved by about a factor of five.

There is great desire to increase our ability to measure at scattering angles as far forward and backward as possible, with the two carts or detectors simultaneously at equal angles. By remodelling the support system of the large liquid nitrogen dewar that cools a cold-finger near our gas targets, we now can locate both detectors at scattering angles of 155 degrees simultaneously. By cutting some steel from the front corner of one cart, we can now locate both detectors at 22 degrees simultaneously. Serious consideration is being given to more modifications that might allow us to reduce the most forward angles to 16 degrees and the maximum angle to 163 degrees simultaneous positions.

The silicon pressure transducer system that was developed to measure gas pressure in our tritium gas target worked beautifully for several months (see TUNL XVIII, 1979). Two problems have recently developed. The first is that hydrogen apparently diffuses through the barrier across which the transducer measures a pressure differential. If, as in some models of the transducers, the comparison pressure chamber is sealed, such diffusion causes an increase in pressure in the comparison chamber and pressure differential reading for a given gas pressure in our target system changes. We believe we have seen this effect. In some models of the transducer, the comparison chamber is open to atmospheric pressure and no such pressure buildup occurs. When using such a transducer on our tritium target, however, routine checks for tritium contamination revealed small quantities of tritium were coming from our transducer. The second problem that has appeared is that the calibration of two such transducers has changed drastically under long term use. At present we do not know the reason. The convenience and added security of the transducer system is sufficient, however, that the reason for the difficulties is being pursued and it is hoped that the system will soon be reinstalled.

3. Studies In The 1p Shell Between 7 and 15 MeV

Elastic and inelastic scattering studies on light nuclei were among the first experiments carried out with the TUNL neutron time-of-flight system. Data for ${}^6\text{Li}$, ${}^7\text{Li}$, ${}^9\text{Be}$ and ${}^{12}\text{C}$ have been reported in the literature [1, 2, 3] and work on ${}^{10}\text{B}$, ${}^{11}\text{B}$ and ${}^{16}\text{O}$ has recently been completed in the thesis of S. G. Glendinning. We have since begun measurements on ${}^{13}\text{C}$. When this work is completed we will have studied neutron scattering from all 1-p shell nuclei except the nitrogen isotopes. In combination with proton scattering data in the literature, we will use these data sets to investigate optical model parametrizations of nucleon scattering from light nuclei.

a. ${}^{10}\text{B}$, ${}^{11}\text{B}$, ${}^{16}\text{O}$

The abstract from the thesis of S. G. Glendinning appears below;

"Neutron scattering cross sections of high quality have been measured for ${}^{10}\text{B}$, ${}^{11}\text{B}$ and ${}^{16}\text{O}$ using the Triangle Universities Nuclear Laboratory neutron time-of-flight facility. These data are useful both for the CTR program and for studies of the isospin dependence of the nuclear force. The neutron data obtained are compared with high quality proton data for ${}^{10}\text{B}$ to determine this dependence using the optical model, assuming that the isospin dependence may be expressed as a correction to the energy of the incident projectile. The energy correction is found to be 4.6-1.4 MeV lowering of the incident energy for protons. The neutron data obtained for ${}^{11}\text{B}$ were compared to the ${}^{10}\text{B}$

neutron and proton data in an attempt to extract the symmetry terms (dependence on target isospin) but the data were insufficiently sensitive to the effect to yield good results. The spherical optical model alone was insufficient to predict the 160° data because of the many resonances in the energy region, so a model which allowed the addition of resonances to an optical model background was used for these data. Three resonances were added to an optical model background and tentative spin-parity and width assignments were made which gave a noticeable improvement in the fits to the data. The $11B$ data (elastic and inelastic) were also fit using the coupled-channel optical model. A value for the coupling parameter was obtained from hyperfine structure results for the electric quadrupole moment in the literature."

The boron scattering data have also been submitted for publication in Nuclear Science And Engineering.

b. ^{13}C

A ^{13}C sample of mass 8.5 g was prepared by compressing ^{13}C powder into a stainless steel can of wall thickness 0.006". The density of the sample was 1.178 g/cm³, which is substantially greater than the density of uncompressed ^{13}C powder (about 0.8 gm/cm³). A time-of-flight spectrum for 10 MeV neutron scattering at 80 degrees is shown in Fig. A3-1. A spectrum corresponding to scattering from an identical empty stainless steel can has been subtracted. The elastic scattering peak is well separated, but the inelastic groups around 3.7 MeV are only partially resolved from the first-excited-state peak at 3.1 MeV.

Fig. A3-1. Time of flight spectrum for 10 MeV neutrons scattered at 80° from a ^{13}C sample

c. Global Optical Model Searches

Global optical model parametrizations of nucleon scattering data from light nuclei [4] have not in general been as successful as for heavier nuclei. [5] In regions where resonance structure is absent, however, good fits can be obtained for individual nuclei. The ^{10}B data are a case in point. The symmetry terms in the optical potential are zero by definition, and proton and neutron scattering parameters differ only in a Coulomb correction term for the proton well depths.

Fig. A3-2 shows the TUNL ^{10}B neutron data, together with proton data from Ref. [4]. The optical model searches were made with the computer code GENOA of F. Perey. A standard spherical Woods-Saxon well shape was used with a surface imaginary potential. The fits are in general quite good and the proton and neutron parameters at a given energy differ only in a Coulomb correction term V_c . The parameters are:

Real well:

$$\begin{aligned} V &= 48.1 - 0.3 E_{\text{cm}} - V_c \text{ MeV} \\ r &= 1.34 \text{ fm} \\ a &= 0.55 \text{ fm} \\ V_c &= 0 \text{ neutrons,} \\ &1.54 \text{ MeV protons} \end{aligned}$$

Imaginary well:

$$\begin{aligned} W &= 0.16 + 0.78 E_{\text{cm}} \text{ MeV} \\ r &= 1.41 \text{ fm} \\ a &= 0.34 \text{ fm} \end{aligned}$$

Spin-orbit potential:

$$\begin{aligned} V &= 5.5 \text{ MeV} \\ r &= 1.15 \text{ fm} \\ a &= 0.57 \text{ fm} \end{aligned}$$

Coulomb radius for protons:

$$r = 1.34 \text{ fm}$$

Fig. A3-2. Spherical optical model fits to $^{10}\text{B}(n,n)$ and $^{10}\text{B}(p,p)$ elastic scattering. The arrows are the Wick's limit cross section values.

In attempting to generalize to neighboring nuclei, the fits are less successful unless the geometries are allowed to vary. But even with fixed geometries, it is possible to obtain reasonable fits.

Fig. A3-3 shows ^9Be , ^{10}B , and ^{11}B neutron scattering data. For these fits

Fig. A3-3. Fixed geometry spherical optical model fits for ^9Be , ^{10}B and ^{11}B neutron scattering. The parameters are listed in the text.

only the real and imaginary well depths were allowed to vary with energy. The parameters were:

Real well:

$$\begin{aligned} V &= 47.2 - 0.32 E_{\text{cm}} - 27.8(N-Z)/A \text{ MeV} \\ r &= 1.39 \text{ fm} \\ a &= 0.57 \text{ fm} \end{aligned}$$

Imaginary well:

$$\begin{aligned} W &= 0.76 + 0.90 E_{\text{cm}} - 1.95(N-Z)/A \text{ MeV} \\ r &= 1.45 \text{ fm} \\ a &= 0.30 \text{ fm} \end{aligned}$$

Spin orbit potential:

as for ^{10}B

The symmetry term is proportional to $[(N-Z)/A]$ in the above potentials. For light nuclei the quantity $[(N-Z)/A]$ is only 1/4 as large as that for heavy nuclei. This makes our data relatively insensitive to the size of the symmetry term. Nevertheless, this term in V is in rough agreement with values found for heavier nuclei. The W symmetry term is

small. However, systematics for this term are not nearly as well established in the literature compared to those for V.

REFERENCES (Section A3)

1. H. H. Hogue et al., Nucl. Sci. and Eng. 69 (1979) 22
2. H. H. Hogue et al., Nucl. Sci. and Eng. 68 (1978) 38
3. D. W. Glasgow et al., Nucl. Sci. and Eng. 61 (1979) 521
4. B. A. Watson et al., Phys. Rev. 182 (1969) 977
5. F. D. Bechetti and G. Greenlees, Phys. Rev. 182 (1969) 1190

4. Elastic and Inelastic Scattering of Neutrons from $^{54,56}\text{Fe}$ and $^{63,65}\text{Cu}$

Cross-section data have been obtained at 8, 10, 12, and 14 MeV for enriched samples of $^{54,56}\text{Fe}$, and $^{63,65}\text{Cu}$ and at 17 MeV for ^{54}Fe . Optical model analyses for $^{54,56}\text{Fe}$ and $^{63,65}\text{Cu}$ are being performed independent of the optical model studies for ^{54}Fe and ^{65}Cu that are discussed below in Section B where neutron polarization measurements for these two isotopes are presented. The main purpose of making two independent searches is to obtain the best representation of the cross section for these nuclei so that comparisons can be made to parameters obtained in studies using a similar approach, i.e., searches which employ only cross-section data. In addition, such representations are perhaps the most useful for interpolating or extrapolating cross sections to other energies for applied purposes. The second reason is to investigate the behavior of a spin-orbit term obtained from searching only on cross-section data and to compare this parameterization to that obtained in later searches which include the additional constraint of polarization data. The comparison should be particularly interesting for Fe and Cu at 14 MeV where it is known from the work in Section B that the cross section for "spin-down" neutrons is greater than that for "spin-up" neutrons over almost the entire angular range measured, i.e., 20 degrees to 155 degrees.

The status of the Fe and Cu data for the region between 8-14 MeV is that the time-of-flight spectra have been stripped a second time following a preliminary sensitivity test of optical model fitting. The 12- and 14-MeV data have been processed with a gaussian fitting routine to obtain estimates for scattering to the first excited state. At 8 and 10 MeV, this inelastic scattering data was obtained with a simple peak summing routine. Examples of the results are shown in the left hand and middle panels of Fig. A4-1 for the samples ^{54}Fe and ^{65}Cu . The curves are polynomial fits of the data.

Constrained Woods-Saxon optical models are being derived for these four nuclei. The energy dependence is contained in the well depths. First best fits were derived, varying all parameters. These are shown in the right hand panels of Fig. A4-1 by the solid curves. Secondly,

Fig. A4-1. Left panels: Comparison of TUNL data to polynomial fits for (n,n) from ^{54}Fe and ^{65}Cu . Middle Panels: Same for (n,n') . Right panels: Results of single-energy spherical optical model fits compared to data from left panels.

the geometry parameters were held at their average values and then the depths were permitted to vary. The energy dependence of the well-depth parameters are being fit presently with simple functions for comparison between isotopes and elements. Calculations using the coupled-channel code ECIS to describe the inelastic scattering cross sections will be initiated soon.

5. Cross Section for Neutron Scattering from ^{58}Ni , ^{60}Ni , ^{116}Sn , ^{120}Sn , and ^{208}Pb between 8 and 17 MeV

Cross-section data for ^{58}Ni , ^{60}Ni , ^{116}Sn , ^{120}Sn , and ^{208}Pb were obtained for the fusion energy program as well as to complement the polarization data reported in Section B1. These data were obtained by the group listed in that part of the report and will be part of the thesis work of C. E. Floyd (^{208}Pb) and P. P. Guss (Ni and Sn). Measurements were made for ^{58}Ni and ^{60}Ni at 8, 10, 12, and 14 MeV. The differential cross sections for ^{58}Ni are shown in Fig. A5-1. The curves are polynomial fits of the data. Optical-model and coupled-channel calculations will be underway when the cross-section data for ^{60}Ni have been adjusted with multiple-scattering corrections, as calculated in the Monte Carlo code EFFIGY.

Fig. A5-1. TUNL data for $^{58}\text{Ni}(n,n)$ and polynomial fits

Cross section data were taken for isotopically enriched ^{116}Sn , ^{120}Sn and ^{208}Pb . Angular distributions were obtained at energies of 10.0 and 14.0 MeV for all three nuclei and at 17.0 MeV for ^{120}Sn and ^{208}Pb . These data complement the polarization data described below, the earlier cross-section results of Finlay *et al.*, [1,2] and the TUNL neutron continuum measurements from tin and lead. In Fig. A5-2 the measured cross sections for the two tin isotopes at 10.0 MeV are presented. These data have been corrected for finite geometry and multiple scattering effects using the code EFFIGY. The angular distribution presented for the second inelastic state is not entirely due to a single channel, but as observed earlier in Ref. [1] the 3- state dominates. For ^{116}Sn and ^{120}Sn inelastic scattering was obtained for the 2+ states at 1.29 MeV and 1.17 MeV, respectively, and according to Rapaport *et al.*, probably for the 3- state at 2.26 MeV and 2.40 MeV, respectively.

The elastic and the 2+ inelastic results measured for both tin isotopes have been found to be fairly well described by the vibrational model. The fits shown in Fig. A5-2 in fact are results of preliminary calculations using the coupled-channel code ECIS. Preliminary attempts to use the spherical optical model to describe both the cross

section and polarization data discussed below have failed until now.

Fig. A5-2. TUNL data for elastic and inelastic scattering from ^{116}Sn and ^{120}Sn at 10 MeV compared to preliminary coupled-channel calculations obtained with ECIS

Before serious calculations for ^{208}Pb are initiated, all of the on-line data (cross sections and polarizations) will be reduced and put into final form. Our preliminary optical model calculations indicate that the cross-section and polarization data cannot be fitted simultaneously if "standard" parameters are used.

REFERENCES (Section A5)

1. R. W. Finlay *et al.*, Nucl. Phys. **A338** (1980) 45
2. J. Rapaport *et al.*, Nucl. Phys. **A341** (1980) 56

6. Double Differential Neutron Scattering
Cross Sections for Fe and Ni between
7.5 and 12 MeV

To complement theoretical predictions of neutron emission cross sections, we have undertaken a program of (n,n') measurements on medium mass to heavy nuclei, with particular emphasis on inelastic scattering to the continuum region. Some details of experimental procedure were given in the progress report last year (TUNL XVIII, 1979, pg. 12 ff.).

Briefly, proton or deuteron beams were pulsed and bunched into about 2 ns bursts at a repetition rate of 1 MHz with typical beam currents on either tritium or deuterium gas targets of 1.5 A. Neutrons thus produced were scattered from appropriate samples into shielded detectors whose radial and angular position from the scatterer could be varied. Scattered neutron flight paths were 2.76 and 3.73 m respectively for two detectors, permitting detection of neutrons below 300 keV in energy without overlap from adjacent beam bursts. Data at incident neutron energy of 7.5 MeV were taken with the $2\text{H}(d,n)$ reaction and at 10 and 12 MeV with the $3\text{H}(p,n)$ reaction.

Neutron angular distributions were typically taken at five angles from 40 degrees to 145 degrees at each energy. At each angle, four time-of-flight spectra were accumulated: (1) gas in, sample in, (2) gas out, sample in, (3) gas in, sample out, and (4) gas out, sample out. "Gas in" refers to deuterium or tritium in the gas target; "gas out" refers to removal of the hydrogen from the gas cell (in the case of 2D, the cell is evacuated, in the case of 2T, it is filled to an equal pressure of 4He). The difference (1) - (2) gives a measure of the number of neutrons actually scattered by the sample and not by other materials; the difference (3) - (4) tells how many of these sample scattered neutrons were neutrons that did not originate in the source gas reaction. The final difference $[(1) - (2)] - [(3) - (4)]$ gives a measure of the number of neutrons which were produced in the source reaction and then scattered by the sample. A time-of-flight spectrum of (1), (2), (3), and (4) is shown in Fig. A6-1; the curve of the final difference of $[(1) - (2)] - [(3) - (4)]$ for that data is shown in Fig. A6-2.

Spectra were obtained at up to five scattering angles for incident neutrons of 7.5, 10 and 12 MeV energy. The data were analyzed by use of computer code EFFIGYC, a Monte Carlo program aimed at producing a realistic simulation of the time-of-flight experiment and data reduction conditions. A major portion of the effort over the past year in the continuum project has been to write and adapt the code to the TUCC computer and accessories and to test the calculations. The code is elegant and massive. It includes the effects of the finite volume of neutron production, the scattering sample and the detector, finite energy resolution, and multiple scattering and attenuation effects. In addition the code corrects for neutrons caused by "breakup" of bombarding particles in the source gas, transforms time-of-flight spectra to energy spectra,

Fig. A6-1. Four experimental spectra required for the measurement of one experimental angle at one energy for 10 MeV incident neutrons. (See text)

Fig. A6-2. Example of a 10 MeV incident neutron energy difference spectrum formed from the data in Fig. A6-1 spectra compressed into 256 channels; (2) is the simulation of the experimental data; (3) is that part of the scattering involving single scattering of primary source neutrons; and (4) is the calculated scattering of all source gas breakup neutrons.

folding in the detector efficiency, and normalizes cross sections to absolute values. It uses estimated continuum cross sections for all incident and exit energies possible, measured cross sections for all discrete states, measured total cross sections for sample material, cross sections for the gas source reaction and geometric information about the time-of-flight system. Spectra are calculated and compared to experiment and the estimated cross section tables are updated. EFFIGYC iterates until the calculation agrees with experiment. Fig. A6-3 is an example of the results of such calculations. In this manner EFFIGYC calculates and applies corrections for experimental curves.

Fig. A6-3. Time-of-flight spectra for simulation calculation at 10-MeV incident neutron energy. Spectrum (1) is the experimental spectra compressed into 256 channels; (2) is the simulation of the experimental data; (3) is that part of the scattering involving single scattering of primary source neutrons; and

Comparison of the TUNL data obtained for Fe with other data and calculations is shown in Fig. A6-4. The results are in fairly good agreement with the work and calculations of others. Agreement in magnitude of cross section is within the errors of these experiments. Energy integrated yields exceed the upper limit of ENDF-B/V total cross sections minus discrete state cross sections by less than 20%.

Fig. A6-4. Comparison of TUNL data with other data and calculations.

● - TUNL data; A) Incident neutron energy $E = 12$ MeV, scattering angle = 125° ; B) $E = 10$ MeV, 100° ; C) $E = 7.5$ MeV, 95°

x - H. Vonach calculations; A) Interpolated between 11 and 14 MeV; B) Interpolated between 8 and 11 MeV; C) 8 MeV

- ENDF/B-V (file 3 + 4, section 91); A) 12 MeV; B) 10 MeV; C) Interpolated between 7 and 8 MeV

Δ - Kinney and Perey data; C) $E = 7.5$ MeV

+ - Owen and Towle data; C) $E = 7.0$ MeV

$\square$ - Biryukov data; B) $E = 9$ MeV

7. Breakup Cross Sections for $3\text{H}+p$ Neutrons

An accurate determination of the zero degree neutron spectrum resulting from proton bombardment of tritium is of importance in making corrections to our neutron emission spectra data. For proton energies above 8.3 MeV the $3\text{H}+p$ neutron source is not monoenergetic and a continuum of neutrons arises from the body breakup of the $3\text{H}+p$ system. The magnitude of the breakup spectrum was recently reported by Drosge *et al.* [1], but the shape of the spectrum was not particularly well characterized. We undertook to measure the breakup spectrum in order to better determine the shape and also to check the results of Ref. [1].

Measurements were made at energies from 10 to 14 MeV using the time-of-flight system. A neutron time-of-flight spectrum converted to energy is shown in Fig. A7-1. (A tritium gas out spectrum has been subtracted in order to remove neutrons arising from (p,n) reactions in the gas cell walls and beamstop.) The extracted breakup neutron cross sections

Fig. A7-1. Raw energy spectrum after transforming the time-of-flight scale to an energy scale.

are shown in Fig. A7-2. The agreement with Ref. [1] is quite good. We have found the tailing of the intense $T(p,n)^3\text{He}$ peak into the continuum region limits the accuracy of the measurements. The overall precision is estimated to be about 15-20%.

Fig. A7-2. Extracted breakup neutron cross sections.

REFERENCES (Section A7)

1. M. Drosg et al., Nucl. Inst. Meth. 140 (1977) 515
8. Coupled-Channel Calculations with ECIS

The versatile coupled-channel ECIS developed by J. Raynal of the Theoretical Physics Institute and the Nuclear Physics Center, Saclay, France was compiled and made functional on both the IBM computer at TUCC and the VAX computer at TUNL. This was done by Raynal during a brief visit in August with the assistance of M. Wright, A. Beyerle and P. Guss. Since then plotting routines have been adapted to the code by P. Guss. Calculations for neutron elastic and inelastic scattering from ^{12}C , ^{40}Ca , ^{54}Fe , ^{58}Ni and ^{116}Sn have been initiated thus far, although those for the latter three targets are still in a very preliminary stage.

B. Neutron Polarization Studies

1. Scattering of Polarized Neutrons

a. Overview

Our current interest in scattering of polarized neutrons from nuclei involves about 12 nuclei ranging from 1H to 208Pb . The work can be grouped into three areas of interest: (i) few nucleon studies (1H , 2H , 4He), involving targets that can be made into scintillator media; (ii) light nuclei (9Be and 12C), which can be interpreted only approximately with the standard optical model; and (iii) medium to heavy nuclei (40Ca , 54Fe , 58Ni , 65Cu , 116Sn , 120Sn , and 208Pb), for which an analysis in terms of the standard optical model should yield suitable tests concerning shapes, sizes and depths of the neutron-nucleus potential. It is significant that never before has such high accuracy been achieved for neutron analyzing power data at energies above 4 MeV. Our new data presents stringent tests for nucleon-nucleon models, three-nucleon models, the Lane optical model for $9\text{Be}(\text{N},\text{N})9\text{Be}$, and previously unclear details of the nucleon-nucleus model.

All of these tests have been made possible through the use of the polarization transfer reaction $2\text{H}(\text{d},\text{n})3\text{He}$, which gives a high flux of polarized neutrons at 0 degrees, the angle where the cross section conveniently is strongly peaked. Our success in being the first to accurately measure analyzing power distributions at energies above about 6 MeV for non-scintillating targets is due to a development reported last year in our progress report and more recently in a paper by Wender *et al.* [1] This development is the ability to obtain 2-ns wide bursts of polarized protons or deuterons with an average beam current of 100-200 nA on target. The repetition rates of 2 and 4 MHz are ideal for detecting 8-17 MeV neutrons with our time-of-flight apparatus.

Before scattering data obtained in the experiment can be analyzed in terms of nuclear models, extensive calculations must be made to determine the effects of neutrons that scatter more than once in the target (see Sec. B1-k). In addition, because a sizeable finite angle (about 10°) is subtended by the scattering samples, the effective scattering angle must be carefully calculated. Two Monte Carlo codes are in use at the present. The first, EFFIGY, contains no polarization effects, so it is used only to correct cross-section data and to obtain estimates of the relative yields for single, double, triple, and higher order scattering. Results from EFFIGY are being used to test results for the relative intensities of the different orders of scattering as calculated in our second Monte Carlo code, JANE, a code which accounts for the polarization effects of the multiple scattering contribution. These comparison tests are still underway.

Highlights of our scattering work during the past two years were reported in ten contributions (Refs. [2-11]) to the 5th International Symposium on Polarization Phenomena in Nuclear Physics. To exemplify the quality of the new data, a comparison is made in Fig. B1-1 between our results for 208Pb at 10 MeV (uncorrected for multiple scattering) and the only other existing polarization data for Pb(n,n) between 5 and 24 MeV. It is obvious that the new data clearly define the structure in the analyzing power function between 20° and 160°.

Fig. B1-1. Comparison of recently reported results for analyzing power for Pb(n,n) to present results (right panel).

Much of the analyzing power data in this Section requires the cross-section information reported in Section A in order to extract nuclear parameters. On the other hand, much of the eventual understanding of the models which describe the data of Section A will revolve around their ability to predict analyzing power data. In this way, Sections A and B1 complement one another in such a manner that the division into two separate analyses may soon become superficial. These statements hold for both elastic and inelastic scattering.

In Section J the development of the polarized target system for studies of the spin-spin interaction is described. The initial experiments will be neutron transmission measurements, i.e., total cross sections. The source of neutrons will be either the $2\text{H}(\vec{d}, \vec{n})^3\text{He}$ reaction as a "mono-energetic" source or the $9\text{Be}(\vec{d}, \vec{n})$ reaction as a white source of polarized neutrons.

The neutron polarization program has been a major effort at TUNL. Personnel involved are from each of the three Universities: C. E. Floyd, P. P. Guss, K. Murphy, C. R. Howell, R. Pedroni, G. Tungate, R. C. Byrd, and R. L. Walter from Duke in Durham; T. B. Clegg and W. J. Thompson from UNC at Chapel Hill; and C. R. Gould

from NCSU in Raleigh. A group from Tübingen has collaborated in a number of the experiments and computer coding: E. Woye, W. Tornow and G. Mack. Some of the analyses for which data were taken a few years ago involved P. W. Lisowski, now at LASL. A correspondent for each of the projects is identified by initials at the end of the subsection. The references for the subsections B1, B2 and B3 are given at the end of each subsection.

b. Review of Advances in Neutron Polarization Studies

A paper which summarized the major advances in neutron polarization studies in the past five years for energies between about 2 and 30 MeV was presented by one of us (RLW) for the 5th International Polarization Symposium in August in Santa Fe. [11] The paper focussed mainly on the recent progress at TUNL. One topic was a summary of the analyzing power data obtained at TUNL for 10 to 14 MeV neutron-nucleus scattering. The results were presented as a composite graph which shows the expected smooth changes of $A(\theta)$ with mass number. This figure is reproduced in Fig. B1-2. One important aspect of these data, in comparison to that for proton-nucleus scattering, is that the magnitude of $A(\theta)$ for the heavier targets is not overwhelmed by the diluting effect of Rutherford scattering.

Fig. B1-2. Global view of observed analyzing power for 10-14 MeV neutron elastic scattering.

c. Analyzing Power for n-p Scattering at 16.9 MeV

A paper describing the precision n-p analyzing power measurements and their comparison to theory has been published in Nuclear Physics A. [12] The abstract follows:

"The analyzing power $A(\theta)$ for neutron-proton scattering has been measured for $\theta = 90^\circ(\text{c.m.})$ from 13.5 to 16.9 MeV and from $\theta = 50^\circ$ to $145^\circ(\text{c.m.})$ at 16.9 MeV. Extensive Monte Carlo calculations have been made to correct for multiple scattering effects. Overall uncertainties are about ± 0.002 . All the $A(\theta)$ data, but primarily those at 16.9 MeV, disagree with predictions based on the phase-shift sets which have been derived previously by way of global analyses of nucleon-nucleon scattering data. Data for the product $\sigma(\theta)A(\theta)$ have been fitted with an expansion of the form $(\sin\theta)[a_1 + a_2 \cos\theta + a_3 (\cos\theta)(\cos\theta)]$. For the first time the need for a non-zero a_3 has been illustrated for energies below 20 MeV. This parameter is shown to be related to the nucleon-nucleon F-state spin-orbit phase parameter. In addition, the P, D, and F spin-orbit phase parameter values derived from the present data differ significantly from the ones based on the Yale-IV and Livermore-X global analyses. The derived D and F spin-orbit phase parameters also differ from those obtained in the recent analysis of nucleon-nucleon scattering data by Arndt *et al.*"

In all low-energy (10-20 MeV) neutron-proton analyzing power experiments reported in the literature, organic scintillators were used as the center (hydrogen) scatterer in order to reduce background problems. However, in such a scatterer multiple scattering effects involving carbon are introduced, and it is well known that the analyzing power $A(\theta)$ for $^{12}\text{C}(n,n)$ scattering is large at some energies and angles. Since the $A(\theta)$ is small for n-p scattering, corrections for the presence of carbon must be carefully investigated and applied. In our experiment abstracted above, we reported precision measurements for $A(\theta)$ for n-p scattering from 13.5 to 16.9 MeV. The data were corrected for the carbon effect by using a Monte Carlo simulation of the single- and double-scattering processes. The necessary input for n- ^{12}C scattering was extrapolated between 8 and 14 MeV.

With the measurements recently conducted at TUNL for n- ^{12}C analyzing powers (Sec. B1-f), the Monte Carlo calculation could be repeated with real $A(\theta)$ data. Fig. B1-3 shows the asymmetry produced in the two separate multiple scattering cases, i.e., first hydrogen, second carbon and first carbon, second hydrogen, for our geometry and time-of-flight coincidence constraints. The corrections to the n-p data were determined to an accuracy of ± 0.0002 and ranged from -0.0012 at forward angles to $+0.0006$ at 145° . These newly calculated corrections are almost

Identical to the estimated ones that were applied in our report above on n-p analyzing powers. Hence, these corrections cannot account for the difference between predictions using existing global nucleon-nucleon phase shifts or nucleon-nucleon potential models and the precision TUNL data. A contribution to the 5th International Polarization Symposium by J. Cote et al. of the Paris potential group addresses these differences. Our new Monte Carlo calculations were also presented at Santa Fe. [2]

[WT, RLW]

Fig. B1-3. Effect of multiple scattering from carbon and hydrogen.

d. Analyzing Power for $4\text{He}(n,n)4\text{He}$ Scattering

These precision data for $A(\theta)$ at 14.0 and 17.1 MeV have been made available for combining with other five-nucleon data sets for nuclear model calculations. No further progress has been made toward publishing our data and our phase shift analysis.

[PWL]

e. Scattering of Polarized Neutrons from 9Be

The first experiment using the TUNL polarized neutron scattering facility was the measurement of analyzing powers for scattering to the ground and 2.43 MeV ($5/2^-$) states of 9Be at 9, 10, 11, 13, and 15 MeV neutron energies. As seen in Fig. B1-4, the $A(\theta)$ data vary smoothly with energy.

Neutron data provide unique information concerning the tail of the nuclear potential through scattering at forward angles, where the Coulomb force dominates the corresponding proton scattering. If 9Be is considered to be a pair of particles with a loosely bound neutron, then the difference between the specifically nuclear force in $9\text{Be}(n,n)$ and $9\text{Be}(p,p)$ would involve only this outer neutron. A comparison of proton and neutron scattering data may therefore be expected to provide insight into isospin dependence, as an incident proton may interact through the singlet and triplet states while a neutron is restricted by Pauli blocking to the singlet state.

The $9\text{Be} + \text{nucleon}$ system has been studied by two theoretical techniques at TUNL. As described in Secs. B2-a and B2-d, a Lane model has been developed to describe the elastic and quasi-elastic processes in the (p,p) , (n,n) , and (p,n) reaction channels. [9,13] This model used one potential to simultaneously fit the (p,p) , (n,n) , and (p,n) cross sections as well as the (p,p) and (p,n) $A(\theta)$ data. Parameters from this analysis were used to generate a prediction for the (n,n) , $A(\theta)$ distribution. As shown in Fig. B1-5, the Lane-model prediction differs from the data at the positive maxima. Inclusion of the data reported here will provide a complete data set for a Lane model analysis (neglecting target spin).

Fig. B1-4. Observed $A(\theta)$ for $9\text{Be}(n,n)$.

Fig. B1-5. Comparison of model predictions to TUNL data for $9\text{Be}(n,n_0)$ and $9\text{Be}(n,n_1)$.

Proton scattering to the ground and 2.43 MeV ($5/2^-$) states has been analyzed using a coupled-channels analysis. The coupled-channels parameterization is that of Votava *et al.* [14] with two nominal modifications resulting from analysis of depolarization data and higher energy data. [15] First, the deformation parameter β_2 is set equal to 1.05. Second, complex form factors are used. Predictions for neutron scattering to the two states are shown in Fig. B1-5. The $A(\theta)$ results for (n,n') are well reproduced, although differences exist between calculation and elastic data at the two positive maxima. The Lane model and coupled-channels calculations were presented at Santa Fe. [4]

[CEF, RCB]

f. Analyzing Power for $^{12}\text{C}(n,n)$ Scattering

One of the cooperative experiments with Tübingen was a study of $A(\theta)$ for elastic and inelastic (4.43 MeV state) scattering from ^{12}C . The data and the analyses will comprise a part of the doctoral thesis of E. Woye from Tübingen. Data have been obtained in about 1 MeV steps from 7 to 17 MeV. The significance of these data for n-p scattering has already been addressed in Section B1-c above. In addition, the Tübingen group has historically been interested in these scattering processes over the last decade. The preliminary data and calculations were shown at Santa Fe. [Refs. 3,5] All the necessary corrections have now been applied to the data.

Until now, two models have been used by us to study the system in the region between 11 and 15 MeV where the resonance effects do not have a strong influence. A standard spherical optical model was investigated, first at each energy, then global in energy. The results of a global optical model for the elastic scattering are compared to the data in Fig. B1-6. Here the cross section data are from the TUNL report of

Fig. B1-6. Global predictions using a spherical optical model for $^{12}\text{C}(n,n)$.

Glasgow *et al.* [16] The model provides a fair representation of the data, considering that standard Woods-Saxon form factors were employed. The most interesting feature of this optical model representation is that the diffuseness of the spin-orbit term favors values that are a factor of two or more smaller than those of heavier nuclei, i.e., less than 0.3 compared to about 0.6 fm. This same feature was obtained in the optical model search on 9Be mentioned in Sec. B1-d.

The $^{12}\text{C}(n,n')$ reaction was investigated using the coupled-channel code ECIS. Again the calculations give a fair representation to the data, both (n,n) and (n,n') . The deformation parameter obtained was similar to that seen in earlier carbon analyses.

[EW, RLW]

g. Cross Section and Analyzing Power for $^{40}\text{Ca}(n,n)$

Additional measurements were obtained to fill in the forward and backward angles for $\text{Ca}(n,n)$ scattering at 10, 12

and 14 MeV. A comparison of the analyzing power to calculations using familiar optical models for neutron scattering is shown in Fig. B1-7. (These plots do not include our newer measurements.) The agreement using the conventional optical model of Becchetti and Greenlees [17] is poorer than that shown here. The cross-section and $A(\theta)$ data have been employed in an optical model search using the code GENOA with the standard Woods-Saxon form factors. Again the results are in fair agreement with the data and are considerably improved over those in Fig. B1-7. The feature of a small spin-orbit diffuseness ($a = 0.3$ fm) surfaced here also, indicating that some feature of the standard Thomas term for the nucleon-nucleus spin-orbit form factor is probably breaking down for light nuclei, as one doesn't expect to observe geometrical effects as sharp as 0.3 fm in the nuclear interaction. Details of these data and calculations were presented at Santa Fe. [6]

[WT, RLW]

Fig. B1-7. Analyzing power for $^{40}\text{Ca}(n,n)$.

h. Elastic and Inelastic Scattering from ^{54}Fe , ^{58}Ni , and ^{65}Cu at 10 and 14 MeV

Analyzing power measurements have been conducted for elastic scattering of neutrons from ^{54}Fe , ^{58}Ni , and ^{65}Cu at 10 MeV and ^{54}Fe and ^{65}Cu at 14 MeV. [7,8] Data for ^{58}Ni at 14 MeV will be obtained in the near future. The $A(\theta)$ results at 10 MeV for ^{54}Fe and ^{65}Cu are shown in Figs. B1-8 and B1-9. All data have been corrected for finite geometry and double scattering effects; triple scattering effects are presently being investigated. The indicated error bars reflect the propagation of all known uncertainties in the measurement. Our analyzing power data are not consistent with the anomalously high polarizations reported by Galloway and Waheed [18] for angles around 20 degrees. Apparently there must have been instrumental asymmetries in the experiment of Ref. [18].

Figs. B1-8 and B1-9. Comparison of TUNL data to spherical optical model calculations using available parameters and using results of GENOA searches on the cross section and analyzing power data.

Our $A(\theta)$ values, together with the total cross section and the differential cross-section data of El-Kadi *et al.* (Section A4), have been fitted using the optical-model search code GENOA obtained from F. Perey. For our purposes, the Mott-Schwinger interaction between the neutron magnetic moment and the Coulomb field of the nucleus (Section B1-j) has been included in the code GENOA and used in the optical model calculations shown here. The data are compared in Figs. B1-8 and B1-9 with optical-model calculations based on a TUNL best fit and the global models of Rapaport *et al.* [19] (RKF) and Wilmore and Hodgson [20] (WH). Due to the scarcity of accurate polarization data for neutrons, the spin-orbit terms in the neutron model have typically been set to zero (as in Ref. [20]) or set to the proton parameters of Becchetti and Greenlees [17] (BG) (as in Ref. [19]). For the present comparison, the BG spin-orbit values were used with the parameter set of WH. While both global sets reproduce the general features of the distributions, neither set predicts the analyzing powers at forward angles, where our data has its highest statistical accuracy.

The spin-orbit term derived in our search has a well depth of about 6 MeV, a radius parameter of 1.1 fm, and a diffuseness of 0.5 to 0.6 fm. Two unusual features of the TUNL parameters should be noted. The description of the forward-angle $A(\theta)$ requires a volume absorptive term in combination with the surface peaked absorption; this volume term is normally set to zero in low energy neutron scattering. Secondly, the data favored the inclusion of an imaginary spin-orbit term, a feature which has been hard to observe in low-energy proton-nucleus scattering.

In Fig. B1-10 experimental results for elastic and inelastic scattering from ^{58}Ni are compared to preliminary coupled-channels calculations. The agreement is quite good, considering that the search has so far been very limited. At present only 10.0 MeV data exist for the analyzing power for ^{58}Ni , but they are soon to be complemented by data at 14.0 MeV. The $A(\theta)$ values for the 1.41 MeV (2+) inelastic state in ^{54}Fe have also been extracted and will be included in a coupled-channel analysis in the near future.

[CEF, PPG]

1. Scattering from ^{116}Sn , ^{120}Sn and ^{208}Pb at 10 and 14 MeV

Neutron analyzing power data have been obtained for isotopically enriched ^{116}Sn , ^{120}Sn , and ^{208}Pb at 10.0 and 14.0 MeV. [8] These Sn data nicely complement the cross sections for these same isotopes at 10.0, 14.0, and 17.0 MeV, also measured at TUNL. A sample of the results is shown in Fig. B1-11a for neutron elastic scattering at 10.0 MeV for ^{116}Sn and ^{120}Sn . These data have been corrected for the multiple scattering that occurs within the target and for the finite geometry of the experimental setup. The first analyses attempted were coupled-channel calculations using the code ECIS. This code, however, does not contain a term for the Mott-Schwinger interaction. In order to obtain a set of

Fig. B1-10. Results of coupled-channel calculation using ESIS compared to TUNL data for ^{58}Ni .

Fig. B1-11. Top: Data for ^{116}Sn and optical model calculation including Mott-Schwinger scattering. Bottom: Coupled channels calculation compared to data modified for M-S scattering.

analyzing power data for use in ECIS calculations, corrections to the data were approximated for the effect of the Mott-Schwinger interaction (see Sec. B1-j). This was done by using the spherical optical model code GENOA to calculate the expected differences in analyzing power with and without the interaction turned on, and the data were then adjusted by the difference for use in a coupled-channel analysis.

Preliminary ECIS calculations were mentioned in Section A5 and the analyzing power results from these calculations are plotted in Fig. B1-11b. The data shown here are the same as in Fig. B1-11a except for the approximate correction to subtract out the Mott-Schwinger effects. The analyzing power for 208Pb are yet to be corrected for double and triple scattering effects and therefore are not available for final calculations with nuclear models.

[PPG, CEF]

j. Effects of Mott-Schwinger Scattering

When a neutron scatters from a charged nucleus it experiences an electromagnetic interaction between its magnetic moment and the Coulomb field of the nucleus, which is moving in the rest frame of the neutron. First recognized for electron scattering by Mott and later applied to neutrons by Schwinger, this effect is termed Mott-Schwinger scattering. This electromagnetic interaction exists in addition to the strong nucleon-nucleus interaction. To avoid a false parameterization of the nuclear potential, this electromagnetic interaction must be calculated and taken into account.

The phenomenological optical model has been used to parameterize much of the available nuclear scattering data. The work of Hogan and Seyler [21] justifies the accuracy of using the Born approximation for the Mott-Schwinger interaction. We have included the Mott-Schwinger interaction in the optical search code GENOA in the Born approximation; its effect appears as a term proportional to $\cot(\theta/2)$ in the spin-flip amplitude. This cotangent dependence gives an enhancement of the forward angle cross section and polarization. Calculations for ^{65}Cu at 10 MeV are shown in Fig. B1-12 for angles less than 9 degrees. In Fig. B1-13 we show optical model calculations which illustrate the effect on the analyzing power in the region between 15 degrees and 45 degrees. In this region the present experimental setup permits accurate $A(\theta)$ measurements, i.e., the error in $A(\theta)$ is typically less than 0.004. The solid curve is an optical model fit including Mott-Schwinger effects. The effect of turning off the electromagnetic interaction is shown in the dashed curve. There is a noticeable effect throughout the angular region, especially where the differential cross section is small. The effect of Mott-Schwinger scattering on the cross section is small for angles greater than a few degrees, at most exhibiting a small contribution in the diffraction minima.

This study was prompted by the concern that exclusion

Fig. B1-12. Calculation of the effect of Mott-Schwinger scattering on analyzing power for small angles.

Fig. B1-13. Comparison of TUNL data to optic model calculation with (solid curve) and without (dashed curve) Mott-Schwinger scattering.

of Mott-Schwinger effects would result in spurious optical model parameters. Indeed, when the Mott-Schwinger interaction is omitted, the parameters are changed by up to 20%, primarily in the absorptive and spin-orbit terms. We conclude that Mott-Schwinger scattering must be included to avoid spurious parameters when fitting data sets which include accurate neutron $A(\theta)$ data.

[CEF, WJT]

k. Multiple Scattering Corrections for $A(\theta)$ Measurements

The computer code JANE does a Monte Carlo simulation of a neutron scattering analyzing power experiment. The code originated at Universität Tübingen with E. Woye and was rewritten here for use on the IBM computer at the Triangle Universities Computation Center and on the VAX-VMS computer at TUNL. The original code was specialized to elastic and inelastic scattering from ^{12}C . A second version was written at TUNL to mock up the neutron scattering from ^9Be . During the past year the code has been generalized to more readily perform calculations for any element.

In its present form, the code JANE requires an input library consisting of the total cross section, the differential cross section, and the estimated analyzing power in the energy region of interest. In addition, the differential cross section of the neutron source reaction is required. The code calculates one time-of-flight spectrum for spin-up and another spectrum for spin-down at each angle given. It automatically sets windows on the peaks and calculates the expected analyzing power. By separately calculating the spin-up and spin-down spectra for multiply-scattered neutrons, the effective analyzing power of the multiple-scattering contribution is determined. Given this function and the ratio of multiple to single scattered events, the point geometry analyzing power is deduced. The code JANE is presently capable of simultaneously calculating up to three possible groups, for example, for elastic scattering and for two states of inelastic scattering.

During the last year major emphasis has been placed on development of the following capabilities: 1) the ability to submit cross-section and polarization libraries, which allows the code to be used for any isotope of interest; 2) the capacity to perform multiple scatterings to third order, that is, triple scattering; 3) the incorporation of effective energies and angles in the final corrected data sets; and 4) the production of a coherent and inclusive manual for this very powerful code.

[PPG, EW]

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2. Studies of (p,n) Reactions

The (p,n) program over the past year has involved contributions from a large number of TUNL staff and students. Major direction, supervision, and intervention has been provided by R.C. Byrd and R.L. Walter; the bulk of the crucial development work on the polarized source and pulsed polarized beam facility was done by S.A. Wender, T.B. Clegg, C.E. Floyd, and C.R. Howell. On-line data acquisition rested primarily on K. Murphy, C.E. Floyd, P.P. Guss, C.R. Howell, H. Pfutzner, and R.C. Byrd -- with technical assistance from T.B. Clegg and S.A. Wender. Most of the off-line spectrum analysis was done by K. Murphy, P.P. Guss, and C.E. Floyd. S.R. Cotanch participated in the Lane model studies, and R.C. Byrd authored or served as local editor on most of the recent papers. The earlier P vs A measurements included P.W. Lisowski (now at LASL), W. Tornow (visiting from Tübingen), and T.R. Donoghue (visiting from The Ohio State University).

We will follow the "Correspondent" convention of the previous section, listing for each project only the initials of the person(s) primarily responsible; these individuals should be contacted for additional information.

a. Overview

The study of (p,n) reactions at TUNL has concentrated mainly on cross section and polarization measurements on light nuclei ($A < 16$) at bombarding energies below 20 MeV. A significant development in this program is the use of a calibrated detection system for our analyzing power measurements; we are therefore able to measure both cross section and analyzing power $A(\theta)$ at the same time. Since interpretation of the data requires that both measurements be made with the same energy and energy spread, further development of this approach can provide an important simplification in experimental procedures.

The interpretation of the data for the lightest nuclei, ^2H and ^3H , is dictated partly by the few-nucleon nature of these systems. Our approach in the heavier cases has generally followed two somewhat complementary avenues. First, comparison of the values of the polarization P of the outgoing neutrons and the analyzing power A of the reaction for an incident polarized beam can provide useful information about the nuclear structure of intermediate states. [1] On the other hand, at higher excitation and bombarding energies these P - A differences disappear, along with the resonance structure to which they are related. At energies above about 10 MeV, therefore, we have attempted to describe our results using the Lane optical model. Our coupled-channels analyses have included all available data for the (p,p), (n,n) and (p,n) cross section and polarization in this energy range.

Summaries of these two programs, i.e., the Lane model

and comparison of polarizations to analyzing powers, have been published or presented at various conferences over the past year. The comparison of P and A was discussed [2] at the Telluride Conference on (p,n) reactions in 1979 and at the Fifth Polarization Symposium at Santa Fe in August, 1980. [3] Briefly, these papers show that P-A splitting is caused by and evidence for isospin symmetry violation which allows different rates for spin up-to-down and down-to-up transitions in (p,n) reactions. Experimentally, (i) no substantial differences have been seen in P and A data for the $^3\text{H}(p,n)^3\text{He}$ and $^9\text{Be}(p,n)^9\text{B}$ reactions, (ii) possible differences exist in data for ^7Li , ^{11}B , and ^{13}C targets, but the P and A results are from different laboratories, and (iii) pronounced splitting has been observed in TUNL data for the $^{15}\text{N}(p,n)^{15}\text{O}$ reaction below about 9 MeV.

An additional paper on P and A comparisons is being written for submission to Physical Review Letters. Part of the current introductory paragraph follows:

"Recent observation of differences between the polarization P and the analyzing power A measured in forward and reverse reactions has led to renewed speculation on the breakdown of time-reversal invariance (TRI) in nuclear reactions. In this Letter we describe related work done at the Triangle Universities Nuclear Laboratory (TUNL) on comparisons of P and A in (p,n) reactions between mirror nuclei. Interpretation of differences between these observables involves somewhat different assumptions than those for either the self-inverse case of elastic scattering or the (p, ^3He)-(^3He ,p) transfer reactions in which differences between P and A have been observed. In particular, identity of these P and A results can involve both TRI and charge symmetry (CS)."

Reviews of the Lane model work were also given at both the Telluride [4] and Santa Fe [5] conferences. The Santa Fe abstract follows:

"Lane model analyses of (p,p), (n,n) and (p,n) data, especially analyzing powers, can provide new constraints on the nuclear symmetry potential. Previous work on the symmetry spin-orbit potential is reviewed, and future directions of study are outlined." [5]

This paper summarizes results for our ^9Be , ^{13}C , and ^{15}N optical model analyses, paying particular attention to polarization-related topics. We also present predictions of our new $^9\text{Be}(n,n)^9\text{Be}$ analyzing power data, obtained with parameters from our Lane model analysis of the $^9\text{Be} + \text{nucleon}$ system. See Secs. B2-d,f,g below for details of these Lane model studies.

Our presentation of the developments in the (p,n)

program over the last year will be arranged in this Report in terms of the targets involved, moving from 2H through 3H , 9Be , 11B , 13C , and 15N .

b. The $2\text{H}(p,n)2\text{p}$ Breakup Reaction

The final publication in an earlier study of (p,n) transverse polarization transfer measurements on light nuclei appeared during the past year; previous studies were covered in Ref. [6]. The abstract and concluding paragraph of our latest paper [7] are included here:

"The transverse polarization transfer coefficient K_{yy} has been measured for the breakup reaction $2\text{H}(p,n)2\text{p}$ at $\theta=0^\circ$ for five incident energies in the range from 10.6 to 15.1 MeV. The results are presented at each proton energy as a function of neutron energy. All of the $K_{yy}(0^\circ)$ data have positive values around 0.4 for low neutron energies and negative values around -0.2 for high neutron energies. The data are compared to predictions from a three-body separable-potential model calculation."

"In summary, the agreement between our data and the calculation of Jain and Doolen [8] and the general disagreement of K_{yy} values with other calculations show the usefulness of this kind of measurement for evaluating different theoretical approaches and approximations in three-nucleon calculations. Certainly, the magnitude and unexpected lack of variation with energy of the polarization transfer coefficients should provide stringent tests for additional theoretical calculations in this energy range." [7]

[PWL, RLW]

c. The $3\text{H}(p,n)3\text{He}$ Reaction: Comparison of Analyzing Power and Polarization

No new data have been obtained for this reaction. The final publications on our previous comparisons between P and A were prepared jointly with T.R. Donoghue of the Ohio State University and G.M. Hale of LASL. The preliminary results of this work were published as a Letter [9] in 1976. A pair of back-to-back papers have been submitted to Nuclear Physics A. The abstracts are reproduced below [10,11]:

"Neutron analyzing powers are measured for the $3\text{H}(p,n)3\text{He}$ reaction both for $\theta_{\text{cm}}=45^\circ$ between 1.75 and 4.0 MeV and as $A_y(\theta)$ for six energies between 2.48 and 3.9 MeV. These data confirm earlier Los Alamos results in the region of overlap, supporting their earlier finding of large differences between the

analyzing power and polarization function in this reaction. Charge-independent R-matrix calculations fitting all nucleon-trinucleon data are shown to provide a reasonably accurate description of the A_y data over most of the energy range, and establish the ordering of the lowest P-wave $T=0$ levels of ^4He as $J^{\pi}=0^-, 2^-,$ and 1^- , in order of increasing energy. These R-matrix calculations also predict for the first time appreciable differences between A_y and P_y , suggesting that comparisons of these experimental quantities will probably not be useful in exploring charge symmetry properties of the nuclear interaction." [10]

"A measurement of the polarization P_y for the $^3\text{H}(p,n)^3\text{He}$ reaction was conducted for the energy range between 2 to 4 MeV. Special care was given to minimizing the effects of background events and to interpreting the experimental spectra. The new values for P_y are significantly higher than those reported earlier, and comparison to the available data for the analyzing power A_y shows that $P_y = A_y$ in this energy range to within experimental uncertainties. This equality negates earlier conclusions that sizeable differences existed between these observables. In particular, our new results demonstrate that in this reaction the effects of charge symmetry breaking on differences between these two observables must be small." [11]

In summary, new R-matrix and shell-model calculations have been obtained near 2.5 MeV. These analyses, which include the effects of the Coulomb interaction, predict that $A(\theta)$ should be larger than $P(\theta)$ by about 0.02 to 0.05 out of a maximum value that is near 0.40 for 55° (c.m.). Since the experimental values are equal to within their uncertainties, i.e., to accuracies of about 0.02 to 0.03, there is no evidence for unexplained (i.e., nuclear) charge symmetry breaking in this case. Fig. B2-1 reproduces an illustration of these conclusions from the polarization paper above, showing the $P(\theta)$ data, R-matrix calculations [10] by Hale, and shell-model results from Florida State. [12]

[WT, RCB]

d. The $^9\text{Be}(p,n)^9\text{B}$ Reaction

The focus of recent data acquisition for this reaction has been on (1) analyzing power results measured with the pulsed polarized beam and (2) higher energy cross sections to support previous Lane model studies (see Overview; also see Refs. [4,5,13]). Preliminary results for the analyzing powers were presented [14] at the Spring meeting of the APS and at the Fifth Polarization Symposium as part of a study of time-of-flight (TOF) analyzing power data for light nuclei:

"Neutron time-of-flight techniques

Fig. B2-1. Comparison of $P(\theta)$ data to calculations of $P(\theta)$ and $A(\theta)$ for the ${}^3\text{H}(p,n){}^3\text{He}$ reaction.

have been used to measure analyzing powers for the reactions $9\text{Be}(p,n)9\text{B}$, $11\text{B}(p,n)11\text{C}$, $13\text{C}(p,n)13\text{N}$, and $15\text{N}(p,n)15\text{O}$ between 7 and 17 MeV. The results show systematic behavior similar to that of Lane model predictions." [15]

New cross section results at 16.4 and 17.5 MeV have not yet been analyzed and will be included in a larger study of $9\text{Be}(p,n)9\text{B}$ cross section results from 8 to 17 MeV, which is due for publication next year. Discussion and presentation of the earlier data from 8 to 16 MeV were included in last year's Report.

Our data set of (p,n) analyzing powers for 9Be now includes (1) proton-recoil scintillator results at forward angles from 8 to 15 MeV, (2) similar 4He -recoil scintillator results [16] at 8.1 and 9.1 MeV, and (3) new TOF data at 8.2, 9.2, 11.1, 13.5, and 15.0 MeV. This latter work is not yet completely analyzed; it extends the other results both to more backward angles and to higher energies.

Fig. B2-2. Comparison of values for the $9\text{Be}(p,n)9\text{B}$ analyzing power. The different data sets were obtained using different analysis techniques.

A paper at Santa Fe compares the techniques and data for the new TOF approach to those of the previous recoil scintillator analyses. Figure B2-2 is reproduced from this paper and shows the comparison of data reduction techniques. The abstract and conclusions of the Santa Fe paper are repeated here:

"Techniques for (p,n) analyzing power measurements using recoil spectrum stripping and neutron time-of-flight have been developed. Results are discussed in terms of the $9\text{Be}(p,n)9\text{B}$ reaction."

"The results of the three experimental techniques as applied to the $9\text{Be}(p,n)9\text{B}$ reaction at 8.1 and 15.0 MeV are Fig. B2-2. The "basic recoil" results use the observed asymmetry in a region

of the proton recoil spectrum judged to have negligible background contamination: no explicit correction is made. The "spectrum analysis" results were obtained from the same spectra by subtracting a smooth background with zero asymmetry. (Note: These two methods are discussed in detail in the paper by Mack *et al.* [18] below.) Finally, the "time-of-flight" values result from stripping of NTOF spectra from a separate experiment. Since ion source problems during the NTOF experiment limited effective beam currents to less than 20% of normal, typical data would have much smaller uncertainties.

Neutron time-of-flight appears to be the preferred experimental method in all but the simplest cases, having advantages in resolution, ease of analysis, and ultimate accuracy. Without this sophisticated hardware, recoil techniques can provide almost as reliable results, but only for well-separated states with low backgrounds. Spectrum stripping may be able to improve accuracies slightly over the simple analysis; but as backgrounds increase at higher energies, the reduction in effective counting rate and increase in analysis complexity make this approach much less appealing than the newer method." [17]

Results of two previous studies were published during the past year. Fig. B2-3 shows the overall Lane model description (see Overview and Refs. [4,5,13]) of the $9\text{Be} + \text{nucleon}$ system; the data shown are those which were included in the search. The (p,n) analyzing powers used here were the forward-angle results of Mack *et al.* [18]. Fig. B2-4 shows the same Lane model predictions, but compared to our more recent and extensive data of Ref. [15]. It is clear that a reanalysis will be necessary to improve the description at more backward angles. In addition, the predictions of the new (n,n) analyzing powers are shown in Fig. B2-5; both Figs. B2-3 and B2-5 are from Ref. [5].

A report on some of our older (p,n) $A(\theta)$ data from 8.1 to 15.0 MeV was recently published. This paper presents measurements using proton recoil scintillators which have been substantiated by the recent unpublished data above. [16,17] Much of the discussion concerns the background problems encountered in an analysis of recoil scintillator data for this reaction. Also, much of the theory for the Lane model and P-A differences is presented here at its most basic level. Last year's Report discusses these measurements in detail and presents figures showing the data in its final form. The abstract from the paper of Mack *et al.* [18] is presented below:

"The analyzing power $A_y(\theta)$ for the $9\text{Be}(p,n)9\text{B}$ reaction was measured at seven energies between 8.1 to 15.0 MeV for reaction angles between 0° and $100^\circ(\text{c.m.})$. The $A_y(\theta)$ values are predominantly negative and exhibit a smooth variation with energy.

Fig. B2-3. Lane model analysis of the $^9\text{Be} + \text{nucleon}$ system. Fits are obtained from a single coupled-channels calculation using an isospin-conserving potential.

Fig. B2-4. Detail of Lane model analysis of the ${}^9\text{Be}(p,n){}^9\text{B}$ analyzing power. Data are the new results of Ref. [15], obtained using neutron time-of-flight.

Fig. B2-5. Lane model predictions compared to data for the ${}^9\text{Be}(n,n){}^9\text{Be}$ analyzing power. Calculations were made with the same potential used for Figs. B2-3 and B2-4.

The significance of these results in Lane model calculations for the $9\text{Be} + \text{nucleon}$ system and in comparisons between the observables $P_y(\theta)$ and $A_y(\theta)$ will be discussed." [18]

[KM, RCB]

e. The $11\text{B}(p,n)11\text{C}$ Reaction

Preliminary measurements for this target have been made this year as an extension of previous P-A comparisons and of our Lane models for the neighboring nuclei 9Be and 13C . The P-A comparison consists of an $A(\theta)$ distribution at 8.56 MeV for comparison to previous $P(\theta)$ data obtained at Livermore Laboratory. The results were presented at the Fifth Polarization Conference, along with a similar comparison for 13C targets. The abstract follows:

"Analyzing powers have been measured for the $11\text{B}(p,n)11\text{C}$ reaction at 8.56 MeV and for the $13\text{C}(p,n)13\text{N}$ reaction at 6.88 and 8.00 MeV. Comparisons are made to earlier measurements of the polarization, and differences are discussed in terms of current theoretical results." [19]

We find possible evidence for small P-A splitting in these reactions. Figure B2-6 is an illustration which summarizes the experimental data from this paper. (The $P(\theta)$ data are from Ref. [20].) The principal difficulty with the evaluation results from the pronounced resonance behavior at the energies where such splitting is expected; any differences in target thickness or beam energy can therefore yield spurious results. Since these comparisons are based on TUNL $A(\theta)$ data and on separate $P(\theta)$ results from Livermore Laboratory (as opposed to the data for 9Be and 15N , where both measurements were made at TUNL), we cannot absolutely verify the existence of the small observed differences.

A considerable amount of thick-target data was measured as cross section angular distributions at 10.5, 11.5, 12.5, 13.5, 14.5, and 15.5 MeV; companion $A(\theta)$ angular distributions were taken at 8.5, 10.5, and 12.0 MeV. These results have not yet been analyzed, but it appears that the remaining resonance structure can be averaged sufficiently to allow an optical model analysis of the results. Such an analysis is particularly inviting, because the comparison of results includes not only (p,p), (n,n) and (p,n) data for 11B targets, but also (p,p) and (n,n) data for the 10B nucleus. Thin 11B targets are being fabricated for use in further experiments.

[KM, RCB]

Fig. B2-6. $P(\theta)$ and $A(\theta)$ results for the $^{11}\text{B}(p,n)^{11}\text{C}$ and $^{13}\text{C}(p,n)^{13}\text{N}$ reactions. The A data are from TUNL; P data are from Livermore Laboratory.

f. The $^{13}\text{C}(p,n)^{13}\text{N}$ Reaction

As with ^{11}B , new measurements consist of analyzing powers at lower energies (6.88, 8.00, and 8.77 MeV) for comparison to previous polarization results and analyzing powers at energies where optical models may be successfully applied. The results of a P-A comparison were presented at the Fifth Polarization Conference; the abstract [19] is given in Sec. B2e on ^{11}B studies. The analyzing powers at higher energies were part of a study of TOF data for light nuclei, also described above. [15]

No new cross section results have been obtained, since our previous data adequately cover this range of energies. A paper on these cross sections is being published in Nuclear Physics A as part of a study of cross sections and analyzing powers and their Lane model interpretation. The abstract follows:

"Angular distributions of the cross section for the (p,n₀) reaction on ^{15}N and the (p,n₀), (p,n₁), and (p,n₂+n₃) reactions on ^{13}C have been measured at energies from 9 to 17 MeV using neutron time-of-flight techniques. A coupled-channels Lane model based on isospin-conserving potentials was used to describe the available (p,p), (p,n), and (n,n) data in this energy range. Although the behavior of the ^{15}N + nucleon system is reasonably well described, no satisfactory potential was found for the ^{13}C case." [21]

Figure B2-7 shows the behavior of the $^{13}\text{C}(p,n)^{13}\text{N}$ cross section data,

Fig. B2-7. Composite figure for $^{13}\text{C}(p,n)^{13}\text{N}$ cross sections measured at TUNL and Livermore Laboratory.

including results from previous studies. Fig. B2-8 shows the Lane model results near 11 MeV; the "data" in this figure, except for the (p,n) $P(\theta)$ results of Walker *et al.*, [20] has been smoothed over energy. The (p,p) results are from Weller *et al.*, [22] and the "Watson" parameters are from a global optical model for light nuclei. [23]

[KM, RCB]

g. The $^{15}\text{N}(p,n)^{15}\text{O}$ Reaction

Much of our interest in the $^{15}\text{N}(p,n)^{15}\text{O}$ system was stimulated by the dramatic observed differences between P and A below 9 MeV, a detailed report of which is now in preparation. Calculations by Philpott and Halderson [1] using a recoil-corrected continuum shell model have been able to reproduce the character of the observed differences (see Overview; also see Refs. [1-3,24]).

The erratic quality of the (p,n) cross section data below 9 MeV led us to obtain supplementary data in this energy range. A considerable amount of effort went into evaluation of all previously

Fig. B2-8. Lane model description of the ^{13}C + nucleon system near 11 MeV.

available data. A paper on our results is being published in Nuclear Physics A:

"In connection with studies of differences between the polarization and analyzing power observables for the $^{15}\text{N}(p,n)^{15}\text{O}$ reaction, differential cross sections at ten proton energies between 5.5 and 9.3 MeV were measured using time-of-flight techniques. These new measurements allowed all previous data to be evaluated through use of the extensive total cross sections measured by Barnett in a study of the mass-16 system. Although some previous data were clearly discrepant, a simple renormalization of Barnett's measurements results in consistency of most of the data." [25]

The results of this analysis were also presented at the 1980 meeting of the Southeastern Section of the American Physical Society in Chapel Hill, N.C. Fig. B2-9 shows the agreement between different data sets. The upper part gives the results before renormalization of the total cross sections of Barnett [26] and rejection of seriously discrepant data; the lower part shows the situation afterwards.

Fig. B2-9. Total cross section for the $^{15}\text{N}(p,n)^{15}\text{O}$ reaction below 9.3 MeV. The solid curve represents the data of Barnett; individual values are obtained from other authors. The upper panel shows data before renormalization of Barnett's results; the lower panel shows the agreement obtained by renormalization.

Above 9.3 MeV the Lane model study [18] of the ^{13}C and ^{15}N systems revealed the need for further cross section and analyzing power measurements at energies between 12 and 17 MeV. Differential cross sections were measured at 16.25 and 17.0 MeV and angular distributions of $A(\theta)$ were taken at 12.0, 15.0, and 16.8 MeV. Although some of the analyzing power data was presented at Santa Fe (see Ref. [15]), most of these new results have yet to be processed; it appears that they will be very useful in resolving the uncertainties in the energy dependence of the parameters of the Lane model analysis. [18] Figure B2-10 shows the behavior of the $^{15}\text{N}(p,n)^{15}\text{O}$ data set published in the ^{13}C - ^{15}N paper [18]; data are from both TUNL and Livermore Laboratory. [27] Fig. B2-11 shows the Lane model predictions, again with the data smoothed over energy. (The (p,p) results are from Ref. [28].)

Fig. B2-10. $^{15}\text{N}(p,n)^{15}\text{O}$ cross sections above 9 MeV. Data are from both TUNL and Livermore Laboratory.

Fig. B2-11. Lane model description of the $^{15}\text{N} + \text{nucleon}$ system.

An interesting pilot study has taken advantage of the high neutron analyzing power [29] and density of ^{12}C to obtain the transverse polarization transfer for the $^{15}\text{N}(p,n)^{15}\text{O}$ reaction at 0° between 12.5 and 16.6 MeV. These results were shown at the 5th Polarization Symposium, [30] and we reproduce the concluding paragraph here:

"An interesting feature of $K_{yy}(0^\circ)$ is that it doesn't exhibit the high values observed in the previous reactions with 1p-shell targets. In fact, at the highest energies, 14.5 to 16.5 MeV, where the cross section is fairly stable, the K_{yy} is 0.0 to within about ± 0.1 . A value of 0.0 means that even if the incident protons are 100% polarized, the neutrons emitted at 0° are "completely depolarized" or unpolarized. It will be interesting to investigate this effect with model calculations. Likewise, it would be of interest to determine experimentally what happens to K_{yy} at higher proton energies." [30]

[KM, RCB]

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3. Neutron Reaction Studies Involving Polarized Deuteron Beams

Polarization studies in (d,n) reactions have historically been a major interest at TUNL, although during the past couple of years this thrust has been small. Several projects involving light nuclei are discussed below. The experimenters are among those listed in Sec. B1-a and are more closely identified in various references to the Santa Fe Proceedings. For the last project, the group consisted of P.W. Lisowski, R.C. Byrd, W. Tornow, G. Mack and R.L. Walter. With the success of the pulsed polarized deuteron beam facility, additional analyzing power measurements can easily be undertaken in the 4- to 16- MeV energy range, and a few may be investigated in the future.

a. Analyzing Power for the $2\text{H}(d,n)$ Reaction

The pulsed polarized beam facility recently developed at TUNL provides proton and deuteron beams of intensities up to 170 nA. This system allows standard time-of-flight techniques to be used for measurements of analyzing powers for neutron producing reactions or neutron scattering processes. We thought it reasonable to check the reproducibility of our successive measurements and to compare with accurate data obtained elsewhere. Vector analyzing powers for the $2\text{H}(d,n)^3\text{He}$ reaction were chosen since they can be measured very accurately with the new system and have been reported with very high precision by groups at Zurich [1] and Wisconsin [2]. Also, a more complete data set would be important in improving the understanding of the 4-nucleon system, already one of the most heavily studied nuclear systems.

We began the program with the intention of complementing the 11.5 MeV data taken at Zurich [1] in 1972. However, during the experimental stage of our program, we received a preprint from Zurich with more recently measured data at 5.5, 7.0, 8.5, 10.0, and 11.5 MeV. [3] In both of the Zurich experiments the outgoing ^3He particles were detected, a method quite different from our neutron time-of-flight technique. As a result, the Zurich group was only able to obtain the vector analyzing power corresponding to back angles for the $2\text{H}(d,n)^3\text{He}$ reaction. Initially our intention was to tie on to the most forward angle data from Zurich. However, it soon became evident that the data sets were not consistent, so we were forced to obtain entire angular distributions.

The comparison is made in Fig. B3-1. Uncertainties for the TUNL data range from 0.002 to 0.008 in analyzing power, with a mean uncertainty of 0.003. Our results are in excellent agreement with the limited data taken in 1972 at 10.0 MeV by Hilscher and Liers at Wisconsin [2]; as at Zurich, the Wisconsin experiment detected the outgoing ^3He particles. We renormalized their data by 3%, in agreement with the 5% absolute normalization uncertainty quoted. Fig. B3-2 illustrates the agreement. We have made polynomial fits to the product $A(\theta)\sigma(\theta)$ and are parameterizing the coefficients as a function of energy.

The data described here were presented at Santa Fe. [4]

Fig. B3-1. Comparison of present data for $2\text{H}(d,n)^3\text{He}$ to previous work from ZÜRICH.

Fig. B3-2. Same results compared to previous work of Hilscher and Liers.

b. Polarization Transfer in $2\text{H}(d,n)^3\text{He}$ between 0° and 20° .

In scattering experiments that utilize the polarized neutron beam produced in the $2\text{H}(d,n)^3\text{He}$ polarization transfer reaction, the scatterer is placed along the original incident deuteron beam axis, i.e., at a reaction angle of 0 degrees for the $2\text{H}(d,n)$ reaction. The average polarization transfer coefficient is known for the angular region between 0 and 2 degrees from previous work at TUNL. [5] However, in our scattering experiments the samples must be relatively large and placed relatively close to the $2\text{H} + d$ source reaction in order to overcome counting rate problems. Typically the scatterer in the (n,n) experiments subtends an angle out to between 5 and 7 degrees; in the (n,γ) experiments, the angle is out to about 15 degrees. It is therefore important to know the angular distribution of the polarization produced in the $2\text{H}(d,n)$ reaction for angles out to 15 degrees.

The outgoing polarization in a polarization transfer reaction depends on four parameters specific to each reaction and two parameters that depend on the nature of the polarization of the incident deuteron beam, i.e., the magnitude of vector and tensor components. We performed an experiment that determined the neutron beam's "effective polarization" for a deuteron beam in the $m = +1$ state [$P(\text{vector}) = P(\text{tensor})$]. The alignment axis is along a vertical axis normal to the horizontal plane containing the detectors. The measured quantity gives an average polarization that enters into scattering experiments that are performed in the conventional way, where the direction of the deuteron beam polarization is alternately flipped from up to down at the ion source. (An attempt to obtain the additional information of the magnitude of the polarization transfer coefficient away from zero degrees was made by manipulation of recorded yields for eight combinations of spin orientation, reaction angle, and analyzing angle, but the result was only partially successful.) The polarization transferred to the neutrons was determined by scattering from ^{12}C at 40 degrees, the angle where TUNL experiments have shown that the figure of merit for $^{12}\text{C} + n$ analyzing power is largest. The deuteron beam energy was 8 MeV, and that of the outgoing neutrons was about 11 MeV. Time-of-flight detection was employed with the standard 4-meter and 6-meter detectors, which had to be positioned relative to the (movable) wedge-shaped carbon analyzer at scattering angles of 40 degrees. For one-half of the measurement the carbon scatterer was on the left side of the deuteron beam axis and for the other half on the opposite side. For each of the two deuteron spin orientations one obtains four yields in this way. By averaging the results for spin-up and spin-down, we obtain a symmetric function representing an "effective polarization" for our neutron beam.

The results were presented at Santa Fe [6] where it was shown that the "effective polarization" of the neutrons is probably equal to the zero degree value for the entire region all the way out to 15 degrees. (It is important to realize that this refers to the average of the neutron beam polarizations for deuteron beams with spin-up and spin-down!) The value of 0.62 at zero degrees was used as a calibration point for the ^{12}C analyzer; its value was determined in Ref. [4] by scattering $2\text{H} + d$ neutrons from 4He . The observed value of 0.62 for our beam indicates that nearly 90% of the polarization of the deuteron beam is "effectively" transferred to the neutrons over the angular region subtended in the TUNL experiments. This result demonstrates another favorable feature of the $2\text{H}(d,n)$ polarization transfer reaction as a source of polarized neutrons. Additional experiments will be performed at forward angles to learn more details about some of the four reaction parameters mentioned above.

[WT,RLW]

c. Polarization Transfer Studies in (d,n) Reactions on Light Nuclei

A revised manuscript on the polarization transfer at zero degrees in (d,n) reactions on ^{12}C , ^{14}N , ^{16}O , and ^{28}Si has been completed. It is in the hands of F.D. Santos of Lisbon for possible

theoretical collaboration. The work on the polarization transfer for deuteron breakup reactions has been inactive and the data will not be published until more experiments are conducted. In cooperation with H.W. Lewis (Duke), we are in the process of reactivating the ^4He scintillator with the intent of studying the polarization of neutrons produced in the white-source spectrum of thick targets. Such beams, used in conjunction with the pulsed polarized deuteron beam capability, present extremely powerful possibilities for the polarized target experiments planned at TUNL.

[RLW]

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C. HIGH RESOLUTION STUDIES

1. High Resolution Elastic Scattering

(E. G. Bilpuch, G. E. Mitchell, B. Dubendorff, R. O. Nelson, K. B. Sales,* B. Warthen, W. A. Watson, C. R. Westerfeldt)

The high resolution elastic scattering measurements at present involve four elements-- ^{29}Si , ^{56}Fe , ^{64}Zn , and ^{66}Zn . The ^{29}Si study is our first measurement on non spin-zero nuclei and in large part is intended as a pilot study for such nuclei. The measurements on the Zn isotopes are an extension to higher A values of our earlier work on proton strength functions. The ^{56}Fe study is the first full scale (multichannel, wide energy range) study with the tandem high resolution system. Here the motivation was twofold--to study fragmented analog states and to measure detailed statistical properties of the resonances.

a. ^{56}Fe

As was reported last year, the reactions $^{56}\text{Fe}(p,p)$ and $^{56}\text{Fe}(p,p')$ have been studied using the high resolution system of the TUNL FN tandem accelerator, extending our program of high resolution experiments to higher energies and hence to higher ℓ -values. The analysis of the data taken last year is now complete, and results will be published in the near future (preliminary results were given at the Washington APS meeting--Bull. Am. Phys. Soc. 25 (1980) 596). This work formed the basis for the Ph.D. dissertation of W. A. Watson.

The experiments covered the proton energy range from 3.1 to 4.0 MeV in typical energy increments of 120 eV. Elastic scattering data for 3 angles (out of 5) and inelastic scattering data for 1 angle are shown in Fig. C1-1. The solid line through the points is an R-matrix fit. The overall energy resolution was approximately 425-450 eV, allowing the observation of resonances with laboratory widths as small as 5-10 eV. Approximately 350 resonances were observed, over half of which were $\ell=2$ levels. Angular distributions of deexcitation γ -rays were measured for those d-wave resonances with appreciable inelastic yield, as well as for selected p-wave resonances (a total of about 140 resonances). These γ -ray data were useful in determining the j-value of many of these resonances.

Five fragmented isobaric analog states were observed: a $5/2^-$ state at $E_p=3.422$ MeV, a $9/2^+$ state at 3.713 MeV, a $5/2^+$ state at 3.763 MeV, a $3/2^-$ state at 3.890 MeV, and a $1/2^-$ state at 3.958 MeV. The fine structure distributions were fit to a theoretical curve to obtain values for the analog state energies, reduced widths, spreading widths, and asymmetry parameters (the last two parameters being poorly determined). Spectroscopic factors were found to be in agreement with (d,p) measurements only to within a factor of 2.

Fig. C1-1. Elastic and inelastic scattering excitation functions for protons on ^{56}Fe .

The statistical properties of the observed levels were investigated in terms of the random matrix theory. Reduced width distributions were calculated and show good agreement with the Porter-Thomas distribution. The comparison also provided an estimate of the number of weak levels unobserved. Nearest neighbor spacing distributions were calculated for the $1/2^+$, $1/2^-$, $3/2^-$, $3/2^+$, and $5/2^+$ sequences and compared with the Wigner distribution. These spacing distributions were also compared with a more exact distribution derived from the orthogonal ensemble, in which higher order spacing distributions were included to compensate for missing levels. In this latter comparison, the agreement was quite good and was limited only by the smallness of the sample sets.

The $1/2^+$ level sequence was found to be quite pure--having no or few missing or spurious levels. This set of 56 s-wave resonances is probably the best set of proton resonances (for statistical studies) observed to date, and is comparable in quality to the neutron data sets which form the bulk of the experimental evidence for the random matrix theory. The results of statistical tests of the quality of the data set (the Dyson F-statistic and the Dyson Mehta Δ_3 statistic) were consistent with no (or few) missing levels. In addition, good agreement was found between the experimental and theoretical values of the adjacent spacing correlation coefficient and the widths of the k-th order spacing distributions for $k=0$ to 10. These widths are compared with the theoretical predictions in Fig. C1-2 where the lower solid curve is the

orthogonal ensemble prediction, the two dashed curves are the 10% and 90% limits of the distribution of widths for a sample size of 56 levels, and the upper curve is the prediction assuming a set of uncorrelated spacings following a Wigner distribution. Since all but one of the experimental numbers fall inside the expected 10% and 90% limits, the agreement with the random matrix is quite satisfactory.

Fig. C1-2. Widths of the k-th nearest neighbor spacing distributions as a function of k.

b. ^{64}Zn , ^{66}Zn

These experiments have been completed and will be prepared for publication in the near future. A preliminary report was presented at the Washington American Physical Society Meeting: Bull. Am. Phys. Soc. **25**, 596 (1980). This work formed the basis for the Ph.D. dissertation of K. B. Sales. The following is the abstract of that dissertation:

"Differential cross sections were measured for $^{64}\text{Zn}(p,p)$ from 2.50 to 3.24 MeV and for $^{66}\text{Zn}(p,p)$ from 2.60 to 3.26 MeV at laboratory angles of 90 degrees, 105 degrees, 135 degrees, and 160 degrees. These experiments were performed with the Triangle Universities Nuclear Laboratory 3 MV Van de Graaff accelerator and associated electrostatic analyzer-homogenizer system. The total overall energy resolution was 420 to 525 eV for $^{64}\text{Zn}(p,p)$ and 360 to 405 eV for $^{66}\text{Zn}(p,p)$.

Resonances observed in the excitation functions were analyzed with a multilevel R-Matrix formalism. Resonance energies, spins, parities, and elastic widths were extracted for 39 resonances in ^{65}Ga and 148 resonances in ^{67}Ga .

The $l=0$ proton strength functions were calculated for ^{64}Zn and ^{66}Zn . The s-wave strength function shows an increase for $A=66$, which is consistent with earlier results from (p,n) cross section studies.

Statistical properties of the $1/2^+$ resonances in ^{65}Ga and ^{67}Ga were examined. The spacing and reduced width distributions were compared with the Wigner and Porter-Thomas distributions, respectively. This comparison indicates that 50% of the $1/2^+$ resonances were missed in ^{65}Ga and that 70% of the $1/2^+$ resonances were missed in ^{67}Ga . The observed s-wave level densities in ^{65}Ga and ^{67}Ga are compared with predictions from conventional level density models.

The analogs of the 0.867 MeV, the 0.910 MeV, and the 1.370 MeV states of ^{65}Zn are observed in ^{65}Ga ; the analogs of the 0.093 MeV and the 0.394 MeV states of ^{67}Zn are observed in ^{67}Ga . The analog states in ^{65}Ga were fragmented into only two or three resonances, while the two analog states in ^{67}Ga were highly fragmented. Fits to the fine structure distributions of these two analogs were obtained and the resulting parameters compared with the Robson model. Coulomb energies were extracted for these five analogs. The spectroscopic factors were calculated for each analog and compared with the parent state spectroscopic factors obtained in (d,p) studies. Most of the values obtained in the direct reaction measurements were approximately a factor of

two larger than those from the present analog studies."

c. ^{29}Si

Analysis of the data from our first elastic scattering experiment on a non spin-zero target is in progress. Sixty-four resonances were observed in the differential cross section for elastic and inelastic scattering of protons from ^{29}Si in the energy range $E_p=1.3-3.3$ MeV. Seven of these sixty-four resonances had not previously been observed, and twenty of the remaining resonances had not been analyzed due to interference effects and/or poor resolution. In addition, two resonances reported earlier were not observed in this work--one can be attributed to a poor fit in a region of interfering resonances, and the other was probably an experimental artifact. A preliminary report on this work was presented at the Washington meeting of the American Physical Society: Bull. Am. Phys. Soc. 25, 595 (1980).

Before final analysis, portions of the data required corrections. Broad resonances due to ^{28}Si (4.36% isotopic abundance in the target material) were apparent in the 160 degrees excitation function; a background subtraction was thus required. To facilitate this subtraction procedure, all sections of the data were normalized to a common factor and a theoretical calculated cross section (with resonance parameters taken from the literature) was subtracted. An additional "hump" appeared in the 160 degrees differential cross section near 1.68 MeV; this anomaly was due to resonances in elastic scattering on the ^{12}C backing. The differential cross section at 160 degrees approaches one barn for these resonances; the detector is flooded with protons from the ^{12}C resonances and sum peaks appear in the spectrum. This problem was eliminated with improved electronics and thinner target backings.

At this time fits have been obtained for forty resonances. Determination of the orbital angular momentum has presented no problem for all but the smallest resonances (less than 10 eV laboratory width). In general, definite spin assignments can be made for resonances having the product $(2J+1)\Gamma_p$ greater than 150 eV. In cases for which channel spin mixing is allowed, the two channel spins lead to very different resonance shapes--as shown in Fig. C1-3. This enables determination of the entrance channel mixing ratio. Analysis of the many interfering resonances in the energy region above 2.8 MeV is in progress.

FOOTNOTE (Section C1)

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Fig. C1-3. Resonance shapes for different entrance channel spins for a 1^- resonance in ^{30}P .

2. High Resolution Inelastic Scattering

(G. E. Mitchell, E. G. Bilpuch, B. H. Chou,* P. Ramakrishnan, J. Shriner, W. A. Watson, C. R. Westerfeldt, K. M. Whatley)

a. General

Emphasis on high resolution inelastic scattering has continued during the past year. These measurements usually provide a definitive spin assignment, thus removing the $1/2^-$, $3/2^-$ and $3/2^+$, $5/2^+$ ambiguities which often occur in elastic scattering measurements. Thus proton strength functions can now be obtained separately for both l and J values. However, the major thrust of these experiments relates to local rather than global statistical properties.

The central point is that statistical theories of spectra, as well as descriptions of doorway states, are formulated in terms of width amplitudes. Essentially all relevant experiments determine only the magnitude of the reduced width amplitudes; the sign of the width amplitude is impossible to obtain. Thus the measurement of interference effects in a multichannel process appears to provide the most sensitive measurements possible.

In these measurements isolated resonances are studied with the reaction $A(p,p')A^*$, followed by $A^* \rightarrow A + \gamma$. For all of these experiments $J_A^\pi = 0^+$ and $J_{A^*}^\pi = 2^+$. Angular distributions of the inelastically scattered protons and of the de-excitation γ -rays are measured. Performing the measurements far below the top of the Coulomb barrier reduces the number of exit orbital angular momenta involved--thus singles measurements are sufficient to analyze many cases. This method permits the study of many resonances and makes statistical analyses possible.

In a typical experiment $l=1$ resonances are studied. The angular distributions provide a definite spin assignment of $1/2$ or $3/2$. The $3/2^-$ resonances decay to the first excited 2^+ state by two $l'=1$ amplitudes-- $p_{1/2}$ and $p_{3/2}$. It is the relative sign between these two amplitudes that is of primary interest: our measurements determine $\gamma_{p_{1/2}}^2$, $\gamma_{p_{3/2}}^2$, and $\gamma_{p_{1/2}}\gamma_{p_{3/2}}$. (Naturally one has to consider any $l'=3$ contributions--these effects are neglected here for simplicity.) Another case of particular interest involves the $l=2$ resonances, where the experiment distinguishes between $3/2^+$ and $5/2^+$ states. For $5/2^+$ states the singles measurements are sufficient to determine γ_c^2 and $\gamma_c\gamma_{c'}$ for the three decay amplitudes $s_{1/2}$, $d_{3/2}$, and $d_{5/2}$. For $3/2^+$ states the singles measurements do not provide sufficient information and two solutions are obtained. This method has also been successfully applied to $l=3$ resonances, where $5/2^-$ and $7/2^-$ states were distinguished, and decay amplitudes were obtained for $5/2^-$ states. In principle this approach also works for $l=4$ resonances, as well as for other angular momentum combinations. In practice our efforts have focussed on $l=1$ and $l=2$

resonances, and after the spin determinations, on $3/2^-$ and $5/2^+$ resonances. Since we observe many $l=1$ analogs (our studies emphasize the $1f-2p$ nuclear shell), the $3/2^-$ resonances are expected to be best suited for the study of doorway states and the $5/2^+$ states most suitable for the study of statistical properties.

b. Theoretical Expectations

The expected distribution for the products of amplitudes depends upon the physical assumptions adopted. Since it is often more convenient to deal with the ratio of amplitudes instead of the product, we define a mixing ratio $\delta \equiv \gamma_{c'}/\gamma_c$ and a mixing angle $\phi \equiv \tan^{-1}\delta$.

First consider two limiting cases: the extreme statistical model and a doorway state mixed with a picket fence background. For the latter case Lane showed that for an isolated common doorway the ratio δ is the same for all levels. Thus for a fragmented doorway state the relative phase between the amplitudes in different channels is the same for all fragments. For a realistic background one expects a relatively narrow spread of values about some δ_0 . This was proven experimentally for the first time on ^{44}Ca (Lane, Dittrich, Mitchell, and Bilpuch, Phys. Rev. Letters 41 (1978) 454 thus; Mitchell, Dittrich, and Bilpuch, Z. Physik A289 (1979) and later confirmed for ^{46}Ti (Chandler, Mitchell, and Bilpuch, Phys. Rev. C20 (1979) 52.

The other limit is the extreme statistical model, in which the amplitudes for each channel (are assumed to obey a Gaussian distribution of zero mean, and the widths in different channels are assumed uncorrelated. For convenience one further assumes that the average channel widths are equal. If one samples at random from these distributions for channels c and c' , for example, then the distribution for the ratio is $P(\delta)d\delta = [\pi(1+\delta^2)]^{-1} d\delta$. The transformation $\phi = \tan^{-1}\delta$ leads to $W(\phi)d\phi = \pi^{-1}d\phi$. The extreme statistical model thus predicts a uniform distribution for ϕ . The assumption that $\langle \gamma_c^2 \rangle = \langle \gamma_{c'}^2 \rangle$ is just cosmetic—if the average widths are unequal, one can simply renormalize. However, the other assumptions are the keystones of the extreme statistical model—the random phase approximation, the Gaussian shape, and the lack of correlations between channels. Our experimental results strongly disagree with the extreme statistical model. It therefore becomes very interesting to consider the problem in more depth.

There is a more general approach to the width amplitude distribution, which was formulated by Krieger and Porter (J. Math. Phys. 4, 1272 (1963). They utilized "the principles of level independence and of invariance with respect to orthogonal transformations of the basis state vectors of the compound nuclei" to derive a multivariate reduced width amplitude distribution. For the two channel case they obtained for the joint distribution function of the width amplitudes

$$P_{cc'} = \pi \gamma_\lambda (|M|^{1/2}/2\pi) \exp [-1/2 \gamma_\lambda M \gamma_\lambda]$$

where M is a real, two by two symmetric matrix and $M = \overline{\gamma_\lambda} \times \gamma_\lambda$, M is the determinant of M , and γ_λ is a two component vector. Unless M is diagonal $P_{cc'}$ is not independent (factorable) with respect to channels, and thus correlations may exist between amplitudes in different channels. Explicitly

$$P(\gamma_1, \gamma_2) = (|M|^{1/2}/\pi) \exp [-M_{11}\gamma_1^2/2 - M_{22}\gamma_2^2/2 - M_{12}\gamma_1\gamma_2]$$

where a factor of two arises from the restriction $\gamma_1 \geq 0$. Transforming to a polar system (r, ϕ) , where $r = (\gamma_1^2 + \gamma_2^2)^{1/2}$ and $\phi = \tan^{-1}(\gamma_2/\gamma_1)$, one obtains

$$P(r, \phi) = (|M|^{1/2}/\pi) r \exp [(-r^2/2) (M_{11} \cos^2\phi + M_{22} \sin^2\phi + M_{12} \sin 2\phi)]$$

Integrating over r one obtains the marginal probability density function (pdf).

$$P(\phi) = (|M|^{1/2}/\pi) (M_{11} \cos^2\phi + M_{22} \sin^2\phi + M_{12} \sin 2\phi)$$

where $|M|^{-1} = \overline{\gamma_1^2} \overline{\gamma_2^2} - (\overline{\gamma_1 \gamma_2})^2$, $M_{11} = \overline{\gamma_2^2} \cdot |M|$, $M_{22} = \overline{\gamma_1^2} \cdot |M|$, and $M_{12} = -\overline{\gamma_1 \gamma_2} \cdot |M|$. There are some interesting special cases contained in this result. If there are no correlations, then $M_{12} = 0$, and $P(\phi)$ is symmetric about $\phi = 0$. In the special case $M_{11} = M_{22}$, the marginal pdf is uniform. although some of our data involve three channels, it is easy to show that the appropriate three channel pdf (function of r, θ, ϕ , say) reduces to $P(\phi)$ after integration over r and θ , and that each pair of channels may be considered separately.

Thus the general statistical theory allows for correlations between channels. The Krieger-Porter distribution had never been explicitly tested until the present work (see section d below). It is also interesting to note that integrating over one of the amplitudes in the distribution $P(\gamma_1, \gamma_2)$ leads to a Gaussian distribution. The corresponding (single channel) distribution for γ^2 is of course the Porter-Thomas distribution. It is important to emphasize that the singlet distribution is obtained independently of the existence of correlations between width amplitudes in different channels. Therefore agreement of experimental data with the Porter-Thomas distribution provides no information concerning channel correlations.

c. $\ell=1$ Resonances in 49V

An extensive study of more than 100 $\ell=1$ resonances in 49V was performed. Detailed information was obtained for a set of 71 $3/2^-$

resonances, for which statistical results were expected. No anomalous behavior was observed in the plot of reduced widths versus energy; the reduced width distributions agreed very well with the Porter-Thomas distributions. Nevertheless striking non-random behavior was observed. These results may be summarized as follows: (1) the distribution $N(\phi)$ versus ϕ shows two distinct anomalies, one for positive ϕ and one for negative ϕ ; (2) the plot of $\sum \gamma_c \gamma_c$ versus energy shows two distinct and separate energy regions (call them A and B) where the product is the same for almost all of the resonances--the slope in both cases is negative; (3) the linear correlation coefficients between widths and width amplitudes are significantly different from those expected on statistical grounds.

In region A ($E_p \approx 2.3-2.6$ MeV) almost all of the resonances correspond to the anomaly with negative ϕ in the $N(\phi)$ plot. Thus this collection of states satisfies our criteria as intermediate structure common to both channels. The correlation coefficients (channel spin representation) are quite interesting: $\rho(\gamma^2) = 0.17$ (not significant) and $\rho(\gamma) = -0.65$ (very significant). Thus this effect occurs only in the signs and not in the magnitudes of the amplitudes!

For region B ($E_p \approx 2.79-2.95$ MeV) the strong resonances have negative ϕ and therefore cannot correspond to the second anomaly in the $N(\phi)$ plot. The data seem scattered throughout the negative ϕ region. The correlations are $\rho(\gamma^2) = 0.51$ and $\rho(\gamma) = -0.58$, both of which are significant. Thus the data in region B have some, but not necessarily all of the attributes of a common doorway state. On closer examination many of the resonances in the anomaly with positive ϕ do occur in energy region B, however their average strength is very small. These states are thus overshadowed except on a plot which weights resonances equally (independent of strength). At face value this collection of states indicates another non-statistical effect.

A preliminary report was published on this work "Observation of Intermediate Structure in Inelastic Proton Amplitudes in 49V", Wells, Bilpuch, and Mitchell, Physics Letters 86B, 18 (1979), and a more detailed paper has been recently been published "Non-Statistical Effects for Inelastic Proton Amplitudes in 49V", Wells, Bilpuch, and Mitchell, Z. Physik A297 (1980) 215. The following is from the summary of the latter paper:

"(i) there are statistically significant correlations between reduced widths and between amplitudes, and the magnitudes of these correlations change dramatically with energy. Two "regions" are tentatively identified. (ii) in at least one region the non-statistical effect appears only in the relative signs and not in the magnitudes. (iii) the correlations are often, but not always, different in the two representations. (iv) the distribution for the mixing angle is not uniform and shows two distinct anomalies, one

of which apparently corresponds to non-statistical effects previously discussed and one of which does not.

It is clear that what once seemed simple and random, now seems complicated and non-statistical. That non-statistical phenomena underlie the apparent randomness may not be too surprising, but the variety and nature of these effects do seem noteworthy. The appearance of non-statistical properties only in the relative signs seems particularly striking. From an experimental viewpoint, it is crucial to establish the generality of this behavior, but there is essentially no relevant data available."

d. $l=2$ resonances in 49V

Over 100 $l=2$ resonances in 49V were studied, with detailed information obtained for 80 resonances. Definitive spin assignments were given for all of these resonances: 45 resonances were assigned $J = 5/2+$ and 35 resonances were assigned $J = 3/2+$. For the $5/2+$ resonances the average $l'=2$ strength was about 10% of the total inelastic strength; this proved sufficient to permit determination of the three reduced widths and the three products of width amplitudes.

There was no anomalous behavior observed in the plot of γ_c^2 versus energy. In Fig. C2-1 the width distribution for each channel is compared with the Porter-Thomas distribution. Considering the size of the sample, the agreement seems excellent.

The three linear correlations for the reduced widths are all significant, while two of the amplitude correlations are very small. However, one of the amplitude correlations (between the $l'=0$ amplitude and the $l'=2, s'=5/2$ amplitude) is remarkably large-- $P(Y) = +0.88$. This result is also shown dramatically in Fig. C2-2, where 43 of 45 mixing angles have positive sign. As discussed in section b, there is a general theory of width amplitude distribution. As reformulated for our type of measurement, the Krieger-Porter distribution involves only the measured quantities $\overline{\gamma_c^2}$, $\overline{\gamma_c^2 l}$, and $\overline{\gamma_c \gamma_c l}$. The solid curves in Fig. C2-2 are the modified Krieger-Porter distribution. The overall agreement between theory and experiment is excellent. There is some semantic question over whether there are indeed no free parameters in this calculation, or whether the experimental averages themselves are to be considered as free parameters. In any event there are no parameters which are adjusted.

Although this first explicit test of the Krieger-Porter distribution is successful, there remain at least two basic questions: What is the physical origin of the strong correlations and how general are these non-random effects. It is worth emphasizing that just from these two studies ($l=1$ and $l=2$ resonances in 49V) there are examples

Fig. C2-1. Inelastic reduced widths in ^{49}V compared with the Porter-Thomas distribution.

Fig. C2-2. Mixing angles in ^{49}V compared with the Krieger-Porter distribution.

of non-random phenomena (1) which occur in both magnitudes and amplitudes (2) which occur in magnitude and not in amplitudes, and (3) which only in amplitudes and not in magnitudes; there are non-random phenomena which are very localized in energy and show properties of isolated doorway states and other effects which persist over at least an MeV. Obviously more experimental data are badly needed.

This work formed the basis of the Ph.D. dissertation of Ms. B. H. Chou. A preliminary report was presented at the Washington meeting of the American Physical Society: Bull. Am. Phys. Soc. **25** (1980) 596. A short version of these results has been published "Correlations for Reduced Width Amplitudes in 49V", Chou, Mitchell, Bilpuch, and Westerfeldt, Phys. Rev. Letters **45** (1980) 1235. A more extensive paper is presently being prepared for publication.

e. $l=3$ resonances in ^{55}Co

The study of $l=3$ resonances in ^{55}Co provided useful spectroscopic information for a fragmented f-wave analogue and verified the applicability of this method to $l=3$ resonances. Perhaps the most valuable contribution of this study was the generalization to four amplitudes. At the start of this work only the $3/2^-$ case (assuming only two decay amplitudes) had been analyzed. The extension to four amplitudes led us to a generalized formulation (and consistent notation) for all of the cases we have now studied, and to a consistent analysis procedure.

For four decay amplitudes (l_L' for the lower l' value and l_U' for the upper value) the following mixing ratios are defined:

$$\delta_L = \langle j' = l_L' + 1/2 \rangle / \langle j' = l_L' - 1/2 \rangle, \quad \delta_U = \langle j' = l_U' + 1/2 \rangle / \langle j' = l_U' - 1/2 \rangle$$

and the corresponding mixing angles

$$\tan \phi_L = \delta_L \quad \phi_L \leq 90 \text{ degrees}$$

$$\tan \phi_U = \delta_U \quad \phi_U \leq 180 \text{ degrees}$$

i.e., arbitrarily assume the amplitude with the lowest l' and j' value to be positive. Also define

$$\Sigma^2 = \langle l' = l_U' \rangle^2 / [\langle l' = l_L' \rangle^2 + \langle l' = l_U' \rangle^2]$$

If one works with ratios of reduced width amplitudes instead of matrix elements, the only change is the introduction of a factor $\cos(\alpha_{l'L} - \alpha_{l'U})$ which multiplies the interference term. For $5/2^-$ resonances the angular distributions take the form

$$a_{2p'} = (1 - \Sigma^2) f_A(\phi_L) + [\Sigma^2(1 - \Sigma^2)]^{1/2} f_A(\phi_L, \phi_U) \cos(\alpha_1 - \alpha_3) + \Sigma^2 f_A(\phi_U)$$

$$a_{4p} = [\Sigma^2(1 - \Sigma^2)]^{1/2} f_B(\phi_L, \phi_U) \cos(\alpha_1 - \alpha_3) - \Sigma^2 K$$

$$a_{2\gamma} = (1 - \Sigma^2) f_C(\phi_L) + \Sigma^2 f_C(\phi_U)$$

$$a_{4\gamma} = (1 - \Sigma^2) f_D(\phi_L) + \Sigma^2 f_D(\phi_U)$$

This illustrates the structure of the equations describing these reactions. Often only one amplitude exists for a particular ℓ' value--for the special $\ell'=0$ case, and because of angular momentum restrictions (for example $7/2^-$ resonances cannot decay to 2^+ states by $\ell'=1$, $j'=1/2$). For these cases only one ϕ is defined. Clearly if there is only one ℓ' value to consider, one simply sets $\Sigma^2=0$.

Large values of Σ^2 present no basic problem, provided there are sufficient experimental pieces of information. However, for small values of Σ^2 , the situation is cloudy. The interference terms become very important when Σ^2 is small; each interference term is weighed by the factor $\cos(\alpha_{\ell'L} - \alpha_{\ell'U})$. For the mass energy region under study this factor is very small for the $\ell'=1$ and $\ell'=3$ combination, but rather large for the $\ell'=0$ and $\ell'=2$ combination. Thus in practice it becomes very difficult to determine separately the $\ell'=3$ components, but feasible to determine the $\ell'=2$ components. A paper has been published on the results for f-wave resonances in ^{55}Co by Watson, Bilpuch, and Mitchell, *Z. Physik A294* (1980) 153. The following is the abstract of that paper:

"The measurement of inelastic proton channel amplitudes has been extended to f-wave resonances. Ten resonances were studied in the $^{54}\text{Fe}(p, p'\gamma)$ reaction. All were established to have $J^\pi=5/2^-$, and inelastic decay amplitudes were determined for these resonances. Elastic and inelastic spectroscopic factors were determined for the $5/2^-$ analogue state at $E_p=3.80$ MeV."

f. $\ell=1$ and $\ell=2$ resonances in ^{45}Sc

Earlier work was performed on $\ell=1$ resonances between $E_p=2.5$ and 2.8 MeV in the $^{44}\text{Ca}(p, p'\gamma)$ reaction. Study of the fragmented $3/2^-$ analog near $E_p=2.65$ MeV first established experimentally that the relative phase between the amplitudes in different channels is the same for all fragments of an analogue state. There are many $\ell=1$ and $\ell=2$ resonances known from our previous elastic scattering measurements; we therefore considered ^{44}Ca as one of the most favorable nuclei to study.

To date we have performed one half of the experiment--the γ -ray angular distributions have been measured for all known $\ell=2$ resonances between $E_p=2.2$ and 3.0 MeV and all known $\ell=1$ resonances (from $E_p=2.8$ to 3.0 MeV (to supplement the earlier $\ell=1$ study). Many

resonances were too weak for detailed study, and a number of resonances were obscured by interference with neighboring resonances. Gamma-ray angular distributions have been obtained for a total of 81 $l=2$ resonances and 45 $l=1$ resonances. The other half of the experiment (the proton angular distributions) must be completed before detailed analysis can begin.

g. Study of resonances in ^{51}Mn

Results from previous elastic and inelastic scattering studies on ^{50}Cr to $E_p=4.3$ MeV (Salzmann, Meyer, and Brandle, Nucl. Phys. A282 (1977) 317 suggested that this nucleus was well suited for detailed inelastic scattering measurements. Most of this experiment is being performed with the tandem accelerator, although some of the lower energy data is obtained with the 3 MeV accelerator.

In preparation for this experiment, several changes were made in the experimental arrangement. For the $^{50}\text{Cr}(p,p'\gamma)$ experiment, a new chamber support table and a new beam collimator near the scattering chamber were built and installed. For the $^{50}\text{Cr}(p,p')^{50}\text{Cr}^*$ experiment, a new detector collimation system was designed, fabricated, and installed. Background levels in both scattering chambers have been reduced. The $^{50}\text{Cr}(p,p')$ experiment presents one special problem. Previously, ^{50}Cr targets have been prepared by evaporating chromium onto thin carbon backings. Unfortunately, protons inelastically scattered from ^{50}Cr and protons elastically scattered from carbon coincide at some energy in the region of interest for every scattering angle except 90° . Since the carbon elastic peak is much larger than the inelastic ^{50}Cr peak, even when very thin ($\mu\text{g}/\text{cm}^2$) carbon foils are used, this would mean losing one to three points out of six in the angular distribution. Our solution to this problem is to use self-supporting aluminum foils as backings. The aluminum proton elastic and inelastic peaks are well separated from those due to scattering from ^{50}Cr . Preliminary tests with such targets appear promising. Resonances in the energy region $E_p=3.24-3.50$ MeV are being studied using the 3 MV Van de Graaff accelerator. The TUNL FN tandem Van de Graaff accelerator is being used to study resonances in the energy region $E_p=3.28-4.30$ MeV. Overlap of these energy regions allows comparison of results for the same resonance taken on different accelerators.

Short excitation functions have been measured for a total of 171 resonances. Of these, 122 resonances were considered suitable for study (i.e., had a sufficiently large yield and were relatively well isolated). Gamma-ray angular distributions at six angles have been taken for these 122 resonances. The distribution of J values of the resonances studied is: $1/2^+(4)$, $1/2^-(11)$, $3/2^-(30)$, $3/2^+(19)$, $5/2^+(47)$, $5/2^-(9)$, $9/2^+(2)$. The $1/2^-$ and $1/2^+$ resonances were measured for normalization purposes, while the $5/2^-$ and $9/2^+$ resonances are analog states.

Measurement of the inelastically scattered proton angular distributions should be carried out in the next few months. Following these measurements a more detailed analysis of the data will be performed.

FOOTNOTE (Section C2)

*Now at Link Division of Singer, College Park, Md.

D. CHARGED PARTICLE EXPERIMENTS WITH POLARIZED BEAMS

1. Isospin Mixing in Light Nuclei

- a. Introduction (J.F. Wilkerson,
E.J. Ludwig, W.J. Thompson,
T.B. Clegg)

Previous investigations of isospin mixing in light nuclei, $A < 40$, have revealed interesting, but not well-understood properties. Isospin symmetry breaking can be directly probed by observing isospin-forbidden decays, for example isospin $T=3/2$ states in $4n+1$ compound nuclei populated through isospin-forbidden elastic and inelastic proton scattering on $4n$, self-conjugate target nuclei. Another less direct method to study isospin mixing is through the use of the isobaric multiplet mass equation on isobaric quartets whose level properties have been determined.

An earlier study of proton elastic-scattering reduced widths for the lowest isospin $T=3/2$ states in $4n+1$ nuclei has shown an interesting periodicity when plotted versus mass number. [1] To understand better isospin mixing and perhaps to determine whether the mixing is taking place in the target nucleus, compound nucleus, or both, we are continuing our study by measuring the properties of high-lying $T=3/2$ states in these same $4n+1$ nuclei. We are investigating systematically the proton reduced widths of the high-lying $T=3/2$ states both as a function of mass, for example the behavior of the second $T=3/2$ states in the $4n+1$ nuclei, and also the behavior of the $T=3/2$ states within a given $4n+1$ nucleus. These states occur at higher energies in the compound nucleus than do the lowest $T=3/2$ states. For elastic proton scattering unique determination of the level properties of these $T=3/2$ resonances requires the measurement of both cross sections and analyzing powers [2] with a high-resolution polarized proton beam. [3] The location of these high-lying isospin $T=3/2$ states in $4n+1$ compound nuclei is in most cases not known to within 50 keV. Finding them through isospin-forbidden (p,p) scattering is not feasible, since their small effects in the cross section and very narrow widths (~ 100 - 1000 eV) require an inordinate amount of beam time to search for and locate these states. Alternatively one can find them by the (p,t) and $(p,^3\text{He})$ reactions. For final states in $4n+1$ nuclei the isospin $T=3/2$ states are prominent in the (p,t) spectra and a comparison of the (p,t) and $(p, ^3\text{He})$ cross section ratios helps distinguish $T=3/2$ from the high background of $T=1/2$ states. Thus the (p,t) and $(p, ^3\text{He})$ reactions are being used to locate the high-lying $T=3/2$ states of interest.

- b. Identification of $T=3/2$ States
Using (p,t) and $(p,^3\text{He})$ Reactions

- (1) Introduction (J.F. Wilkerson,
E.J. Ludwig, T.B. Clegg,
Y. Tagishi)

The (p,t) and $(p, {}^3\text{He})$ reactions offer a spectroscopic tool to distinguish nuclear levels of different isospin. On isospin $T=1/2$ targets the (p,t) , two-neutron transfer reaction favorably populates $T=3/2$ states relative to the many surrounding $T=1/2$ states. This isospin-favored population occurs for those $T=3/2$ states which have fairly simple nuclear structure, since they are analogs of the lowest states in the parent nucleus. The surrounding $T=1/2$ states of the daughter nucleus have fairly complicated structures and are reduced in strength.

Angular distribution comparisons of (p,t) and $(p, {}^3\text{He})$ reactions can help distinguish $T=3/2$ from $T=1/2$ levels. In a direct one-step (p,t) reaction, the transfer of two neutrons, the isospin transfer must be one and hence the spin transfer must be zero. However, for the $(p, {}^3\text{He})$ reaction, the transfer of a neutron and a proton, there can be a transfer of isospin one and spin zero or isospin zero and spin one. For populating a $T=3/2$ state from a $T=1/2$ target nucleus the $(p, {}^3\text{He})$ reaction must transfer isospin of one and spin of zero, analogous to the (p,t) case. Because the $T=3/2$ states formed by (p,t) and $(p, {}^3\text{He})$ are mirror states with identical nuclear wavefunctions, excepting the T component, their cross sections vary only by a constant factor related to the isospin, and by kinematic factors. For a $T=1/2$ initial state and a $T=3/2$ final state this is about one, and the angular distributions must be identical.

The large negative Q -value of the (p,t) reaction, (about -15 MeV) and the fact that the high-lying $T=3/2$ states in $4n+1$ nuclei occur at energies of about 8 MeV or higher requires incident proton energies greater than 40 MeV, and makes the experiment impossible to perform at TUNL. Hence, a proposal was submitted for beam time at the Indiana University Cyclotron Facility (IUCF) to use 60-MeV protons and the Indiana spectrograph. Although receiving beam time at IUCF, we followed the recommendation of the IUCF scheduling committee and considered alternative laboratories which had high-resolution spectrographs and reasonable proton energies (>40 MeV). After some preliminary consultations we found that both Princeton Cyclotron Laboratory and the Lawrence Berkeley Laboratory (LBL) 88" Cyclotron facility were interested. Princeton offered the advantage of the high-resolution QDDD spectrograph, while Berkeley offered polarized beam.

The selection of suitable targets for the (p,t) and $(p, {}^3\text{He})$ was based on three considerations: the ability to perform the (p,p) high-resolution isospin-forbidden experiment at TUNL, the availability of a stable target for the (p,t) experiment, and the current knowledge on the $T=3/2$ states in the $4n+1$ nuclei. The targets selected for the experiment were ${}^{27}\text{Al}$, ${}^{31}\text{P}$, ${}^{35}\text{Cl}$, and ${}^{39}\text{K}$.

- (ii) Search for $T=3/2$ States
 Using The Princeton QDDD
 (J.F. Wilkerson, T.B. Clegg,
 E.J. Ludwig, Y. Tagishi [UNC/TUNL],
 R.T. Kouzes and R. Sherr
 [Princeton University])

Three days of beam time at the Princeton Cyclotron were acquired, enough time to perform the (p,t) and $(p, 3\text{He})$ reactions on the four different targets at one reaction angle. A search for the high-lying $T=3/2$ states in ^{25}Al , ^{29}P , ^{33}Cl , and ^{37}K was performed using the QDDD spectrograph. The targets of ^{27}Al , ^{31}P , $\text{Ba}^{35}\text{Cl}_2$, and ^{39}K , prepared at UNC and transported under vacuum to Princeton, were bombarded with a 42.3-MeV proton beam. Outgoing tritons and 3He particles were detected at a scattering angle of 15 degrees. A 4-MeV region of excitation energy above the lowest $T=3/2$ state in each residual nucleus was searched. Several new $T=3/2$ candidate states were observed in each residual nucleus. Fig. D1-1 shows sample (p,t) spectra.

Fig. D1-1. Sample spectrograph spectra for $^{31}\text{P}(p,t)^{29}\text{P}$ showing strong peaks associated with $T=3/2$ final states in ^{29}P .

Performing (p,p) isospin-forbidden scattering at TUNL on a few of these candidate states has shown that the preliminary identification of $T=3/2$ states using the (p,t) reaction along with considerations of the spacing of the states in the corresponding parent nucleus is very successful. As an example, the second $T=3/2$ state in ^{33}Cl had previously been identified at a compound nucleus energy of 6.95 MeV. [4] However, lengthy searches at TUNL using the isospin-forbidden reaction of $^{32}\text{S}(p,p)^{32}\text{S}$ had revealed no possible narrow states in this energy region. Our Princeton data showed a very strong peak at 6.849 MeV, over 100 keV lower than Vignon's reported state [4] (Fig. D1-2). A search in this energy region at TUNL using the high resolution (p,p) scattering

Fig. D1-2. Spectrograph spectrum showing peak corresponding to the 2nd $T=3/2$ state populated in the $^{35}\text{Cl}(p,t)^{33}\text{Cl}$ reaction.

quickly located this $T=3/2$ resonance. Thus, the Princeton data should enable us to locate and analyze with a high-resolution polarized proton beam the isospin-forbidden resonances.

However, the use of the (p,t) and (p, ^3He) reactions to distinguish $T=1/2$ from $T=3/2$ states has been inconclusive since the data were taken at only one angle. It will be necessary to take complete angular distributions to use this spectroscopic tool. Plans are to accumulate these distributions using a polarized beam at Berkeley, or

if this is not possible, to perhaps return to Princeton and make the measurements.

- (iii) Preliminary (p,t) Test
at LBL, Berkeley (E. J.
Ludwig [UNC/TUNL], H.E.
Conzett, R.M. Larimer,
J. Mahoney [Lawrence
Berkeley Laboratory])

Tests are underway with 42-MeV protons at LBL to see if tritons can be detected with good resolution (< 20 keV) using the LBL spectrometer. This spectrometer has resistive-wire position detectors designed for heavy ions. Recent tests have indicated that tritons can be detected; however, the resolution during those tests was poorer than required. Further tests are planned. Should the spectrograph work sufficiently well, an experiment will be scheduled at Berkeley using targets of ^{27}Al , ^{31}P , and $\text{Ba}^{35}\text{Cl}_2$, bombarding them with a polarized proton beam so that comparisons of the angular distributions can be made not only for the cross section, but also for the analyzing power. This will help determine both the L and J of the final states, which should be those of the parent states and consistent with those determined in the (p,p) resonance reaction.

c. High-Resolution Isospin-
Forbidden (p,p) Scattering

- (i) Introduction (J.F.
Wilkerson, E.J. Ludwig,
T.B. Clegg, W.J. Thompson)

The isospin-forbidden high-resolution scattering program has progressed a little slower than hoped in the past year due to problems with the tandem accelerator. However, a number of improvements and accomplishments have been made. Notably, the confirmation from (p,p) high-resolution data that the (p,t) identification of the high-lying $T=3/2$ states is correct. Also significant is the work on the role of atomic effects in the resonance analysis and their implications.

(ii) Developments

Target Voltage Ramping-- J.F.
Wilkerson, C.G. Torre

Currently, high-resolution energy-excitation functions are acquired by stepping the beam energy with the entire high energy beam transport system, which includes the two momentum-analyzing magnets, two quad singlets, two sextupoles, two quad triplets, and a bending magnet. For stepping over large energy regions this automatic system is invaluable. However, for excitation functions of about 5 keV, ramping the target rod voltage is a more stable method for a number of reasons. First, if during an excitation function the line voltage fluctuates, these fluctuations can introduce energy shifts in the excitation function and ruin hours of data taking. Also any positional shifts of the beam on the target can cause shifts in the cross section magnitude due to target nonuniformities. The energy and cross section magnitude shifts cause serious problems when looking at the small isospin-forbidden processes. Ramping the target voltage at a few Hertz over the excitation energy region and storing the multi-parameter data in event mode can overcome these problems. There is the additional advantage that one can observe the entire excitation energy region being covered, and can tell quickly if the scan is centered about the resonance.

During the past year the acquisition of ramped excitation functions was accomplished. A 5 keV fast programmable power supply was used for ramping the target rod while the tandem energy was kept fixed. A multi-parameter, event-mode tape-storage data acquisition program, HRAMP, was written, debugged and used on the DDP-224 computer system. In test runs, the system worked well, but was limited by the slow time of data acquisition in multi-parameter mode. However, with the DEC-VAX computer, multi-parameter data acquisition will be no problem and the target ramping for final data acquisition will be utilized.

New High-Resolution System
Slit Preamplifier--C.G. Torre,
J.F. Wilkerson

A new design high-resolution slit preamp was bench tested with good overall performance. The slit preamp presently being used has linearity problems and channel cross-talk difficulties. The new preamp, modeled after a University of Washington-Seattle design, eliminates cross-talk while also insuring very good characteristics over a very broad range of frequencies and input currents. This preamp will be especially useful with polarized beams, for which there is less feedback current available. A production version will be tested in the near future.

Magnet Calibration--J.F.
Wilkerson, T.B. Clegg,
E.J. Ludwig

The 90-90 magnet calibration, essentially completed last year [5], had an energy gap between the calibration points of $^{27}\text{Al}(p,n)^{27}\text{Si}$ (at 5.8803 MeV) and $^{12}\text{C}(p,p)^{12}\text{C}$ (at 14.2307 MeV).

Although the magnet constant, k , between these two points was assumed to be constant, and non-absolute calibration points suggested that this was indeed true, we felt it important to verify this with an absolute calibration point.

The $^{58}\text{Ni}(p,n)^{58}\text{Cu}$ threshold at 9.514 MeV was therefore measured. However, unlike the previous (p,n) measurements made with a $^{10}\text{BF}_3$ long counter at lower energies and with low neutron backgrounds, the $^{58}\text{Ni}(p,n)^{58}\text{Cu}$ measurement was made by measuring the positron decay of ^{58}Cu . The technique used irradiated the target for a few half-lives and then removed the beam and counted the positrons in a NaI detector. A data acquisition program, CHOPBS, was written to chop the beam and control data collection automatically. The chopping of the beam was accomplished with a beam stop located before the final bending magnet into the beam line.

The results of this measurement agreed with the earlier non-absolute calibration points and confirmed that the magnet constant, k , is constant in this energy region.

(III) Data and Analysis

Analysis the First $T=3/2$
State in ^{13}N --W.J. Thompson,
J.F. Wilkerson

The $^{12}\text{C}(p,p)^{12}\text{C}$ data acquisition with polarized beam was reported in last year's progress report. An analysis of the resonance which included atomic effects has been performed and published. [6] A description of these atomic effects is reported elsewhere in this progress report. The analysis of the data was performed using T32GRD, which fits the cross-section and analyzing power data simultaneously while also folding in all resolution effects. The final fits were for the overall best fits to all four angles. The reduced proton width was 285 ± 15 eV (FWHM) with a total width of 1010 ± 30 eV (FWHM). The beam resolution was found to be 850 ± 40 eV (FWHM), but this did not really degrade the total resolution very much, since the Doppler broadening width (FWHM) was 940 ± 40 eV. The data and analyzed fits are shown elsewhere in the progress report.

Third $T=3/2$ State in ^{25}Al --
J.F. Wilkerson, B.L. Burks,
R.L. Varner, C.R. Westerfeldt

Using the energy level information from the (p,t) experiment a search was performed for the third $T=3/2$ level in ^{25}Al .

by the $^{24}\text{Mg}(p,p)^{24}\text{Mg}$ reaction. A high-resolution beam, of about 450 eV (FWHM) resolution was used. The resonance was located at proton energy of 7.136 MeV, within 2 keV of the energy predicted from the (p,t) data.

Second $T=3/2$ State in ^{33}Cl --
J.F. Wilkerson, B.L. Burks,
R.L. Varner, C.R. Westerfeldt

Using the energy level information from the (p,t) experiment a search was performed for the second $T=3/2$ level in ^{33}Cl by the $^{32}\text{S}(p,p)^{32}\text{S}$ reaction. A high-resolution beam, of about 450 eV (FWHM) resolution was used. The resonance was located at proton energy of 4.717 MeV, within 1.5 keV of the energy predicted from the (p,t) data.

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2. Nuclear Spectroscopy with Polarized Deuterons

- a. Vector and Tensor Analyzing Powers for (d, α) Reactions on s-d Shell Nuclei (Y. Tagishi, E. J. Ludwig, T. B. Clegg, S. A. Tonsfeldt, J. F. Wilkerson)

In previous studies of the (d, α) reaction on s-d shell nuclei, it was found that the angular distributions depend distinctly on the orbital angular momentum L and total angular momentum J transferred. [1] Our present work shows that angular distributions of the tensor analyzing powers provide considerable sensitivity of a different nature to differences in the J-transfer.

Cross sections and vector and tensor analyzing powers, T_{11} , T_{20} and T_{22} were measured at 16 MeV for $^{32}\text{S}(d,\alpha)^{30}\text{P}$, $^{36}\text{Ar}(d,\alpha)^{34}\text{Cl}$, and $^{38}\text{Ar}(d,\alpha)^{36}\text{Cl}$. These target nuclei were chosen so that well separated states would be reached via the (d,α) reaction. The 13 final states analyzed provided examples of $J = L-1$, L and $L+1$ transfers. The experiment was performed using the polarized deuteron beam to bombard targets of H_2S , ^{36}Ar and ^{38}Ar gas contained in a cell at pressures of 1 atm or less. The $^3\text{He}(d,p)^4\text{He}$ reaction was used to monitor the polarization of the incident deuteron beam.

Typical experimental results of the tensor analyzing powers, T_{22} and T_{20} , for different L and J transfer cases are shown in Fig. D2-1. For $J^\pi = 3^+$ and $J^\pi = 1^+$ states, two L values $L = J-1$ and $L = J+1$ are allowed; however, comparisons of cross section and vector analyzing power angular distributions to DWBA calculations (see Fig. D2-2) indicate that a single L transfer provides an adequate representation of the data. The T_{22} angular distributions are predominantly negative in value for cases of $J = L\pm 1$ transfers, while for $J = L$ transfer the T_{22} patterns are more oscillatory and more predominantly positive at forward angles. These patterns are typical of all of the transitions studied. A more surprising feature for the measured tensor analyzing powers is that the T_{20} angular distributions for $J = L\pm 1$ transfers are out of phase with the T_{22} distributions. The corresponding pattern for $J = L$ do not exhibit these relations nor do the DWBA calculations for these tensor analyzing powers.

The observed sign rule for T_{22} can be understood from the definition of T_{22} . Assuming an aligned beam of deuterons (no $m = 0$ deuterons) then:

$$T_{22} = (\sigma_x - \sigma_y) / \sqrt{3} \sigma_0$$

where σ_0 is the cross section with an unpolarized beam and σ_x and σ_y are cross sections with a purely aligned beam of deuterons along the x- and y-axis respectively. The y-axis is normal to the reaction plane and x-axis is normal to the incident beam direction and y-axis. Since outgoing alpha particles have zero spin, the spin transfer $S = 1$ is anti-parallel to the incoming deuteron spin. When σ_y is measured, S is along y, L and S add or subtract, and a $J = L\pm 1$ deuteron cluster tends to be transferred. A larger σ_y compared to σ_x then implies a negative T_{22} . When σ_x is measured, S is along x, L and J are perpendicular, and there will be more probability of transferring a $J = L$ deuteron cluster. A larger σ_x compared to σ_y then implies a positive T_{22} . This simple vector-model coupling argument is not possible for T_{20} and T_{21} .

In summary, the angular distribution patterns of T_{22} in (d,α) reactions clearly distinguish between $J = L$ and $J = L\pm 1$ transfers in an understandable way. For the $J = L\pm 1$ transfer cases studied, the patterns for T_{22} are out of phase with T_{20} although this effect is not predicted by the DWBA calculations performed to date. The information provided by tensor analyzing power distributions complements that provided by vector analyzing powers which readily distinguishes between

Fig. D2-1. Tensor analyzing power measurements for (d, α) reactions leading to the final nuclei and states indicated at $E_d = 16$ MeV. The curves are drawn to guide the eye.

Fig. D2-2. Cross-section and vector analyzing power data for (d,α) reactions on s-d shell nuclei compared with results of DWBA calculations.

$J = L+1$ and $J = L-1$ transfers.

This work has been reported at the Washington meeting of the American Physical Society and at the Fifth International Symposium on Polarization Phenomena in Nuclear Physics. A paper has appeared in Physical Review Letters.

- b. Polarized Beam Study of The
207Pb(d,t)206Pb Reaction (J. Willis,
T. B. Clegg, M. Kalitckuk, E. J.
Ludwig, W. J. Thompson)

The analysis of this work has been completed and a paper accepted for publication in Nuclear Physics A. The abstract is as follows:

"Cross-section and vector-analyzing-power angular distributions have been obtained for states up to 3.12-MeV excitation in 206Pb populated by the 207Pb(d,t)206Pb reaction at $E_d = 15$ MeV. DWBA calculations of the distributions for single l and J transfers have been combined to fit the experimental distributions. Spectroscopic factors have been obtained and are compared to theoretical estimates. Sum rules show that almost all the $3p_{1/2}$, $3p_{3/2}$, and $2f_{5/2}$ transfer strength is to states below 2 MeV in excitation. The usefulness of vector-analyzing-power data for spectroscopic studies in this mass region is investigated."

- c. A Polarized Beam Study of The
40Ca(d,6Li)36Ar and 24Mg(d,6Li)20Ne
Reactions (W. W. Jacobs [Indiana],
E. J. Ludwig, J. F. Wilkerson [UNC],
H. E. Conzett, P. Von Rossen [Berkeley])

We previously reported that the 40Ca(d,6Li)36Ar and 24Mg(d,6Li)20Ne reactions were measured using the 46 MeV polarized deuteron beam at the Lawrence Berkeley Laboratory. Cross section and vector analyzing power angular distributions were analyzed for several states in each final nucleus. At present DWBA calculations, assuming an α -cluster transfer, are being carried out to compare with the data and provide spectroscopic factors for these reactions.

- d. 78Kr(d,p)79Kr Reaction (B. L.
Burks, R. R. Cadmus, Jr., T. B.
Clegg, E. J. Ludwig)

A paper describing this work is being submitted to Nuclear Physics. A brief summary of that paper is given below:

The structure of ^{79}Kr has been investigated via the $^{78}\text{Kr}(d,p)^{79}\text{Kr}$ reaction using an isotopically enriched gas target and an 11 MeV vector-polarized deuteron beam. Differential cross sections, $d\sigma/d\Omega$, and vector analyzing powers, A_y , have been measured from 25 degrees to 95 degrees for 10 proton groups leading to states below 2.5 MeV in excitation. Comparisons of these distributions to DWBA calculations were made to extract spectroscopic factors and values of spin (J) and parity (π) for these states.

The target was 99% enriched in ^{78}Kr and experimental resolution was about 55 keV FWHM. Rutherford scattering at 7.0 MeV provided a reference for absolute measurement of the cross sections to within a 5% uncertainty. An optical-model analysis of deuteron elastic scattering at 11 MeV was fitted to $d\sigma/d\Omega$ and A_y data from 25 degrees to 125 degrees as shown in Fig. D2-3. The resulting optical model potentials are presented in Table D2-1 along with proton potentials deduced from proton scattering on natural krypton at 12 MeV. [2]

Table D2-1

Optical Model Parameters Used in DWBA Calculations

Particle	V	r_o	a_o	W_D	r_w	a_w	V_{so}	r_{so}	a_{so}	r_c
p	50.40	1.26	0.65	13.77	1.20	0.53	6.80	1.26	0.72	1.27
d	89.10	1.21	0.82	23.30	1.35	0.66	6.90	1.00	0.55	1.30

Potential depths are given in MeV, geometrical parameters are given in fm.

Using the optical model potentials of Table D2-1, DWBA calculations were performed. The value of l for each transfer was determined by fits to $d\sigma/d\Omega$. For each possible j -transfer ($j=l\pm 1/2$), angular distributions were calculated and compared to the A_y data to determine J .

Two of the proton groups were found to be populated by two or more excited states in ^{79}Kr which were not resolvable by this experiment. Values for the spin and parity of these states were determined by use of the MIXNPL0T program which fits distributions of $(d\sigma/d\Omega)A_y$ with combinations of two or three TDWUCK predictions for different possible angular momentum transfers (see TUNL XVIII page 57).

Fig. D2-3. Optical-model fits to cross section and analyzing power data for $^{78}\text{Kr}(\vec{d}, d)^{78}\text{Kr}$.

Table D2-2

Summary of Spectroscopic Information for States in ^{79}Kr

E(MeV)	J		S
	this work	N. D. S.[3] adopted levels	
0.0	1/2-	(1/2)-	0.26
0.130*	7/2+	(7/2)+	0.47
0.147*	5/2-	(5/2)-	0.20
0.149*	9/2+	(9/2)+	0.03
0.384**	1/2-	(1/2-, 3/2-)	0.07
0.402**	5/2-	-----	0.08
0.533	1/2+	(1/2+)	0.15
0.639	5/2+	(3/2+, 5/2+)	0.09
0.688	3/2+	(1/2- to 5/2-)	0.11
0.752	(3/2)+	-----	0.04
0.810	1/2-	(1/2-, 3/2-)	0.12
1.912	1/2+	(1/2+)	0.07
2.060	5/2+	(3/2+, 5/2+)	0.09

*part of a triplet of states

**part of a doublet of states

e. Deuteron Tensor Polarization
Monitor (S. Tonsfeldt, T. B.
Clegg, E. J. Ludwig)

The deuteron tensor polarization monitor continued to be used effectively for experiments during the past year. A contribution describing this apparatus and its use was submitted to the Santa Fe polarization conference, and a manuscript is being prepared for publication in Nuclear Instruments and Methods. The device is described most completely in the Ph.D. thesis of S. A. Tonsfeldt available from University Microfilms in Ann Arbor, Michigan.

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3. Time Reversal Invariance Tests Via the
 $^{11}\text{B}(\text{p},\text{d})^{10}\text{B}$ and $^{13}\text{C}(\text{p},\text{d})^{12}\text{C}$ Reactions
 (B. L. Burks, R. E. Anderson, T. B. Clegg,
 R. L. Varner and J. F. Wilkerson)

The subject of violations of fundamental quantum mechanical symmetries in nuclear processes was recognized very early as an important topic. Parity violation was seen in nuclear beta decay in the famous experiment of Wu et al., [1] after the earlier suggestion of Lee and Yang. [2] Violation of time reversal invariance was seen in K_0 decay in 1962, [3] an experiment for which this year's Nobel prize in physics was awarded. Both of these experiments involved weak interaction processes, and to date no violation of the fundamental symmetries of charge conjugation, parity, and time reversal has been seen in strong interaction processes. During the past few years a violation of parity in p+p elastic scattering at 15 MeV [4] and at 6 GeV [4,5] have been observed, but again this is felt to be due to the presence of the weak force.

Recently, Slobodrian et al [6] have claimed to observe a violation of time reversal invariance based on differences in the polarizations seen in the $^7\text{Li}(^3\text{He},\text{p})^9\text{Be}$ reaction and the analyzing powers seen in the time reversed reaction, $^9\text{Be}(\text{p},^3\text{He})^7\text{Li}$. Smaller differences are observed when proton polarizations in the $^9\text{Be}(^3\text{He},\text{p})^{11}\text{B}$ reaction are compared with the analyzing powers from the $^{11}\text{B}(\text{p},^3\text{He})^9\text{Be}$ reaction. In the first experiment the differences are quite large, presumably too large to be due to the weak interaction. Thus this work, if correct, represents the first case where the strong interaction is seen to violate one of the fundamental quantum mechanical symmetries. Such an observation would have enormous impact on our understanding of nature, and we felt that a substantial body of corroborative data should be assembled.

We have obtained from the literature what appears to be two reliable sets of polarization measurements. One of these is for the $^{12}\text{C}(\text{d},\text{p})^{13}\text{C}$ reaction at $E_d = 12.35$ MeV [7] and the other is for the $^{10}\text{B}(\text{d},\text{p})^{11}\text{B}$ reaction at $E_d = 1.85$ MeV. [8] Since the high quality polarized proton beams of the appropriate energy for the time-reversed reactions could be obtained from the Triangle Universities Nuclear Laboratory tandem Van de Graaff, we observed the analyzing powers for the $^{13}\text{C}(\text{p},\text{d})^{12}\text{C}$ and $^{11}\text{B}(\text{p},\text{d})^{10}\text{B}$ reactions. Both sets of measurements utilized four identical ΔE -E telescopes mounted in the 52 degrees scattering chamber, two mounted to the right of the beam and two at identical angles to the left. Particle identification was easy for the $^{13}\text{C}(\text{p},\text{d})^{12}\text{C}$ measurements, but difficult for the $^{11}\text{B}(\text{p},\text{d})^{10}\text{B}$ measurements because of the very low deuteron energy (<1.8 MeV). Measurements were made both spin up and spin down for each angle and the analyzing power was obtained from the formula $A_y = \epsilon_y / P_b$ where P_b is the beam polarization measured both using an online $^4\text{He}(\text{p},\text{p})^4\text{He}$ polarization monitor or via the quench ratio method, and ϵ_y is the asymmetry defined as $\epsilon_y = (r-1)/(r+1)$. The quantity r is defined as $r = (\text{DR} \cdot \text{UL} / (\text{UR} \cdot \text{DL}))^{1/2}$ where DR is the number of counts in the right detector as measured with spin down, etc. This method causes instrumental asymmetries to drop out to a high degree of accuracy. Angular distributions for the analyzing powers in the $^{13}\text{C}(\text{p},\text{d})^{12}\text{C}$ reaction

were obtained at seven energies between $E_p = 13.82$ MeV and 14.42 MeV in 100 keV steps. The target in the $^{12}\text{C}(d,p)^{13}\text{C}$ polarization measurement was about 500 keV thick; therefore, analyzing powers were measured for proton energies of ± 300 keV from the calculated mean proton energy in the target, 14.12 MeV, to assure that the correct region of the compound nucleus was accessed by the inverse reaction. Data were taken in 10 degree steps between 25 degrees and 155 degrees in the laboratory. These data are shown in Fig. D3-1. For the $^{11}\text{B}(p,d)^{10}\text{B}$ reaction data were obtained at six energies between $E_p = 11.37$ MeV and 11.87 MeV in 100 keV steps over an angular range of 25 degrees to a maximum angle where outgoing deuterons could be detected, 130 degrees at the highest energy. The target thickness in the polarization measurement was again about 400

Fig. D3-1. Comparison of present results for A_y (symbols indicated at each energy) and published results for P_y (solid circles with error bars). The present A_y data have experimental errors the size of the symbols.

keV and for the reasons cited above analyzing powers were measured for a range of proton energies ± 200 keV from the mean proton energy in the target, 11.57 MeV. In addition to these angular distribution data, excitation functions were taken at two angles for both targets. The carbon measurements were made every 33 keV between 13.82 and 14.45 MeV at scattering angles of 105 degrees and 125 degrees and are shown in Fig. D3-2. For boron measurements were made every 10 keV between 11.37 and 11.77 MeV at angles 75 degrees and 95 degrees. Both these data sets show no resonance structure sharper than was revealed by the angular distribution data taken in the larger energy steps. Thus we feel that the angular distribution measurements provide a data set which is directly comparable to the published polarization data.

Some differences between the polarization and analyzing power data are apparent at the back angles, while very good agreement is obtained for angles forward of 100 degrees in the carbon data and in the boron data. Although the observed differences are not as striking as those seen in ref. 6, we are nonetheless unable to reconcile the polarization and analyzing power measurements at the back angles. The excitation function data do not indicate that the polarization measurements averaged over any large resonances which could give an apparent $P \neq A$ the size of the observed discrepancy. Thus we cannot conclude that these experiments provide convincing proof for the polarization-analyzing power theorem.

Fig. D3-2. Excitation curve data for A_y at two laboratory angles showing smooth energy dependence over the energy range studied.

We are presently considering how to extend the present measurements in order to provide a convincing and believable data set which would settle the question of P vs. A in nuclear reactions.

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4. Nucleon Elastic Scattering Experiments
and Optical Model Analyses (R.L.Varner,
W.J.Thompson, T.B.Clegg, D.W.Vaughn)

We are embarking on a project to take and analyze elastic cross-section and analyzing power data for (p,p) and (n,n) at a number of energies and on a variety of nuclei, for the purpose of making a global nucleon optical model. The data will be carefully selected and taken at a limited number of labs to maximize the consistency of the results. In addition, we hope to include a broader range of nuclei and a better understanding of the optical model than were available in the survey of Becchetti and Greenlees, [1] and to find a parametrization of sufficient quality to be compared with recent Microscopic Optical Model calculations. [2] We are currently working along two fronts, experimental and computational.

a. Experimental Program

The experimental plan calls for proton and neutron elastic data to be taken at TUNL at 15-16 MeV and 10 MeV, respectively, and proton data to be taken at the University of Tsukuba at 22 MeV and at the Eindhoven Cyclotron Laboratory at 24 MeV. The TUNL experiments will consist of cross-section and analyzing-power angular distributions at the highest feasible energy on nuclei $40 < A < 130$, with some measurements at higher A's on nuclei of general interest and/or availability.

To date, proton measurements have been made on $^{76-82}\text{Se}$, [3] ^{208}Pb , ^{58}Ni , ^{63}Cu and ^{65}Cu at 12 MeV and 16 MeV. In addition, a new detector assembly has been constructed to allow reproducible setting of angular positions and detector solid angles, increasing the run-to-run consistency of the data. Further, we are using a ^4He polarimeter to supplement the use of the quench ratio in the determination of the proton beam polarization.

The neutron elastic scattering data will come largely from the TUNL pulsed polarized neutron facility. These measurements are discussed elsewhere in this progress report.

Due to the difficulty of separating the first-excited state groups from the elastic groups for the rare earth and actinide targets, using the solid state detectors available at TUNL, the University of Tsukuba has agreed to make measurements with its magnetic spectrograph of proton elastic scattering from the rare earths and some actinides, including ^{232}Th , ^{238}U , and ^{242}Pu , all at 22 MeV.

The Eindhoven Cyclotron Laboratory has also agreed to share its data on proton elastic scattering at 24 MeV which it has been collecting for several years.

b. Analysis of the Data

The analysis of the data is being planned for in two ways, (1) the establishment of a database for the organization of, and quick access to, the data, and (2) through modifications and improvements of OPTICS. [6]

(1) The data will be analyzed by energy and incident nucleon, including those parameters that are necessary to achieve reasonable, physical fits. Then the resulting fits for protons and neutrons will be compared in order to extract the energy and isospin dependence. Analyzing this much data (estimated to be in excess of 5000 points) requires a carefully organized database, rapidly accessible to any searching program for the calculation of chi-squared. To this end we are constructing a set of utility programs to insert, retrieve and maintain a database of the experimental data, the computed best fits to the data, and the value of chi-squared as a function of the parameters. These routines will include the capability to display the data and fits simultaneously for evaluation and visual examination, and to display chi-squared surfaces on a Tektronics storage scope. These utilities will be installed on the TUNL DEC - VAX 11/780.

(2) The analysis will also require an accurate optical-model code that is fast and which can perform a quick parameter search. We are upgrading OPTICS by installing it on the VAX, improving its calculation speed and adding search routines. We are currently examining the available searching algorithms for the one best suited to our needs.

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5. A Test of Collective Effects in Se(d,d)Se
(Y. Tagishi, B. L. Burks, T. B. Clegg,
E. J. Ludwig, R. L. Varner, J. F.
Wilkerson, W. J. Thompson)

Deuteron elastic and inelastic scattering from the even-A Se isotopes with $A = 76-82$ at 12 MeV deuteron energy is being used to test the suggestion by the ETH-Zurich, group that the change in elastic-scattering vector analyzing powers in the backward hemisphere as A varies can be attributed to changing collectivity of these isotopes with A . The inelastic-scattering vector analyzing power data obtained at TUNL are the first to be used to examine this phenomenon. In a preliminary analysis it is apparent that the parameters used in the Zurich analysis do not give a satisfactory description of the strong coupling to the lowest 2^+ state, which is supposed to provide the major change with A .

Since the collective properties of even these low-lying states are not well understood, we are examining the spectroscopic properties of these Se nuclei before embarking on extensive reaction analyses.

A suggestion from the Madison group is that there are also significant effects from neutron shell closure, as is evidenced by their data in the $A \cong 60$ and $A = 80-96$ range. This is also being examined theoretically as part of our analysis.

6. Nuclear Target Preparation (J. F.
Wilkerson, R. L. Varner, B. L. Burks,
D. P. Sanderson, Y. Tagishi [UNC/TUNL],
C. B. Childs [UNC])

In the past year a variety of thin nuclear targets have been prepared using numerous evaporation techniques. The evaporation equipment, maintained by C. Childs, consists of two bell-jar- evaporator pumping stations. The evaporators have six-inch oil diffusion pumps with LN baffles, producing typical vacuums in the 10^{-6} Torr region. Each station is equipped to allow two resistive heating evaporations at once. There is also an electron gun assembly that can be used on either evaporator system. Both stations have water-cooled Sloane Meter vibrating-crystal, thickness measurement devices. Additional support equipment consists of an interferometer for measuring thickness, an evacuable oven to bake materials under vacuum, and a dessicator pumping station.

The following table is a summary of targets prepared at UNC this year.

TABLE D6-1

TARGET PREPARATION TABLE

Target	Evaporation Material	Method of Evap.	Boat or Crucible Material	Target Thickness ($\mu\text{g}/\text{cm}^2$)	Backing/Thickness ($\mu\text{g}/\text{cm}^2$)	Release Agent	Special Notes
^{11}B	^{11}B	E-gun	Ta crucible	100-200	self-supporting	BaCl_2	Boron slurry formed by adding alcohol drop.
^{24}Mg	$^{24}\text{MgO}_4\text{Zr}$	Resistive heating	Ta boat	3-50	carbon / 3-5	---	Zr used as reducing agent. ²
Al	Al	E-gun	Vitreous carbon crucible	100-500	self-supporting	BaCl_2	
SiO	SiO	E-gun	W crucible	3-50	carbon / 3-5	---	
P	P	Resistive heating	Special Spectroscopic carbon crucible	~ 100	carbon / 10	---	Special crucible and oven used to produce red phosphorus
Sb_2S_3	Sb_2S_3	Resistive heating	Closed Ta boat	3-50	carbon / 3-5	---	
$\text{Ba}^{35}\text{Cl}_2$	$\text{Ba}^{35}\text{Cl}_2$	Resistive heating	Ta boat	3-150	carbon / 3-10	---	
K	K	Resistive heating	Mo boat	100-250	carbon / -10	---	$\sim 30 \mu\text{g}/\text{cm}^2$ Au evaporated onto K, before letting up to Ar
^{58}Ni	^{58}Ni	Resistive heating	W boat with Al_2O_3 coat	~ 450	self-supporting	BaCl_2	
$^{63, 65}\text{Cu}$	$^{63, 65}\text{Cu}$	E-gun	Vitreous carbon crucible	~ 500	self-supporting	BaCl_2	CuO isotope reduced in hydrogen atmosphere oven
$^{76, 78, 80, 82}\text{Se}$	$^{76, 78, 80, 82}\text{Se}$	Resistive heating	Ta boat	200-400	carbon / 5-10	---	
^{208}Pb	$^{208}\text{PbCO}_3$	Resistive heating	Mo boat	~ 400	carbon / 5-10	---	

¹ A. H. F. Muggleton and F. A. Howe, Nucl. Instr. 13 (1961) 222.² S. Takayanag et al., Nucl. Instr. 45 (1966) 345.³ H. Tzeng et al., Nucl. Instr. 150 (1978) 143.

E. RADIATIVE CAPTURE REACTIONS

1. The Capture Program (C. Fitzpatrick, M. Jensen, S. King, S. Manglos, G. Mitev, F. I. Olness,⁺ N. R. Roberson, D. R. Tilley, L. Ward, H. R. Weller, S. A. Wender, M. Wright, H. Kitazawa,* H. Hasan, R. G. Seyler**)

a. Scope of Program

The capture program has had five major goals this year:

1. To observe the isoscalar GQR as electromagnetic strength in neutron and/or proton capture reactions.
2. To use polarized-neutron and polarized proton capture measurements simultaneously in tests of capture reaction theories.
3. To initiate studies of giant resonances built on excited states using capture reactions.
4. To measure capture to unbound final states and to develop and test direct-capture theory for unbound final states.
5. To continue to employ n and p capture reactions in the study of few nucleon systems.

In the next sections of this report we shall describe the progress in the various projects underway in this program. We believe that we have gone far towards achieving the goals above. Due to the installation of a second NaI spectrometer presently underway in our laboratory, this is an especially exciting time for the capture group.

b. General Discussion

Previous studies, mainly of nuclei with $A \leq 20$, have shown that polarized proton capture measurements can be used to extract E2 strength rather unambiguously. However, it has been found that when the resulting E2 cross sections are compared with those predicted by a simple direct (non-collective) capture model, there is rather good agreement. Therefore, it is difficult, if not impossible, to draw any firm conclusions about the effects of the GQR in the (p, γ) channel.

Polarized neutron capture measurements duplicate the physics of polarized proton capture measurements in many respects but with one important difference: The E2 effective charge for neutrons is down by Z/A^2 so that the troublesome direct E2 capture strength is virtually eliminated in most cases. If indeed most E2 strength were associated with direct capture, we would expect to see little or no E2 strength in neutron capture measurements. Our $^{13}\text{C}(n,\gamma)^{14}\text{C}$ results are, however, quite contrary to this expectation and indicate a substantial amount of E2 strength; about 20% of the IS-E2-EWSR in the region of ^{14}C expected to contain the IS-GQR. Since direct capture in this case is near zero, the direct-semidirect (DSD) model must attribute all of this E2 strength to collective E2 states. Our latest calculations indicate that fair agreement with experiment is obtained if a volume type form factor is used with reasonable parameters for the isoscalar GQR. So it appears, at this time, as though (n,γ) measurements are a promising tool for observing the isoscalar GQR.

Since we have measured both the $^{13}\text{C}(n,\gamma)^{14}\text{C}$ and the $^{13}\text{C}(p,\gamma)^{14}\text{N}^*(0^+, T=1)$ reactions, we are in a position to test the DSD model where p and n data leading to virtually the same giant resonance state are available. Another case: $^{14}\text{N}(n,\gamma)^{15}\text{N}$, along with $^{14}\text{C}(p,\gamma)^{15}\text{N}$, has also received our attention. In addition, we have been measuring $^3\text{He}(n,\gamma)^4\text{He}$ which can be related to $T(p,\gamma)^4\text{He}$ measurements done here and elsewhere. Having both sets of data should provide more stringent tests of our reaction theories. The differences in the abilities of the DSD model and the Pure Resonance Model (PRM) of Dietrich and Kerman to simultaneously predict n and p capture should be revealing. In the case of ^4He the experimental comparison, especially of the polarization data, should help us to understand the reaction mechanisms (see below).

Our study of capture reactions leading to "highly excited" final states has progressed quite well in the past year. We have done some of this in collaboration with S. L. Blatt of the Ohio State University. We have been finding that, in the cases of ^{12}C , ^8Be and ^{14}N (via $^{11}\text{B}(p,\gamma)$, $^7\text{Li}(p,\gamma)$ and $^{13}\text{C}(p,\gamma)$), many of the features of the available data can be accounted for with a direct-capture model. These results suggest, for example, that the strength seen in $^{11}\text{B}(p,\gamma)^{12}\text{C}$ reaction leading to the 19 MeV state in ^{12}C is largely due to single particle $f_{7/2} \rightarrow d_{5/2}$ transition strength, not collective strength. However we are finding some discrepancies with direct capture predictions in the absolute strengths seen, for example, in $^7\text{Li}(p,\gamma)^8\text{Be}(16.6)$. Nevertheless, the direct-capture model seems to be able to account for much of the energy and angle dependence of the capture data which we have obtained leading to highly excited states.

In the case of $^{11}\text{B}(p,\gamma)^{12}\text{C}^*$ the final state near 19 MeV is unbound. We have recently evaluated the direct-capture strength when taking the continuum nature of the final state into account. To do this we employed the technique of Vincent and Fortune to perform the necessary integrations. The results are quite encouraging and seem to provide a reasonable description of several essential features of the data.

In order to perform the capture experiments which lead to highly excited states we must find nuclei for which special "highly excited" states exist which are strongly populated. Given these, we can obtain data for a variety of final states with excitation energies up to over 20 MeV. One of the interesting questions which we are hoping to explore in this work involves the nature and properties of giant resonances built on highly excited states. In most of the cases which we have studied thus far, our data do not exhibit any clear evidence for the presence of such GDR's. We are trying, however, to investigate the question of just how broad and how weak such GDR's must be in order to be consistent with our observations. An effort to compute the "expected" results using the direct-semidirect theory with "reasonable" estimates of the widths and coupling strengths is underway.

We have, however, been surprised by the success of direct capture calculations involving the capture to highly excited bound and continuum final states. If this turns out to be a valid description, say for certain mass and energy regions, then capture may prove to be a valuable means for studying final state structure. For example, in the case of direct capture of polarized protons into the 2^+ state at 16.6 MeV in ^8Be , the calculations indicate that the analyzing power has a distinct pattern depending upon whether the final single particle is in a $p_{1/2}$ or a $p_{3/2}$ state. Careful measurements of this analyzing power should allow us to determine the relative strengths of these configurations.

We have had considerable success in our continuing study of few-nucleon systems. In addition to measuring the first angular distribution for the $^3\text{He}(n,\gamma)^4\text{He}$ reaction, we have performed the first polarized neutron capture measurement for this reaction. It appears as though we can measure the angular distributions for this reaction with an accuracy greater than that achieved in previous works which used the $^4\text{He}(\gamma,n)^3\text{He}$ reaction to obtain this information. Although the statistics in the case of the polarization experiment require improvement, our preliminary results indicate that the percentage of spin-flip E1 strength is similar in magnitude to that deduced from the $T(p,\gamma)^4\text{He}$ reaction. The same result holds for the percentage of E2 strength in the two experiments if triplet E2 strength is ignored. These results are especially interesting in view of the fact that our absolute cross section measurements on $^3\text{He}(n,\gamma)^4\text{He}$ indicate that the (γ,p) cross section on ^4He is about 1.6-1.8 times as large as the (γ,n) cross section. These experiments ($T(p,\gamma)^4\text{He}$ and $^3\text{He}(n,\gamma)^4\text{He}$) demonstrate the utility of polarized capture rather nicely since it is only the polarized capture data which are sufficiently sensitive to the ^3P E1 (spin-flip) capture strength to allow us to measure it. The operation of our second NaI spectrometer (see below) should enable us to make a considerable improvement in the accuracy to which we can determine this strength.

A significant amount of the machine time given to capture experiments in the past year has been applied towards improving the quality of our (n,γ) and $(\bar{n},\gamma)$ data. Careful and complete measurements are required if we are going to extract definite results about the E2 strength in these reactions. In the future we are counting

on the second large NaI detector, presently being installed, to make it possible for us to significantly improve the quality and quantity of these data. Along with the installation of this detector, we are re-examining our basic techniques of shielding and signal processing in an effort to improve our setup. Several promising changes including the addition of Boron Carbide shielding, better pile-up rejection circuitry, and the addition of gain monitoring electronics are underway. These improvements, especially the change from one to two detectors, should allow us to achieve a new level of accuracy in the near future.

FOOTNOTE (Section E1)

+ Now at University of Wisconsin, Madison

* Visitor from Tokyo Institute of Technology, Tokyo, Japan

**Summer visitor from The Ohio State University

2. Installation of A Second Large NaI Spectrometer System

We are presently in the process of installing a second large (10"x10") anticoincidence shielded NaI detector system. The detector has been purchased from Bicron Corporation of Solon, Ohio. In concept, this detector system will be almost identical to the one which has been in use for the past four years.

A schematic diagram of the detector arrangement is shown in Fig. E2-1 below. Detector A represents the present system while detector B denotes the system being installed. The 10" x 10" NaI crystal of detector B is viewed by six RCA photomultiplier tubes, as was detector A. The shield for detector B, made of one ingot of NE110, has been cut back at the corners in an attempt to permit easier measurements at extreme angles. The shield of detector B is viewed by eight 3" Amperex PM2312 photomultiplier tubes. These 12-stage tubes should provide larger signals than the XP1031 tubes (now obsolete) used on the older shield. It is hoped that these tubes will allow for a cleaner separation between noise and events corresponding to second escape events in the NaI crystal. Since less amplification should be needed, it is hoped that this arrangement will be easier to operate. These features of the new shield have been in response to the problem of excessive count rate incurred at extreme angles with our present setup, a limiting factor in some of our measurements, especially those involving neutron capture reactions with small Q-values.

The passive shielding for the new detector has also been varied somewhat from the former arrangement. We have added a 3/8" sheet of plastic + Boron Carbide to the arrangement. This should give us an attenuation factor of 10^{11} for thermal neutrons. The four inches of lead following the ^{10}B should effectively eliminate the 478 keV γ -rays produced in the $^{10}\text{B}(n,\alpha)$ reaction.

Fig. E2-1. Schematic diagram of the detector arrangement for radiative capture experiments.

We have constructed the Paraffin plus Lithium Carbonate shielding for detector B. The Boron Carbide shielding is being prepared by mixing Boron Carbide with a liquid plastic, pouring it into molds to form 3/8" sheets, and adding a hardener to the mixture.

The mechanical arrangement to allow detector B to be rotated and translated has been constructed in our shop. This arrangement will allow us to go to more extreme angles (20 degrees to 160 degrees) than previously possible. Improvements are being made in the readout devices for the target to detector distance and the detector angle on both the old and new detector carriages.

The electronics to be used with detector B will also duplicate those which we have been using with detector A. Two possible improvements are however, under investigation. Although our experiments to date have not been troubled by high-low pile-up, some preliminary studies of low Q-value neutron capture reactions with rather small cross sections indicates that this may be a problem when we attempt to increase the count rate with increased beam. We are therefore adding an updating discriminator which can be set at a lower threshold than our usual setting (TD101) and used to discard pulses if a second pulse occurs 400 nsec before or after a pulse out of the TD101. We are also planning to add another prescaled discriminator which will allow us to sample the spectrum below the TD101 threshold (usually set at $E_\gamma \sim 9$ MeV). This should allow us to see the fixed energy lines usually present in this portion of the spectrum--a valuable observable for monitoring possible gain instabilities which may occur as we push the net count rate of our detector systems, as well as for monitoring the counting efficiency of the detector system.

We expect to have detector B operating in early 1981.

3. Computer Codes for The Radiative Capture Program

a. Gamma-Ray Response Functions And Data Fitting Programs

In the past, our radiative capture experiments have been concerned with the study of transitions leading to the ground and first excited states of residual nuclei. In most cases, the part of the measured gamma-ray energy spectrum analyzed consisted of two or three strong and clearly separated peaks. Consequently, the exact shape of the tail of the NaI gamma response function several widths below the centroid was unimportant. As a result of our new experiments to study capture leading to highly excited states, the exact shape of the tail is more important. The gamma-ray spectra used to determine our new line shapes were obtained using the $T(p,\gamma)$ reaction at $E_p=5$ MeV with the anticoincidence shield electronics set for both high and low rejection. Since the spectra measured with the $T(p,\gamma)$ reaction have background

gamma-rays in the low energy region, we have fixed the shape of the tails for the new line shapes guided by spectra obtained at NBS [1] with a 25.4 x 25.4 cm NaI crystal and 15.1 MeV monochromatic gamma-rays. The new shapes are given by the following function, but with different coefficients for different shield rejection settings.

$$F(X) \begin{cases} \exp(C_5 + C_6X + C_7X^2 + C_8X^3) & k \leq x \\ \exp(C_1 + C_2X + C_3X^2 + C_4X^3) & q \leq xck \\ C_{10}X & xcq \end{cases} \quad (1)$$

where k was determined by the fitting procedure and is usually slightly below the centroid, q is equal to the centroid minus $5x(\text{FWHM})$, and x is a normalized channel number. The matching at k required equal values and derivatives, but at q only the values were set equal. The small difference in slopes at this point is not perceptible.

The fitting of peaks to gamma-ray transitions when there are many closely spaced states or when there are states with high excitation energies in the presence of several low lying transitions must be done simultaneously. To provide us with this capacity, a new peak fitting program, MULFIT, has been written which fits up to 10 peaks simultaneously using our standard line shapes and a χ^2 minimization technique. By iteration, this program may be extended to any number of peaks. The program uses the subroutine ROCORD which searches the variables for a χ^2 minimum [2]. There are three parameters for each peak (width, height, and centroid) which may be varied freely or subject to restrictions such as fixing the relative positions of the peaks. The program also includes an option to convolute one peak with a Lorentzian line shape making it possible to fit transitions to states with large level widths. Other options available are a constant background variable, restriction of the width and centroid positions, a fit to the line shape without the linear tail, and the ability to smooth data.

The new line shapes do not change the area in the peak region when compared with our old line shapes, but since the tails are different, they increase the tail subtraction under highly excited states. For example, the transition to the 16.6 MeV state in $7\text{Li}(p, \gamma)$ changed by only 1% when the new line shape was used. The convolution of the line shape with a Lorentzian function has been successful with this reaction in fitting the peak due to the transition to the first excited state. Also, the simultaneous fitting and constant background option in MULFIT has enabled a fit to unresolved peaks due to transitions to ground, first, and second excited states in the $208\text{Pb}(n, \gamma)$ reaction.

b. Finite Size Corrections for (n, γ) Data

In order to interpret the results of neutron capture experiments, several corrections must be made to the data. These corrections are necessary because of the finite extent of the neutron source, sample and detector. They may be grouped into three categories: first, the neutron flux from the finite source must be averaged over the volume of the sample, and the subsequent gamma-ray flux must be averaged over the volume of the detector. Second, the effects of neutron and gamma-ray attenuation must be evaluated. Finally, the multiply-scattered neutron flux must be added to the primary flux.

A Monte Carlo code, FIXER, has been written to calculate these finite geometry effects. The deuteron beam in the deuterium gas cell is modeled (see Fig. E3-1) as a cone having an initial radius of $r_{g,i}$ and a final radius of $r_{g,f}$ ($r_{g,i} < r_{g,f}$). Although the deuteron beam's cross sectional area increases as it passes through the gas cell, any radial momentum is ignored. The beam slows in the gas cell, losing an energy of δE_g so that $E_g(z) = E_{g,i} - \delta E_g / l_g$, $E_{g,i}$ being the incident deuteron beam energy and l_g being the gas cell length. A Gaussian spread in deuteron beam energy is included with a mean energy of $E_g(z)$ and a constant standard deviation.

The space between the $2H(d,n)$ event and the sample and the space between the sample and the detector does not attenuate the beam.

The sample is a cylinder of radius r_s and height h_s . Its center is l_{gs} from the end of the gas cell. It contains a uniform density of nuclei having a number density of ρ_s . The total neutron cross section of the sample element is used to attenuate the neutron beam in the sample; however, only elastically scattered events may re-enter the calculation by multiple scattering, neutrons from all other processes are ignored.

The gamma ray detector is modeled as a disk detector of radius r_d and distance l_{sd} from the center of the sample. It has a position independent efficiency of ϵ_d .

The neutron multiple-scattering effects are introduced by including the neutron flux from elastic scattering. Neutrons may undergo several elastic scattering events before the (n,γ) reaction occurs. Each order (single, double, triple, etc.) of scattered neutrons depends upon the previous orders, i.e., the amount of triple scattering depends upon the double scattering flux. Each order scattering requires another integration over the sample.

The neutron capture experiment measures an observed cross section, σ_{obs} , which has all the finite geometry effects included. The true cross section must be deduced from this observation and our knowledge of the finite geometry effects.

Fig. E3-1. Third angle and isometric projections of the geometry modeled by FIXER.

The process used is similar to that used in neutron scattering studies.

Fig. E3-2 is a plot of the correction ratio, $R = \sigma_{\text{pred}}/\sigma_{\text{obs}}$, at $\theta_l = 90$ degrees as a function of energy for several elements. This is the correction factor which must be applied to the data after they have been corrected for the 0 degree yield of the $2\text{H}(d,n)$ reaction. They all display a positive slope which results from the narrowing of the cone of neutrons emitted from the $2\text{H}(d,n)$ reaction. The neutron total cross section used to calculate absorption and multiple scattering is generally constant over the energy region. The gamma ray attenuation is falling in this energy region which tends to counteract the peaking of the $2\text{H}(d,n)$ reaction; however, the effect is small.

The correction factor for the cross-section data as a function of angle (see Fig. E3-3) is fairly constant for unpolarized cross

Fig. E3-2. The 90° correction ratio, $\sigma_{\text{obs}}/\sigma_{\text{pred}}$, as a function of energy.

Fig. E3-3. An example of the finite geometry correction ratio, $\sigma_{\text{obs}}/\sigma_{\text{pred}}$, as a function of detector angle. Corrections for both polarized and unpolarized beam are displayed.

section data. As a result there are no significant effects on the shape of the angular distributions of cross section in the cases we have studied to date.

The upper plot of Fig. E3-4 shows the corrected angular distribution of cross section with its Legendre fit for the case of $^{13}\text{C}(n,\gamma_0)^{14}\text{C}$ at 10.2 MeV. The data points on the lower plot show the difference between the corrected and uncorrected data on a scale expanded by a factor of ten. The curve is the difference between the fits to the corrected and uncorrected data. The mean correction represents 5% of an error bar. Finite geometry has no significant effect on the angular distribution of the cross-section in (n,γ) reactions.

Fig. E3-4. Finite geometry corrected, normalized cross section and differences with the uncorrected cross sections. The curves are a Legendre fit to the data and the differences between the fits to the corrected and uncorrected cross section. The difference scale is expanded by ten.

The finite geometry effects on analyzing powers are also calculated using FIXER. FIXER only calculates the effects on cross section, so the analyzing power is decomposed into a spin-up cross section, σ^+ , and a spin-down cross section, σ^- . The iteration scheme is applied to spin-up and spin-down cross sections. The product of analyzing power times cross section is reformulated from σ^+ and σ^- and refit to associated Legendre polynomials, $P_l^m(\cos\theta)$. An example of the correction factor as a function of angle for spin-up and spin-down may be seen in Fig. E3-3.

The analyzing power of the $^{13}\text{C}(n, \gamma_0)^{14}\text{C}$ reaction may be seen in the upper part of Fig. E3-5. The data and fit are for the

Fig. E3-5. Finite geometry corrected analyzing power and differences with the uncorrected analyzing power. The curves are an associated Legendre fit to the data and the differences between the fits to the corrected and uncorrected cross section. The difference scale is expanded by twenty.

corrected data. The data points in the lower plot show the difference between the corrected and uncorrected data on a scale expanded by a factor of twenty. The curve is the difference between the fits to the corrected and uncorrected data. The mean correction represents 10% of an error bar. As with the angular distribution of cross section, finite geometry has no significant effect on the angular distribution analyzing power in the (n, γ) reactions which we have measured to date.

c. Application of Angular Distribution Formalism to Tensor Polarized Beams

The differential cross section for angular distributions encountered in gamma reactions initiated by the capture of vector or tensor polarized particles can be expanded in terms of Legendre polynomials. The angular distribution for a beam of arbitrary spin polarized with moments of rank 2 can be written in the form: [3]

$$\sigma(\theta, \phi) = (1/2 \lambda)^2 \hat{X}^{-2} \hat{a}^{-2} \sum_k (a_k P_k + b_k P_k' \cos \phi + c_k P_k + 2d_k P_k' \cos \phi + e_k P_k^2 \cos^2 \phi + f_k P_k^2 \sin^2 \phi)$$

for a reaction of the form: $a(x, L)c$, where a is the spin of target, x the spin of the projectile, L the multipolarity and c is the spin of the residual state.

The a_k represent the unpolarized cross section. In the case of a tensor polarized beam, the other coefficients can be measured by a series of measurements in which the polarized beam is prepared in various states.

We have written a program which allows one to express the $a_k \rightarrow e_k$ coefficients in terms of the transition matrix elements for particles of arbitrary spin polarized with moments of rank ≤ 2 . For E1 and E2 only, this results in five a_k and c_k ($k = 0-4$), four b_k and d_k ($k = 1-4$) and three e_k ($k = 2-4$) coefficients. The channel spin representation of angular momentum was used. The form of the equations was taken from the paper by Seyler and Weller, differing only in normalization. The program uses the spins and parities of the projectile, target and residual particles as input and outputs the selected a to e coefficients, indexed by the corresponding interference channels.

The results for the a and b coefficients were checked against corrected versions of the tables of Laszewski and Holt, [4] and against values from a work by George King, [5]. They were found to be in agreement except for an overall minus sign difference with respect to the b s of King [5]. This is presumably due to a different choice of phase convention or coupling order.

d. Spectroscopic Factors in Capture Reactions

Some confusion has existed as to just how the spectroscopic factors computed from say, shell model wavefunctions, enters into the calculations of direct capture cross section. For example, in using the results of Cohen and Kurath, [6] should one take their values of S or their (cfp) values? Can S be greater than one in a direct

capture reaction? We have examined this question in some detail considering the origin of the factor N which relates S to $\{CFP\}$. It turns out that if we consider the matrix element

$$M = \langle \psi_{B=A+1}(0,1,\dots,A) | \sum_{i=0}^A f_i | \psi_{INIT}(0,\dots,A) \rangle,$$

where $\psi_{INIT}(0,\dots,A)$ is fully antisymmetrized--including the part between the incident nucleon and the target,

$$\text{then } M = \binom{A+1}{1}^{1/2} \langle \psi_{B=A+1} | \sum_{i=0}^A f_i | \psi_0 \psi_A \rangle$$

$$\text{where } \psi_B = [1 - \sum P_{i0}] \sum \{CFP\} [\psi_{n l j} \psi_{J_A}]^B.$$

This can be written as:

$$M = [\sqrt{n} \{CFP\}] \langle (1 - \sum P_{i0}) [\psi_{n l j}(0) \psi_{J_A}(1,\dots,A)]^B | \sum f_i | \psi(0) \psi(1,\dots,A) \rangle.$$

Since only f_0 contributes (no core excitations), and $\sum P_{i0}$ doesn't contribute (orthogonal states), we get:

$$M = \sum S^{1/2} \langle [\psi(0) \psi_{J_A}(1,\dots,A)]^B | f_0 | \psi_{ji}(0) \psi_{J_A}(1,\dots,A) \rangle.$$

So we find that $S^{1/2} = \sqrt{n} \{CFP\}$, or $S = n \{CFP\}^2$, where n is the total number of active nucleons in the residual nucleus B . Adding the isospin Clebsch-Gordon consideration, the factor (F) which multiplies the direct cross section is:

$$F = \langle T_A T_{AZ} 1/2 t_Z | T_B T_{BZ} \rangle^2 n \{CFP\}^2 = C^2 S$$

Hence we find that the S to be used is exactly as tabulated in [6] and that, in general, $S \leq n$.

e. Evaluation of the Direct M1 Capture Cross Section

The direct M1 cross section for $A(x,\gamma)B$ reactions, where x is a neutron or a proton and A is the target nucleus is given in the long wavelength approximation by:

$$\sigma_T(M1) = \frac{4\pi}{9} \frac{k_f^3}{k_a E_a} \frac{2J_B+1}{(2J_A+1)(2j_f+1)} |(J_f || M || J_i)|^2 (1)$$

Here k_f and k_a are the outgoing and incident wave numbers respectively, while E_a is the incident center of mass energy. J_A is the target spin, J_B the spin of the final state, and j_f the total angular momentum of the single particle in the final state. M is the single particle M1 operator given in the long wavelength limit [7] by:

$$\vec{M} = \mu_0 [\mu \vec{\sigma} + \alpha \vec{L}]$$

where $\vec{\sigma}$ is the Pauli spin matrix, $\vec{L}$ the angular momentum operator for

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Rather than being a collective phenomenon it is conceivable, as argued by Arnold, [9] that the observed transition strength is directly related to single particle or particle-hole strength in the final nucleus. Tsai and Londergan [10] have performed a direct-capture calculation with bound $1p-1h$ states. Their calculation required certain large exchange currents in order to reproduce the data. A preliminary report of a direct capture calculation [11] has indicated that the bremsstrahlung emitted in a single-particle transition can account for many of the features observed in the experiment. We have performed direct capture calculations in which we have (i) approximated the 19 MeV state as a bound $d5/2$ single particle state, and (ii) treated the 19 MeV state as a continuum state represented by a resonance in a complex optical model potential. The following is a description of these calculations and a report of our preliminary results:

The cross section for direct capture is proportional to the square of the following radial matrix element:

$$\sigma_T^L \propto \left\langle U_{\ell f j f} \left| \frac{d}{dr} (r j_L(k_Y r)) \right| \Psi_{\ell i j i} \right\rangle^2$$

A numerical integration to some reasonable radius can be performed if we have a bound state wave function to assure rapid convergence of the integral. In our first calculation (i) the final state, $U_{\ell f j f}$, was treated as a bound state. A Woods-Saxon potential was employed, with parameters adjusted to place a $d5/2$ state at 15 MeV in ^{12}C . It was found that the results were relatively insensitive to the amount of binding energy specified, from 100 keV to 5 MeV. An optical model fit to 30 MeV $^{11}\text{B}(p,p)$ scattering data [12] was used to determine the initial state wave function $\Psi_{\ell i j i}$. Furthermore, although the wave function describing the final state does not have the proper experimental energy, appropriate energies and wave numbers, corresponding to the continuum states of interest at 19.2 MeV, were used in the computation.

The curve in Fig. E3-6 is a pure E1 calculation as a function of incident proton energy. Data of Kovash, Blatt *et al.* [8,13] are the crosses while TUNL data, about 20 points taken in 500 keV steps, are represented by the solid dots. The calculation does quite well, peaking slightly to the right of the experimental maximum at 28 MeV. The magnitude of the cross section shown assumes a spectroscopic factor of 0.73.

Other radiations besides E1 have been computed. The relative cross sections for E1, E2 and M1 direct radiative capture are shown in Fig. E3-7. M1 is comparable to E2 up to 25 MeV.

The experimental angular distribution has been fitted to an expansion in Legendre polynomials according to the equation:

$$\sigma(\theta) = A_0 \left(1 + \sum_{k=1}^N a_k Q_k P_k(\cos \theta) \right)$$

where the Q_k coefficients correct for the finite geometry of the

Fig. E3-6. The $^{11}\text{B}(p, \gamma)^{12}\text{C}$ yield curve at $\theta_{\text{lab}} = 60^\circ$. Both TUNL and Blatt data are shown. The solid curve is the result of the bound direct-capture calculation while the dashed curve is the result of the continuum direct-capture calculation.

Fig. E3-7. The calculated direct capture cross sections for E1, E2 and M1 radiation. The relative contributions at $E = 25 \text{ MeV}$ are indicated.

experiment. Theoretically, the a_k coefficients are related to the amplitudes and phases of the E1 and E2 transition matrix elements. Table E3-1 lists a comparison between experiment and our E1 + E2 calculation. Including M1 in the computation has the effect of reducing a_1 by .06.

TABLE E3-1

	Exp	Bound	Continuum
a_1	0.36 ± 0.02	0.38	0.42
a_2	-0.52 ± 0.03	-0.57	-0.42
a_3	-0.29 ± 0.03	-0.13	-0.12

A study of the relative size of the transition matrix elements for the various initial partial waves involved in transitions to a $d_{5/2}$ final state at 15 MeV in ^{11}C has been performed. The relative strengths of the largest calculated transition matrix elements are the $f_{7/2}(\text{E1}) \rightarrow d_{5/2} : 81\%$, $p_{3/2}(\text{E1}) \rightarrow d_{5/2} : 7.4\%$ and $g_{9/2}(\text{E2}) \rightarrow d_{5/2} : 6\%$. A phase shift analysis for scattering from the final state potential is displayed in Fig. E3-8. It is significant that the partial wave which gives rise to 81% of the capture cross section, $f_{7/2}$, also resonates at about 30 MeV incident proton energy, approximately where the capture data peaks.

Fig. E3-8. The scattering phase shifts obtained from the optical potential designed to place the $d_{5/2}$ the single particle resonance at $E = 4$ MeV. Only the real part is shown.

In conclusion proton capture to the 19.2 MeV region of ^{12}C can be described rather well as direct capture from a predominantly $f_{7/2}$ incident state into a $d_{5/2}$ single particle final state. No collective behavior is implied in this model.

A direct capture calculation (11) which treats the final state as unbound has also been performed. The radial matrix element now involved has the form:

$$\langle \psi_{\ell f j f} \left| \frac{d}{dr} (r j_{\ell}(k_{\gamma} r)) \right| \psi_{\ell i j i} \rangle$$

Integration to some finite value of r is insufficient because the continuum wave functions $\psi_{\ell i j i}$ and $\psi_{\ell f j f}$ are not damped. This difficulty is overcome by dividing the radial integral into two parts:

$$\int_0^{\infty} \psi_{\ell f j f}(r) O_p(r) \psi_{\ell i j i}(r) dr = \int_0^{R_{\text{MAX}}} + \int_{R_{\text{MAX}}}^{\infty}$$

where, for electric transitions $O_p(r) = \frac{d}{dr} (r j_{\ell}(k_{\gamma} r))$.

R_{MAX} is chosen large enough such that the nuclear potential is essentially zero for all greater values of r . Consequently, only Coulomb wave functions are involved in the second term. Setting R_{MAX} equal to 12 fm was found to be suitable for the $^{11}\text{B}(p, \gamma)^{12}\text{C}^*$ reaction.

The integral from zero to R_{MAX} is evaluated numerically as was done in the bound state calculation. The remaining integral is evaluated by the method of Vincent and Fortune [14]. This involves integration along a contour in the complex plane (Fig. E3-9). Thus for an analytic function f we would have:

$$\int_{R_{\text{MAX}}}^{\infty} f(r) dr = \lim_{Y_{\text{MAX}} \rightarrow \infty} (\pm i \int_0^{Y_{\text{MAX}}} f(R_{\text{MAX}} \pm iy) dy + \int_{C_{\pm}} f(r) dr)$$

Fig. E3-9. Diagram showing the path of integration used to evaluate the matrix elements for direct-capture to continuum final states.

Recall that we are dealing with asymptotic Coulomb wave functions:

$$\psi \sim \frac{i}{2} [H^-(r) - \eta_\ell H^+(r)] e^{i\sigma_\ell}$$

where: η_ℓ : Nuclear scattering amplitude
 σ_ℓ : Coulomb phase shift.

The functions H^+ and H^- are analytic everywhere in the complex plane for $r \geq R_{MAX}$. For computational purposes, H^+ and H^- can be derived by the method of Fox and Goodwin. [15]

$$H^\pm(r) = G(r) \pm iF(r) \xrightarrow[r \rightarrow \infty]{} (f(r) \pm ig(r)) e^{\pm i(kr + \text{phase})}$$

Thus, asymptotically we have

$$H^\pm(r) \sim e^{\pm ikr}$$

This form implies that the integrands involved along the contours $C_\pm$ are exponentially small, the contributions vanishing as $Y_{MAX} \rightarrow \infty$. In our calculation it was sufficient to use $Y_{MAX} = 80$ fm to assure convergence of the computation even at the lowest proton energies.

Defining $r_\pm = R_{MAX} \pm iy$, $y \geq 0$, we arrive at the result:

$$\int_{R_{MAX}}^{\infty} \psi_{\ell f j f}(r) O_p(r) \psi_{\ell i j i}(r) dr = \eta_\ell I_+ + I_-$$

where

$$I_\pm = -i \int_0^{Y_{MAX}} H_{\ell f}^\pm(k_f r_\pm) \frac{i}{2} e^{i\sigma_{\ell f}} O_p(r_\pm) [H_{\ell i}(k_i r_\pm) - \eta_{\ell i} H_{\ell i}^\pm(k_i r_\pm)] \frac{i}{2} e^{i\sigma_{\ell i}} dy$$

Preliminary results for $^{11}\text{B}(p, \gamma)^{12}\text{C}^*$ are shown in Fig. E3-6. The final state wave function was obtained from a potential which was constructed to place the $1d^{5/2}$ resonance at 19.2 MeV in ^{12}C . The initial state wave function is the same as in the bound calculation. We find that the calculated cross section, after integrating over the final state energies, peaks at a lower proton bombarding energy: 22 MeV. However, the general shape of the data is reproduced. When E2 radiation is included in this continuum direct capture calculation, the values of the a_k coefficients obtained at the energy where the cross section peaks are in reasonable agreement with the data. These results are shown in Table E3-1. We find our single-particle calculations encouraging and are doing more studies to test the sensitivity of the results to the potential parameters. Further investigation of the absolute cross section in the experimental data is required before any firm conclusions can be drawn (see Sec. E6).

g. Development of a Computer Code for the Analysis of Nucleon Radiative Reactions (Hideo Kitazawa)

We have developed the computer code "HIKARI" which calculates the angular distributions of cross sections and analyzing powers of the gamma-rays produced by the radiative capture of polarized nucleons by unpolarized nuclei. The formalism is based on the direct-semi-direct capture model and takes account of the electric dipole, quadrupole, octupole and magnetic dipole transitions. Special features include the ability to calculate transitions from the isovector (E1, E2, E3, M1) and isoscalar (E2, E3) resonances and to take the isospin-splitting of the electric giant dipole state into account. The use of complex coupling between an incident particle and the target nucleus is optional. Options are also given for the particle-vibration coupling form factor for E2 and E3 transitions and for the form of the optical potential. The program needs the approximate memory size of 130 KB.

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4. Evidence for a 2^+ Resonance in ^4He at 40 MeV

The results of this work were published in a paper by McBroom, Weller, Manglos, Roberson, Wender, Tilley, Skopik, Arnold and Seyler in Phys. Rev. Letters 45 (1980) 243. The following is the abstract of that paper.

"The fore-aft asymmetry in the angular distribution of the reaction $^3\text{H}(p,\gamma)^4\text{He}$ has been measured as a function of energy for protons from 17 to 31 MeV. The same quantity was also measured using the reaction $^4\text{He}(e,^3\text{H})pe^+$. These asymmetry data were fitted

with an expression which consisted of a term which varied slowly with energy plus a 2^+ resonance having parameters of $\Gamma_{cm} = 3.5$ MeV and $E_x(\text{res}) = 40.2$ MeV."

5. The $^3\text{He}(n,\gamma)^4\text{He}$ Reaction

There has been considerable controversy over the magnitude of the photoneutron cross section of ^4He . Our $^3\text{He}(n,\gamma)^4\text{He}$ cross section indicates a value of about 1.0 mb for the $^4\text{He}(\gamma,n)^3\text{He}$ reaction in the energy region of $E_x = 23$ to 33 MeV. This result, when combined with the previously reported (γ,p) cross section, implies a (γ,p) -to- (γ,n) cross section ratio of 1.6 to 1.9 in this energy region. In the past year efforts to improve the accuracy of the absolute cross section have continued. In addition, the measurement of angular distributions of cross section and analyzing power have continued.

The experimental detail has been described previously.[1] The $\text{D}(d,n)$ reaction was used to produce the fast neutrons. A 2.54 cm long Deuterium cell was used for the yield curve measurement. The deuterium pressure was 90 PSIA; this produced a neutron energy spread of 760 KeV at $E_n = 6$ MeV and 170 keV at $E_n = 18$ MeV. For the angular distributions a 5.08 cm long Deuterium cell with 90 PSIA was used which resulted in an energy spread of 770 keV at $E_n = 9$ MeV. The ^3He cell pressure was raised to 140 ATM from 118 ATM which was reported last year.

We have attempted to evaluate the absolute cross section as carefully as possible. The yield curve has been corrected for the energy dependence of the detection efficiency. The program FIXER was used to evaluate the effects of the finite geometry of the apparatus. We estimate that the average angular spread of the source, target and detector system is approximately 25 degrees. Tests were performed to evaluate the effects of the steel target vessel on the neutron flux. The 1/16" wall attenuates the flux, and the steel flange scatters neutrons into the gas volume. These effects were estimated to lead to an effective increase of flux by only 1%. The steel wall was found to attenuate the gamma ray intensity by 5%. In an effort to determine precisely the number of target atoms, the gas was weighed and the computed number of atoms was compared to the number computed from the measured pressure using the relation $PV/nRT=z$, where z is the compressibility of the gas. These results agreed to within 4%.

In addition to determining the cross section more accurately, the yield curve was extended to $E_n = 18$ MeV. This extension allows a comparison of the $^3\text{He}(n,\gamma)$ and $^3\text{H}(p,\gamma)$ cross sections in a region where their ratio has been consistently measured to be approximately one. Fig. E5-1 shows our data together with the $^3\text{H}(p,\gamma)^4\text{He}$ data from Stanford. [2] Both of these are 90 degree yield curve measurements. Fig. E5-2 gives a comparison of our data to some of the (γ,n) measurements; [3,4,5] as well as the only other capture measurement. [6] A total (γ,n) cross section has been deduced by the

Fig. E5-1. The TUNL $^3\text{He}(n, \gamma)$ 90° cross section data along with the $^3\text{H}(p, \gamma)$ Stanford data.

Fig. E5-2. Comparison of TUNL data with (γ, n_0) measurements.

principle of detailed balance, and by the relation $\sigma_T = (8\pi/3) (90)$. The angular distribution at $E_x = 28$ MeV verified this relation to within 5%. Fig. E5-3 shows the angular distribution of cross section and analyzing power for the present experiment as well as for the ${}^3\text{H}(p,\gamma){}^4\text{He}$ experiment performed at Stanford. [7] The a_k and b_k coefficients for each are shown for comparison. These data have been corrected for finite geometry effects.

Fig. E5-3. Angular distributions of cross sections and analyzing power. (p, γ) data are from Ref. [7].

There are two E1 and two E2 amplitudes in this reaction corresponding to channel spin $S=0$ and $S=1$. The a_1 and a_3 coefficients are dominated by terms representing interference between $S=0$ (E1) and $S=0$ (E2) amplitudes. Interference between $S=0$ and $S=1$ terms give rise to b_2 . It would be virtually impossible to obtain information on the $S=1$ (spin flip) strength without the use of polarized beams. As shown in Fig. E5-3, the b_2 coefficient for the n and p channels are quite similar. This suggests that the relative $S=1$ to $S=0$ E1 strength is about the same for these two channels.

If the equations for the a_k and b_k coefficients are expressed in terms of the $S=0,1$ E1 amplitudes and the $S=0$ -E2 amplitude, a fit to the data indicates that the $S=0$ E2 amplitude accounts for about 2.5% of the total cross section while the $S=1$ E1 amplitude accounts for about 1% of the total. The $(\bar{p}, \gamma)$ experiment gave similar results for these two numbers. The relative phases for the three amplitudes obtained from the (n, γ) data are also in good agreement with those found from the (p, γ) data.

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6. Proton Capture to Highly Excited States in Light Nuclei

Preliminary measurements of γ -ray spectra for radiative proton capture to highly excited states in various light nuclei were reported in TUNL XVIII. We have expanded these measurements, obtaining yield curves and angular distributions (including some polarized beam measurements) for capture to excited states in ^8Be , ^{12}C , and ^{14}N . The data have been compared with calculations based on a direct capture model.

The spectra for the reaction $^7\text{Li}(p,\gamma)^8\text{Be}$ show capture to the ground state (0^+) of ^8Be , to the first excited state (2^+), and to a region which contains a pair of well-known 2^+ isospin-mixed states [1] at excitation energies of 16.63 and 16.92 Mev in ^8Be . It is not possible to separate these two states in this experiment. We will discuss here only the capture to this region. The yield curve for capture to this region, as measured with the TUNL-Nal-spectrometer, is shown in Fig. E6-1 for incident proton energies of 11.5 to 30 Mev. Plotted along the top is the excitation energy above the final 16.6 Mev state. The data show very

Fig. E6-1. The $^7\text{Li}(p,\gamma_x)^8\text{Be}^*$ yield curve along with the result of the direct capture calculation normalized to fit the data.

little structure. It should be noted that no giant resonance shape is seen at the expected energy (about 20 Mev excitation above the final state). The solid curve shown is the result of a direct E1-E2 calculation, obtained with the code RADCAP, using the description of Sweeney and Marlon [1] for the isospin-mixed pair. In the calculation we have neglected the contribution of the 16.92 Mev state, since this state has a negligible $7\text{Li} + p$ spectroscopic factor. The agreement between the shape of the data and the the shape of the calculation is rather remarkable, but a spectroscopic factor of about 6 is necessary to normalize the absolute cross section of the calculation to the data. This large spectroscopic factor may suggest the presence of non-direct effects. It should be noted that the experimental absolute cross section is still somewhat uncertain due to target thickness uncertainties but should be correct to within a factor of 1.5. We intend to remeasure our absolute cross section in order to determine it more precisely.

Angular distributions for $7\text{Li}(p,\gamma)8\text{Be}$ ($E_x=16.63$ and 16.92 Mev) have been measured at six energies from 12 to 22 Mev and compared with E1-E2 direct capture. A sample angular distribution is shown in Fig. E6-2 where the curve is the result of an E1-E2 direct calculation, normalized to the data. The a_k coefficients obtained from the Legendre polynomial fits to the data, $\sigma(\theta)=A(1+\sum a_k P_k(\cos\theta))$, along with the results of the direct calculation, are shown in Fig. E6-3. There is qualitative agreement between the data and the calculation, except at the two lowest energies, 12 and 12.5 Mev. However, there is some evidence in the spectra at these two energies for a contaminant in the 16.6 Mev excitation region, so that the data here is suspect.

Fig. E6-2. The measured angular distribution for the $7\text{Li}(p,\gamma_x)8\text{Be}^*$ reaction at $E_p=22$ MeV. The solid curve was calculated using a direct E1+E2 capture model.

In the future we intend to extend the yield curve down to lower energies to determine the position of the peak in the cross section. Unfortunately, due to the presence of contaminants in the spectra at lower energies and due to the limited resolution of our NaI spectrometer, it is not possible with this system to measure the capture cross section to the isospin-mixed pair below $E_p = 11.5$ Mev.

Consequently, we are presently considering two other possible experimental methods. The first is to use a GeLi detector with its increased resolution to measure the γ -rays. Alternatively, since it is known that the isospin-mixed pair decays essentially 100 of the time into two alpha particles, we could attempt to measure the (p, γ) cross section by observing the production of the coincident alpha particles. Work is proceeding on this experiment.

Fig. E6-3. Comparison between the measured a_k coefficients and the direct-capture predictions.

Blatt *et al.* have recently measured a yield curve for the reaction $^{11}\text{B}(p, \gamma)^{12}\text{C}^*$ where the final state is a state, or group of states, at about 19.2 Mev excitation energy, which may be the 4^- stretched configuration $(d5/2 p3/2^-)4^-$. This state is above the single-particle decay threshold (unbound). We have attempted to reproduce some of their data with our NaI spectrometer. A sample spectrum taken at TUNL is shown in Fig. E6-4. The yield curve of Blatt *et al.*, which has been

Fig. E6-4. The TUNL spectrum obtained for the $^{11}\text{B}(p, \gamma)^{12}\text{C}$ reaction at $E_p = 27$ Mev. The solid curve is a fit which was generated using our standard line shape.

renormalized by a factor of 1.27, and our data are shown in Fig. E3-6. The solid curve shown is the result of an E1-E2 direct capture calculation, with the final state being approximated as a slightly bound $d5/2$ single-particle state. The spectroscopic factor used in the calculation is 0.73. The dashed curve represents the results of a similar calculation which treats the final state properly as an unbound (continuum) state. The details of this calculation are described in Sec. E3.f. We see here that the yield curve shows a resonant-like shape at about the correct energy for a giant dipole resonance but that this shape may be described by a direct (non-resonant) capture model.

An angular distribution measurement at 28.7 Mev for $^{11}\text{B}(p,\gamma)^{12}\text{C}^*$ has been made at TUNL, for comparison with the measurement of Blatt. [3] The two results are in good agreement, as shown in Table E6-1, which gives the Legendre polynomial coefficients, a_k .

TABLE E6-1

$^{11}\text{B}(p,\gamma) (E_x = 19.2 \text{ MeV})$

	<u>Blatt</u>		<u>TUNL</u>	
a	0.34	0.03	0.36	0.02
a	-0.60	0.06	-0.52	0.03
a	-0.27	0.07	-0.29	0.03

A sample spectrum for proton capture on ^{13}C is shown in Fig. E6-5. Capture to the ground state and first excited state of ^{14}N , capture to a set of states at about 5.7 Mev excitation (labeled γ_A), and

Fig. E6-5. The spectrum and line-shape-fit for the $^{13}\text{C}(p,\gamma)^{14}\text{N}$ reaction at 26 MeV.

capture to a set of states at about 8.9 Mev (labeled γ_B) are seen here. We have analyzed only the peak γ_A , which appears to be composed of the $1p_{1/2} \otimes (1d_{5/2} \text{ or } 2s_{1/2}) T=0$ multiplet. [4] The 90 degrees yield curve from 20-30 Mev is shown in Fig. E6-6, including both TUNL data and the data of Paul *et al.* [4] The curve shown is the result of an E1-E2 direct capture calculation, using the spectroscopic factors of Bobbitt *et al.* for the final states, which has been renormalized upward by a factor of 1.9 to give agreement with the data. The presence of some structure in the yield curve, in addition to the higher cross section for the data relative to the calculation, suggests the existence of non-direct effects.

Fig. E6-6. The 90° cross section for the $^{13}\text{C}(p, \gamma_A)$ reaction along with the prediction of the E1+E2 direct capture model.

We have measured cross section angular distributions for $^{13}\text{C}(p, \gamma_A)^{14}\text{N}$ at five energies from 12 to 25 Mev proton energy, and analyzing power angular distributions at three energies. Sample angular distributions at 14 Mev are shown in Fig. E6-7 and Fig. E6-8 along with

Figs. E6-7 and E6-8. Angular distribution data for cross section and analyzing powers in the $^{13}\text{C}(p, \gamma_A)^{14}\text{N}$ reaction shown along with the predictions of the direct (E1+E2) capture model.

the results of the E1-E2 direct calculation, represented by the solid curves. The absolute cross section of the calculation has been normalized by 1.5 here. The data have been fit to Legendre polynomials according to: $\sigma(\theta) = A_0(1 + \sum a_k P_k(\cos\theta))$ and $\sigma(\theta) A(\theta) = A_0(1 + \sum b_k P_k(\cos\theta))$ where the P_k are associated Legendre polynomials. Shown in Fig. E6-9 are a_k and b_k , as a function of energy, obtained from these fits. For comparison, the results of the E1-E2 direct calculation are again shown as the solid curve. The overall agreement is not particularly good.

Fig. E6-9. A comparison of the measured a_k and b_k coefficients with the results of the direct capture calculation for the $^{13}\text{C}(p, \gamma)^{14}\text{N}$ reaction.

In summary, our analysis has yet to provide any clear evidence for giant dipole resonances built on the excited states which we have studied, although such resonances are not ruled out. One possibility is that the giant resonances are present but are too broad and/or too weak to be seen in the observed proton channel. It is also true, though, that a simple direct capture model has been unable so far to describe all the features of the data (in particular, the absolute cross section). In addition to taking more data (extending yield curves and making more angular distribution measurements), we intend to investigate the results of our capture calculations more thoroughly. In particular, we will investigate the sensitivity of the direct capture calculation to various input parameters (i.e. continuum and bound state potential parameters). We also intend to perform Direct Semi-Direct calculations to determine the predicted importance of giant resonance effects in our observed channels.

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7. Measurement of the Angular Distribution and Absolute Cross-Section of $^{12}\text{C}(n,\gamma)^{13}\text{C}$ at $E_n = 12\text{ MeV}$

We have measured the angular distribution for the $^{12}\text{C}(n,\gamma)^{13}\text{C}$ reaction at $E_n = 12\text{ MeV}$ ($E_x = 16.08\text{ MeV}$) in collaboration with Jim Jury (Trent University) and John Woodworth (Lawrence Livermore Laboratory). This experiment was performed in order to check the magnitude of the previously reported a_3 coefficients obtained earlier in a photoneutron experiment. These previously reported a_3 's, of the order of 0.5, could not be obtained in a DSD calculation [1] and, in fact, would require anomalous behavior in non-E1 multipoles.

Our measured angular distribution is shown in Fig. E7-1. The fit shown is a third order fit (through $P_3(\cos\theta)$). The coefficients were $a_1 = -0.135 \pm .073$, $a_2 = -0.788 \pm 0.95$ and $a_3 = 0.044 \pm 0.123$. In fact, the lowest reduced chi-squared is obtained in a second order fit. These results indicate that the a_3 coefficient at $E_x = 16.08\text{ MeV}$ is essentially zero. After performing this measurement, the $^{13}\text{C}(\gamma,n)$ data were re-examined and it was concluded that the data were not accurate enough to be able to extract reliable a_3 coefficients.

Fig. E7-1. The angular distribution data obtained for the $^{12}\text{C}(n,\gamma)^{13}\text{C}$ reaction are shown here. The solid curve is the result of a Legendre polynomial fit to the data through P_3 .

Our measurements also allow for an independent check of the absolute cross section of the $^{13}\text{C}(\gamma,n)^{12}\text{C}$ reaction. After correcting for such things as finite geometry, neutron and γ -ray attenuation and detector efficiency, we obtain a total cross section of $50\text{ }\mu\text{b}$ for the $^{12}\text{C}(n,\gamma)^{13}\text{C}$ reaction at $E_n = 12\text{ MeV}$. This corresponds to a (γ,n) cross-section of 1.86 mb , in good agreement with the value reported in Ref. [2].

Further work is planned in collaboration with Woodworth and Jury. An effort to measure the excitation curve for neutrons of 12 to 18 MeV is planned. This is of current interest since there appears to be a sizeable discrepancy between the experimental (γ, n) cross sections and the DSD predictions in this energy region, [1] the DSD calculation giving substantially lower values than those expected when Isospin Clebsch-Gordon arguments are applied to the proton data.

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8. A Study of The $E_p = 3.11$ MeV Resonance in ^{14}N via The $^{13}\text{C}(p, \gamma)$ Reaction

Several years ago, we attempted to determine the efficiency of our N I spectrometer system for 10 MeV gamma-rays by using the reported [1] peak cross section of the $E_p = 3.11$ MeV resonance in the $^{13}\text{C}(p, \gamma)$ reaction. The value of $d\sigma/d\Omega(90^\circ) = (66 \pm 13) \mu\text{b/sr}$ lead to an efficiency for our spectrometer that was clearly not consistent with other measurements.

We have subsequently calibrated our detector for gamma-ray energies from 10 to 35 MeV. Our procedures have been described in detail in Refs. [2] and [3] and only the salient features will be given here. The detector efficiency for 15.1 MeV gamma rays is obtained by measuring the thick target yield curve for the $^{12}\text{C}(p, \gamma)$ reaction between $E_p = 14.2$ and 14.4 MeV. The number of gammas per proton is well known in the 15.07 MeV resonance. The efficiencies at other energies are obtained by correcting for the energy dependence response function, the gamma-ray attenuation of the shielding and the rejection rate due to the anti-coincidence shield.

Using our calibrated system, we have remeasured the 90° peak cross section for the ^{14}N resonance at $E_p = 3.11$ MeV. In order to check for consistency, two measurements were made, one with a $62 \mu\text{g/cm}^2$ target and one with a $48 \mu\text{g/cm}^2$. The thicknesses were determined from the energy loss of 5.48 MeV alpha particles and have estimated errors of about 5%. The thicknesses were also obtained directly from the experimental yield curves, as will be discussed below, and the results agreed with the values given above well within the 5% uncertainty.

The 90° yield curve obtained with the thin target is shown in Fig. E8-1 where the step size is 10 keV in the region of the resonance. The energy loss of the protons is about 6 keV. A similar yield curve was taken with the thicker target where the energy loss for the protons is about 42 keV. For both measurements, the TUNL high-resolution system was

in operation so the energy spread of the beam should be approximately 500 eV and should not be significant.

The data were fitted with a function obtained by integration of the Breit-Wigner dispersion formula over the energy interval represented by the energy loss in the target. [4] The averaged results obtained from the two yield curves are $\Gamma(\text{lab}) = (37 \pm 22) \text{ keV}$, $E(\text{res}) = (3112 \pm 4) \text{ keV}$ and $d\sigma/d\Omega(\text{lab}) = (47 \pm 4) \mu\text{b/sr}$. The quoted errors are based on estimates of the target thickness detector efficiency and beam current integration errors as well as the statistical accuracy of the data.

Fig. E8-1. Thin target yield curve for $^{13}\text{C}(p, \gamma_0)^{14}\text{N}$ at 90° .

The use of the new value of the cross section to renormalize the $^{13}\text{C}(p, \gamma)^{14}\text{N}$ data of Reiss *et al.* [5] removes most of the discrepancy of this latter experiment relative to other studies (see Ref. 5 for a fuller discussion of this point).

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9. The $^{13}\text{C}(n, \gamma)$ Reaction

a. Experiment and Analysis

We have continued our study of ^{14}C by neutron capture on ^{13}C . Angular distributions of analyzing power and cross section have now been measured at $E_n = 7.75, 9.2, 10.2, 11$ and 12 MeV. The analyzing powers were measured from $\theta_{\text{lab}} = 45$ degrees through 142 degrees and the cross sections were measured from $\theta_{\text{lab}} = 35$ degrees through 150 degrees. Legendre and Associated Legendre polynomials - $P_\ell(\cos \theta)$ and $P'_\ell(\cos \theta)$ were used to fit the data seen in Fig. E9-1.

Fig. E9-1. Angular distributions with Legendre polynomial fits.

The polarized and unpolarized angular distributions were corrected for the finite geometry of the source gas cell, the target and the detector, neutron and gamma ray attenuation, multiple scattering, and the angular dependence of the $2\text{H}(d, n)$ reaction. Analyzing powers were corrected by using the Legendre expansions of our data to construct spin-up and spin-down cross sections. These were then

corrected as if they were unpolarized cross sections. After correction, the polarized cross sections were combined to produce an analyzing power angular distribution which was refit. The shapes of the angular distributions are little changed as can be seen in Table E9-1. The highest order polynomial included in each fit was determined by statistical criteria. The corrected coefficients are plotted in Fig. E9-2. Note that the triangles at 7.75 and 9.2 MeV represent the a_k coefficients obtained when the fit included a $l=3$ term, even though this term was not statistically justified in these cases.

Fig. E9-2. Coefficients of Legendre expansions as a function of energy. The solid curves represent DSD calculations using a volume form factor. The dashed curves represent DSD calculations using a surfaced peaked form factor.

The excitation function has now also been corrected for finite geometry, including the energy dependence of the angular spread of the $2H(d,n)$ reaction. The finite geometry correction factor at 90 degrees as a function of energy is shown in Table E9-2. The corrected 90 degrees excitation function is shown in Fig. E9-3.

Fig. E9-3. 90° excitation function for $^{13}\text{C}(n, \gamma_0)^{14}\text{C}$.

If one considers just the dominant E1 cross section, we can write the A0, a2 and b2 equations in terms of the two E1 matrix elements and their relative phase. If we label the relevant complex T-matrix elements by the quantum numbers of the incident partial wave, the two E1 matrix elements are $s_{1/2} e^{i\phi_s}$ and $d_{3/2} e^{i\phi_d}$. The equations are quadratic and have 2 solutions, characterized by a dominant $d_{3/2}$ term and a dominant $s_{1/2}$ term. The equations were solved and the solutions are seen in Fig. E9-4. The circles represent the dominant $d_{3/2}$ and the triangles represent the dominant $s_{1/2}$ solutions. The solid lines represent the results of a direct capture calculation which indicates that the $d_{3/2}$ dominant solution is the physical solution.

Once the E1 cross section makeup is determined, M1 and E2 radiation may be investigated. Our calculation of the direct M1 contribution to the cross section has shown that this strength is down by 4 orders of magnitude in relation to the E1 cross section. If we assume that the M1 strength may be neglected, then the angular distributions may be fit directly to the E1 and E2 matrix elements and their relative phases. We have, as above, the two E1 matrix elements, $s_{1/2} e^{i\phi_s}$ and $d_{3/2} e^{i\phi_d}$, and also two E2 matrix elements, $p_{3/2} e^{i\phi_p}$ and $f_{5/2} e^{i\phi_f}$.

The E1 matrix elements are close to those obtained from a pure E1 analysis, and the E2 cross section amounts to a few percent. For the E2 matrix elements we find one or two solutions at the various energies. Taking the small solutions, the Energy Weighted Sum, $\int dE \sigma(E2) E \gamma^{-2}$, in the excitation region from 13.4 through 21.2 MeV is $1.32 \mu\text{b} \cdot \text{MeV}^{-1}$, which exhausts 22% of the IS-E2-EWSR.

Fig. E9-4. Results of E1 analysis.

TABLE E9-1

Angular Distribution Coefficients for The $^{13}\text{C}(n,\gamma_0)$ Reaction

<u>En(lab)</u> <u>(MeV)</u>	<u>coef</u>	<u>---Finite Geometry---</u>	
		<u>-Uncorrected-</u>	<u>-Corrected-</u>
7.75	a1	-0.09 $\pm$ 0.03	-0.09 $\pm$ 0.03
	a2	-0.16 $\pm$ 0.05	-0.16 $\pm$ 0.05
	b1	0.00 $\pm$ 0.04	-0.03 $\pm$ 0.04
	b2	0.33 $\pm$ 0.03	0.33 $\pm$ 0.03
9.2	a1	-0.02 $\pm$ 0.03	-0.01 $\pm$ 0.03
	a2	-0.65 $\pm$ 0.04	-0.62 $\pm$ 0.04
	b1	-0.11 $\pm$ 0.05	-0.13 $\pm$ 0.05
	b2	0.20 $\pm$ 0.04	0.18 $\pm$ 0.04
10.2	a1	-0.06 $\pm$ 0.02	-0.06 $\pm$ 0.03
	a2	-0.63 $\pm$ 0.04	-0.60 $\pm$ 0.04
	a3	0.13 $\pm$ 0.05	0.11 $\pm$ 0.05
	b1	-0.25 $\pm$ 0.04	-0.24 $\pm$ 0.05
11.0	a1	-0.09 $\pm$ 0.02	-0.08 $\pm$ 0.02
	a2	-0.65 $\pm$ 0.03	-0.63 $\pm$ 0.03
	a3	0.15 $\pm$ 0.04	0.13 $\pm$ 0.04
	b1	-0.01 $\pm$ 0.03	-0.02 $\pm$ 0.03
12.0	a1	-0.16 $\pm$ 0.04	-0.16 $\pm$ 0.04
	a2	-0.83 $\pm$ 0.05	-0.80 $\pm$ 0.06
	a3	0.22 $\pm$ 0.07	0.19 $\pm$ 0.07
	b1	0.01 $\pm$ 0.06	-0.02 $\pm$ 0.06
12.0	b2	0.26 $\pm$ 0.04	0.22 $\pm$ 0.04

TABLE E9-2
Finite Geometry Correction for $^{13}\text{C}(n, \gamma)$ at $\theta_{\text{lab}} = 90$ degrees

E_n	Correction Factor
7.75	1.24
9.2	1.31
10.2	1.34
11.0	1.38
12.0	1.43

b. Direct Semi-Direct Calculations

Attempts to attribute the E1 and E2 strength to the GDR and the iso-scalar GQR in ^{14}C by means of the direct-semidirect (DSD) model are in progress.

Two DSD E1 models have been compared with the data, one having a real volume coupling form factor ($V = 100$ MeV, $W = 0$) and the other having a complex coupling form factor ($V = 75$ MeV, $W = 38$ MeV). The two main peaks in the excitation function were assumed to be due to two resonances located at $E_x \simeq 15$ and 18 MeV. The strength of each resonance was adjusted to best fit the excitation function. The resulting resonance parameters for each type of form factor are presented in Table E9-3 with the fits to the cross section displayed in Fig. E9-5. Both calculations imply that these resonances exhaust about 60% of the Classical Dipole Sum Rule. [1]

Fig. E9-5. The 90° excitation data with DSD calculations. The solid line represents the real volume coupling form factor ($V=100$ MeV, $W=0$) calculation. The dashed line represents the complex coupling form factor ($V=75$ MeV, $W=38$ MeV) calculation.

Two DSD E2 models were added to the analysis. One having a real volume form factor and the other having a real surface peaked form factor. Both these models include an iso-scalar E2 resonance having an excitation energy of 20 MeV, with a width of 4 MeV, and exhausting 50% of the IS-E2-EWSR. The resulting Legendre coefficients are shown as the curves in Fig. E9-2. Although the odd terms in the Legendre expansion are indeed introduced by the inclusion of E2, the DSD model provides only a qualitative description of the data.

TABLE E9-3

Parameters of Assumed E1 Resonances

Resonance	Location (MeV)	Width (MeV)	Strength (η) ($\frac{1}{2}$ -Sum Rule)
Real Volume Coupling			
1	15.1	2.0	38
2	17.7	2.0	27
Complex Coupling			
1	15.2	2.0	31
2	17.8	2.0	28

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10. The $^{14}\text{N}(n,\gamma)^{15}\text{N}$ Reaction In The Giant Resonance Region of ^{15}N

A paper describing this work has been submitted for publication in "Nuclear Physics". The abstract follows.

"The $^{14}\text{N}(n,\gamma)^{15}\text{N}$ reaction has been studied over the neutron energy range from 6 to 15 MeV. Data include an excitation function in 200 keV steps, and 7 angular distributions. The data show good agreement with results of direct semi-direct model calculations. The shape and magnitude of the cross section as a function of energy is similar to the $^{14}\text{N}(p,\gamma)^{15}\text{N}$ reaction and different from the $^{14}\text{C}(p,\gamma)^{15}\text{N}$ reaction.

These differences can be understood in terms of the different isospin states allowed in each reaction."

11. Polarized Neutron Capture in ^{28}Si

Radiative capture on spin zero targets leading to $s(1/2)$ final states is unusual for electric transitions. For these cases the partial waves involved in the capture process have $l+1/2$ and $l-1/2$, and we expect the relative phase between the two complex T-matrix elements, $T(l+1/2)$ and $T(l-1/2)$, to be very sensitive to the spin-orbit term of the optical model. This sensitivity should be most apparent in the b_2 -coefficient obtained from the angular distributions of analyzing power. By investigating the transitions to s-states with polarized nucleons, it may be possible to obtain more information about the spin-orbit force.

We have recently published a study of the $^{30}\text{Si}(p,\gamma)^{31}\text{P}$ reaction with polarized protons. [1] The b_2 -coefficients for this reaction are given (for pure E1 radiation) by

$$b_2 = -p(1/2)p(3/2)\sin(p_1,p_3),$$

where $p(1/2)$ and $p(3/2)$ are the real amplitudes of the complex T-matrix elements for $p(1/2)$ and $p(3/2)$ capture, respectively, and (p_1,p_3) is the relative phase between the two matrix elements. These b_2 -coefficients were small and negative (~ -0.1). Calculations based on the direct-semidirect model using a real surface-peaked spin-orbit term in the optical model gave b_2 values that were small but positive indicating that the predicted relative $p(1/2)$ - $p(3/2)$ phases have opposite signs from the experimental values. A preliminary re-analysis of this data using the code HIKARI suggests that the introduction of an imaginary spin-orbit term into the optical potential may explain the negative sign of the b_2 -coefficients.

To extend this investigation, we have measured the angular distribution of cross section and analyzing power for the reaction $^{28}\text{Si}(n,\gamma)^{29}\text{Si}$ at $E_n=10$ Mev. The neutrons were produced with a pulsed polarized deuteron beam incident on a 1 inch cell filled with deuterium at a pressure of 90 psia. Time-of-flight techniques were used to separate the gamma rays from scattered neutrons. The target was a 38 x 38 mm cylinder of natural Silicon with an abundance of ^{92}Si . Differential cross sections were measured with spin up and with spin down at six angles ranging from 55 to 140 degrees.

The gamma ray spectra for transitions leading to the ground and first excited states have been fitted using the multiple peak fitting program MULFIT. Corrections for finite geometry and the angular dependence of the $D(d,n)$ differential cross section are currently in progress. The preliminary and uncorrected angular distributions of cross section and analyzing power were fit with expansions of Legendre and Associated Legendre polynomials ($P_l(\theta)$ and $P_l^m(\theta)$), respectively, through

$l=3$. The results are given in Table E11-1 below.

On the basis of a standard DSD calculation we predict a positive sign for the b_2 -coefficients in the $^{28}\text{Si}(n,\gamma)^{29}\text{Si}$ reaction. Work is underway to determine the effect of adding a complex spin-orbit term. We plan to make more measurements at 10 Mev and at 12 Mev.

TABLE E11-1

Polarized neutron capture on ^{28}Si

Ground state	First excited state
$a_1 = 0.080 \pm 0.057$	$a_1 = -0.093 \pm 0.041$
$a_2 = -0.841 \pm 0.079$	$a_2 = -0.242 \pm 0.044$
$a_3 = 0.039 \pm 0.080$	$a_3 = 0.096 \pm 0.055$
$\chi^2 = 0.90$	$\chi^2 = 0.030$
$b_1 = -0.031 \pm 0.027$	$b_1 = -0.096 \pm 0.019$
$b_2 = -0.036 \pm 0.020$	$b_2 = 0.206 \pm 0.015$
$b_3 = 0.023 \pm 0.019$	$b_3 = -0.010 \pm 0.015$
$\chi^2 = 2.2$	$\chi^2 = 1.1$

12. Polarized Proton Capture to the First Excited State in ^{31}P

A paper reporting on $^{30}\text{Si}(p, \gamma_0)^{31}\text{P}$ and $^{30}\text{Si}(p, \gamma_1)^{31}\text{P}$ 90° yield curves for $E_p = 5.0$ to 28 MeV and angular distributions of cross section and analyzing power at twelve energies between $E_p = 6.36$ and 14.45 MeV has been published. [1] The paper dealt primarily with the groundstate transition and included comparisons with direct-semidirect calculations. During the past year a more detailed analysis of the (p, γ_1) data has been carried out.

The curve at the top of Fig. E12-1 was obtained by averaging the 90 degree yield curve (Fig. 2 of Ref. [1]) with a 1.1 MeV energy interval. Two broad peaks are observed near $E = 16$ and 20 MeV respectively. These peaks may be identified with the $T_<$ and $T_>$ components of the GDR built upon the first excited state of ^{31}P . Potokar [2] has carried out a detailed analysis of this yield curve.

Angular distributions of cross section and analyzing power were measured at seven angles with $\theta = 42$ degrees to 142 degrees. At some energies the cross sections were measured at nine angles (30 degrees to 154 degrees). Typical results are shown in Fig. E12-2. The solid

Fig. E12-1. The experimental a_k and b_k coefficients and results of DSD calculation.

Fig. E12-2. Typical angular distributions.

lines represent a fit of the data to an expansion of Legendre polynomials

$$\sigma(\theta) = A_0 \left[1 + \sum_{k=1}^n a_k Q_k P_k(\cos \theta) \right],$$

and associated Legendre polynomials,

$$A(\theta) \sigma(\theta) = A_0 \sum_{k=1}^n b_k Q_k P_k'(\cos \theta).$$

The coefficients Q_k correct for finite geometry. The a_k and b_k coefficients obtained from the fits are shown in Fig. E12-1.

We first assumed that only E1 is important. Since the first excited state spin of ^{31}P is $3/2^+$, the complex T-matrix elements which contribute to the E1 strength are $p_{1/2} \exp(i\phi_{p_{1/2}})$, $p_{3/2} \exp(i\phi_{p_{3/2}})$ and $f_{5/2} \exp(i\phi_{f_{5/2}})$. Having to determine five unknowns with only three measured quantities A_0 , a_2 and b_2 means that some simplifying assumptions must be made. Calculations using the direct-semidirect theory [3] with a form factor $\propto r$ showed that the $p_{3/2}$ T-matrix elements (spin-flip) should be small and that the $(p_{1/2} - p_{3/2})$ relative phases are determined primarily by the spin-orbit term in the optical-model potential. The analysis was carried out by setting the ratio $(p_{1/2}) / (p_{3/2})$ and the relative p-wave phases equal to the DSD calculated values. Two sets of solutions were found: one corresponds to having $\sigma(f_{5/2}) / \sigma(E1) \sim 0.7$ and the other to ~ 0.25 . The DSD model calculations suggest that the solutions with $f_{5/2}$ dominant are the physical ones.

A calculation [4] based on extended DSD model [2,5] which includes amplitudes corresponding to direct electric dipole and quadrupole capture, semidirect $T_<$ and $T_>$ GDR components, and semidirect isoscalar and isovector GQR components has been performed. The effect of the isovector GQR is quite small in the excitation energy region studied here. The parameters used for the calculation were taken from our earlier study of the $^{30}\text{Si}(p, \gamma_0)$ reaction. [1] The results are shown as the solid lines in Fig. E12-1. Also shown as dashed lines are the pure E1 calculations discussed above. The overall agreement with the experimental data is good, especially at the higher energies, but there are some substantial deviations.

The calculated (p, γ) E2 cross sections were converted by the method of detailed balance to (γ, p) cross sections and used to determine the fraction of the E2-EWSR for $E_p = 8.5$ to 15.5 MeV. When compared to the predictions of Nathan and Nilsson, [6] this calculation gives 1.5 of the IS-E2-EWSR. For the case of pure direct E2 capture we calculate 1.6% of this sum rule.

The authors acknowledge helpful conversations with M. Potokar during early stages of this work.

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13. The $^{40}\text{Ca}(n,\gamma)^{41}\text{Ca}$ Reaction

We have continued our study of the $^{40}\text{Ca}(n,\gamma)^{41}\text{Ca}$ reaction for excitation energies in the region of the giant resonances. Since our last progress report, we have extended the 90 degrees yield curve from $E_n(\text{Ex}) = 13(21)$ to $17(24.9)$ MeV. We also remeasured $\sigma(90^\circ)$ at $E_n = 10, 11$, and 12 MeV. The results are shown in Fig. E13-1 where the new points are shown as open triangles and our previously published data [1] are shown as solid dots. The two sets of data are given in absolute

Fig. E13-1. $\sigma(90^\circ)$ for the reaction $^{40}\text{Ca}(n,\gamma)^{41}\text{Ca}$. The data reported in [1] are indicated by solid dots, while the new are represented by open triangles.

units, both sets having been corrected for the finite size of the neutron source, target, and detector, neutron and gamma attenuation, multiple scattering, and detector efficiency. There is no relative normalization. The reproducibility is excellent and these measurements confirm the value of $16 \mu\text{b/sr}$ for $\sigma(90 \text{ degrees})$ near 10 to 11 MeV. It should also be noted that the structure in the region of $E_n = 12.5$ to 13.0 MeV has been reproduced.

Fig. E13-2. The a_k and b_k coefficients obtained from the $^{40}\text{Ca}(n,\gamma)^{41}\text{Ca}$ experiment are shown along with the results of DSD calculations (see text).

The first polarized neutron capture measurement which we reported [2] was for the reaction $^{40}\text{Ca}(n,\gamma)^{41}\text{Ca}$ at $E_n = 10.0$ MeV. Since that time we have also measured angular distributions of analyzing power at $E_n = 8, 9$, and 11 MeV. These data have not been corrected for the effects mentioned above. Our preliminary calculations show that at 90 degrees these factors are small, but we are currently investigating the possibility that they would introduce an additional correction to analyzing power measurements at other angles. The a_k and b_k coefficients obtained from fitting the angular distributions to expansions of Legendre and associated Legendre polynomials, respectively, through second order are shown in Fig. E13-2. The points at 12 and 13 MeV are from Refs. [1] and [3]. Higher order coefficients were not statistically significant.

If, however, we fit through 3rd order, the extracted a_3 coefficients tend to be slightly negative albeit with large uncertainties; at $E_n = 10.0$ MeV, $a_3 = -0.048 \pm 0.052$. The solid curves in the figure are direct-semidirect (DSD) model calculations made by Dietrich [4] which include the isoscalar GQR at $E_x = 18.0$ MeV with a width of 4.0 MeV. [5] The fraction of the $1S - E2 - EWSR$ exhausted by the $1S - GQR$ was taken as 39%. [5] The calculations for the a_2 and b_2 coefficients, which are determined primarily by $E1$ radiation, are in good agreement with the experimental values. However, the calculated values of a_1 clearly have the opposite sign with respect to the data. The energy dependence of the a_1 coefficient is accounted for by this calculation, but the predicted magnitudes are too small. Also note that the DSD values for the b_1 coefficients disagree especially at lower energies where the experimental values of b_1 seem to be increasing.

We have used the program HIKARI to investigate the discrepancies in the a_k and b_k coefficients. New DSD calculations were carried out using a volume $E2$ form factor ($r U(r)$) rather than the surface-peaked form factor ($-rdU/dr$) used in the calculation discussed above. [4] The new DSD results are shown in Fig. E13-2 as the dotted line; the GQR parameters for this case are the same as for the surface-peaked calculations. [5] While these new calculations are in better agreement with the measured a_2 coefficients, very little change is seen for the b_1 , b_2 , and a_1 coefficients, and there is a bigger disagreement with the a_3 coefficient. It should be noted that the volume form factor leads to an $E2$ cross section of $4.11 \mu b$ at $E_n = 11$ MeV as compared with 0.534 for the surface-peaked form factor. DSD calculations using the volume type $E2$ form factor are being made and compared with other data to determine if the improvement observed here persists for nuclei in different mass regions (see Section C in this report).

The dashed line in Fig. E13-2 represents an extended calculation which includes direct $M1$ strength due to $f_{5/2}$ neutron capture. [6] No adjustable parameters were involved in adding this term to the original DSD calculation which used the surface-peaked $E2$ form factor. (Since these calculations were made, the option of including $M1$ amplitudes has been added to HIKARI.) The effect of adding direct $M1$ is to cause a rise in b_1 at lower energies, but little change in the other coefficients.

To further investigate this apparent observation of direct $M1$ radiation, we have started a program to measure the 90 degrees analyzing power, $A(90 \text{ degrees})$, as a function of energy from $E_n = 6.0$ to 13.0 MeV. The values of $A(90 \text{ degrees})$ should be sufficient to determine the b_1 coefficients since both our previous measurements and the DSD calculations suggest that b_1 is small. The results of our preliminary measurements are shown in Fig. E13-3 for $E_n = 7.0$ to 11.0 MeV, uncorrected for any of the effects mentioned above. Also shown are calculations made with HIKARI which assume a volume $E2$ form factor, both with and without direct $M1$. The general trend of the data is predicted, but the small experimental values at $E_n = 7.0$, 9.0, and 9.5 MeV remain to be accounted

for. More experimental work to verify and extend these results is planned.

Fig. E13-3. 90° analyzing power measurements at $E_n=7.0$ to 11.0 MeV. In some cases the data represent the weighted averages of more than one measurement. The solid line is the result of an E1-E2 DSD calculation made with Hikari, assuming an E2 volume form factor. The dashed curve is the same calculation, but including direct M1. Both calculations use the GQR parameters from ref. [5].

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14. Polarized Proton Capture to The First Excited State of ^{60}Ni *

We have used the reaction $^{59}\text{Co}(p, \gamma_1) ^{60}\text{Ni}$ to study the giant dipole resonance built on the first excited (2^+) state of ^{60}Ni . [1,2] The gamma-rays were detected with our 25.4 x 25.4 cm NaI detector assembly incorporating a plastic anticoincidence shield. The target was a 4.2 ± 0.4 mg/cm self-supporting natural Co foil. A standard line-shape fitting procedure was used to strip the γ_0 and γ_1 peaks from the spectra.

Yield curve measurements were taken at 90 degrees in 100 keV steps for E_p of 5.7 to 16.5 MeV. When these data are averaged over a 500 keV interval, the curve shown in Fig. E14-1 is obtained. The two peaks seen in this curve near E of 15.8 and 19.0 MeV are shifted up by about 0.4 MeV in ^{60}Ni with respect to two peaks observed in the $^{59}\text{Co}(p, \gamma_0) ^{60}\text{Ni}$ reaction. In the latter case these two peaks have been previously associated with the T^- and T^+ components of the GDR of the ground state of ^{60}Ni . [1]

Fig. E14-1. Energy Averaged Yield Curve

Fig. E14-2. Angular Distribution Data

Angular distributions of cross section and analyzing power were measured at several energies across the region of the experiment. Data were taken at five angles for each proton beam energy. Typical results are shown in Fig. E14-2. The differential cross section data were fitted to an expansion of Legendre polynomials:

$$\sigma(\theta) = A_0 \left[1 + \sum_{k=1}^2 a_k Q_k P_k(\cos \theta) \right]$$

while the product of the cross section and the analyzing power fitted by an expansion in associated Legendre polynomials:

$$\frac{A(\theta)\sigma(\theta)}{A_0} = \sum_{k=1}^3 b_k Q_k P_k'(\cos \theta)$$

The coefficients Q_k correct for finite geometry. The solid lines in Fig. E14-2 are the result of this procedure.

The resulting a_2 and b_2 coefficients are shown in Fig. E14-3. Since the angular distributions of cross sections and analyzing powers for the $^{59}\text{Co}(p, \gamma_0)^{60}\text{Ni}$ reaction could be reasonably well accounted for by the direct-semidirect model with a form factor $\propto r$, a similar calculation was performed for this case. [2]

The results of this calculation which takes the 2^+ state of ^{60}Ni to be an $f_{7/2}$ single particle state are shown as the solid curves in Fig. E14-3. The overall trend of the coefficients is in fair agreement with the predictions of the calculation. Stripping reactions have indicated a significant $p_{3/2}$ single particle spectroscopic strength in the first excited state of ^{60}Ni . [3] However, attempts to improve the agreement of the DSD calculation by including this strength were unsuccessful.

Fig. E14-3. Angular Distribution Coefficients are shown along with the results of the DSD calculation (solid lines). Errors are statistical.

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15. Polarized Proton Capture on ^{88}Sr

This work was reported in a paper contributed to the Fifth International Symposium on Polarization Phenomena in Nuclear Physics in Santa Fe. The abstract is reproduced below:

"Cross sections for $^{88}\text{Sr}(p, \gamma_0)^{89}\text{Y}$ and $^{88}\text{Sr}(p, \gamma_1)^{89}\text{Y}$ have been measured at 90 degrees for $E_p = 5.5$ to 27.0 MeV. Angular distributions of cross section and analyzing power for (p, γ_0) were measured at 14 proton energies in the GDR region for $E_p = 6.05$ to 15.0 MeV. The resulting a_k and b_k coefficients are compared with direct-semidirect calculations."

16. Study Of The $^{208}\text{Pb}(n,\gamma)^{209}\text{Pb}$ Reaction

The direct-semidirect model has been a useful tool in interpreting the radiative capture angular distributions measured with polarized and unpolarized projectiles. However, the calculated angular distributions have not been, in general, very sensitive to the various E1 form factors used with the DSD model. These form factors which represent the nucleon-nucleus vibrational coupling interaction vary from the simple form derived by Brown [1] to the complex form proposed by Potakar [2]. A possible test of the validity of the different E1 form factors is suggested by recent DSD calculations by Likar *et al.* [3] for the $^{208}\text{Pb}(n,\gamma)$ reaction leading to the $1(11/2)$ first excited state of ^{209}Pb . Their calculations for the a_2 angular distribution coefficients as a function of energy is shown in Fig. E16-1. The dotted line is for $V(r)=0$, i.e., for direct E1 capture, the solid line is for the real form factor proposed by Potakar, and the dashed line is for the complex form also developed by Potakar [3].

Fig. E16-1. Experimentally extracted a_2 coefficients shown with calculations using DSD model in Ref. [3] for $^{208}\text{Pb}(n,\gamma)^{209}\text{Pb}$.

We have measured an angular distribution at 10 MeV, the yield at $\theta=55, 90$, and 125 degrees for $E_n=10.5, 11.0, 11.5$, and 12.0 MeV, and the 90 degree yield curve from 7.0 to 13.0 MeV. Preliminary discussion of these data was given in TUNL Progress Report XVII. A new analysis of this data has been done using the new peak fitting program, MULFIT, with the background option. The 90 degree yield curves from 7.0 to 13.0 MeV for transitions to the ground state and the first excited

state are shown in Figs. E16-2 and E16-3, respectively. The data have been arbitrarily normalized to the total cross section data of Bergqvist, Drake, and McDaniels. [4] Both sets of data give giant dipole resonance shapes for the two transitions. The error bars on the TUNL data include both statistical and fitting errors. Further analysis is underway to extract absolute cross sections. The transition to the first excited state ($E_x = 0.78$) peaks approximately 1.0 MeV higher in neutron energy than the transition to the ground state.

Fig. E16-2. $^{208}\text{Pb}(n, \gamma_0)$ cross section data (dots) shown along with data from Ref. [4].

Fig. E16-3. $^{208}\text{Pb}(n, \gamma_1)$ cross section data (dots) shown along with data from Ref. [4].

The 10.0 MeV angular distribution for transitions leading to the ground state and 0.78 MeV first excited state are shown in Fig. E16-4. The solid line is a fit to an expansion in Legendre polynomials thru second order. The coefficients are also given in the figure. The errors are from statistical uncertainties only. The a_1 coefficients have an additional uncertainty because of the subtraction

Fig. E16-4. Angular Distribution for $^{208}\text{Pb}(n, \gamma_0)$ and $^{208}\text{Pb}(n, \gamma_1)$.

of a large angular dependent background. The a_2 coefficients from the analysis of our data are shown in Fig. E16-1 with the previously described DSD model calculations. We have investigated the sensitivity of the calculations to the optical model parameters used. The DSD results of Likar *et al.*, shown in Fig. E16-1 were obtained with the Rosen [4] optical model parameters. We have found that using the Bechetti and Greenlees [5] parameters, for example, results in significant changes in the a_2 's, especially for the real form factor in the region of 7 to 12 MeV, but the a_2 's are still positive for complex coupling and are negative for real coupling over the energy range of our data. Our results clearly support the use of a complex form factor in neutron capture in this mass region. We hope to extend these measurements to other energies. This work was done in collaboration with M. Potokar. (See TUNL XVIII, Sec. E. 15)

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F. ACCELERATOR BASED ATOMIC PHYSICS

1. General Status of The Program (M. Clark, T. McAbee, J. Swenson, S. M. Shafroth, E. N. Strait,* J. Willis,** J. A. Tanis,*** R. Mowat, A. Waltner, S. L. Varghese)

The major experimental progress at TUNL has been to construct and make operational equipment which was used for measurements of dielectronic recombination cross sections and which can be used for gas target radiative electron capture studies. Further studies of target thickness effects and REC have been done. The angular distribution of REC and of Pb L x-rays excited by 3 MeV protons has been measured, in order to compare with theory. Deviations from isotropy are due to enhanced depopulation of $m=0$ substates at small impact parameters.

Cyclo-Graaff runs were done in which protons were accelerated in the range from 2-30 MeV in 2 MeV steps. The object of this work was to determine the cross sections for K shell ionization of Pb so that comparison with theory could be made. A preliminary run at the Cornell synchrotron was done to search for resonant Raman Auger Electrons. In the spring of 1980 we were awarded a grant of \$8,175.00 by the North Carolina Board of Science and Technology to obtain a small computer which would control the Auger Spectrometer.

FOOTNOTES (Section F1)

- * Macalester College, St. Paul, Minnesota
- ** Lawrence Berkeley Laboratory, Berkeley, California
- *** Western Michigan University, Kalamazoo, Michigan
- University of S. Alabama, Mobile, Alabama

2. Target Thickness Effects in Heavy Ion Collisions
(S. M. Shafroth, J. A. Tanis, J. Willis, J. R. Mowat, W. W. Jacobs)

During 1980 we have consolidated our target thickness studies and have gained new insight into projectile double K vacancy production, REC processes and H.I. induced target K vacancies.

a. Double K Vacancies

A paper entitled "Evolution of Projectile Double K Vacancy Fractions with Target Thickness in Ion Atom Collisions" by J. A. Tanis, S. M. Shafroth, J. E. Willis and J. R. Mowat has been published in Phys. Rev. Letters 45 (1980) 1547. The abstract follows:

"The dependence of projectile double-K-vacancy (hypersatellite) x-ray yields on target thickness for ions moving in thin solid targets is examined. For 2.3-MeV/amu Cl ions incident on C foils, the double- to single-K-vacancy x-ray yield ratio increases by a factor of 3.5 over the range of thicknesses investigated, reaching values as high as 0.3. A quantitative explanation of the observed results is obtained using a formulation based on K-vacancy production and filling cross sections."

This work has also been reported on at Stirling, Scotland at the International Conference on X-Ray Processes, August 25-29, 1980, by Shafroth in a paper entitled "Three Component Model of Cl Projectile Hypersatellite K X-Ray Intensities vs. C Foil Thickness" by J. A. Tanis, S. M. Shafroth, J. E. Willis and J. R. Mowat. We point out the importance of this target thickness effect in inferring the ratio of single to double K vacancy production in heavy ion collisions. Some discussions in the literature have ignored this effect which in our case can be as big as a factor of six. Furthermore, double K vacancy sharing ratios have been deduced from measurements of single-to-double K vacancy x-ray intensity ratios for target and projectile in near-symmetric collisions without regard for target thickness effects. Finally determinations of ratios of two-electron one-photon to single electron transition ratios where double K vacancies exist, i.e., $K_{\alpha\alpha}^h/K_{\alpha}^h$ require separate experiments—one to determine $K_{\alpha\alpha}^h/K_{\alpha}^h$ and one to measure K_{α}^h/K_{α} . Unless the targets for these two measurements have the same thickness, large errors can result.

Two interesting conclusions resulting from this work are: first, that double collisions ($\sigma_{01} - \sigma_{12}$) predominate over single collisions (σ_{02}) for the production of projectile double K vacancies in this collision system and second, σ_{12} is considerably bigger than expected on the basis of Coulomb ionization alone. Thus inner shell vacancy transfer is probably the most important mechanism for producing double K shell vacancies.

b. Systematic Studies of K Xrays and REC

A paper entitled "Systematics of Target and Projectile K_2 X-Ray Production and REC for 20-80 MeV Cl^{19+} Ions Incident on 25-200 $\mu g/cm^2$ Cu Targets" by J. A. Tanis, W. W. Jacobs and S. M. Shafroth has been published in Physical Review A22 1980 483-495. This paper summarizes some of our recent work on target thickness effects and REC. Among the most interesting results described in it are the zero thickness target K electron ejection cross sections for Cu when bombarded with Cl^{19+} ions of varying energies and charge states. We parameterize the Cu K electron ejection cross section vs target thickness in terms of the basic charge changing cross sections using a two component model and compare them with theory. Thus comparison is made with "zero target thickness cross sections", which is the only meaningful way of doing this. We find

that PWBA and BEA calculations overestimate this cross section by factors of 10 or more at the lower bombarding energies. However if corrections are made for Coulomb deflection, relativity and electron capture to the L and higher shells of the projectile (CPSSR + ECR) the agreement between theory and experiment improves considerably, especially at the higher bombarding energies.

Interestingly, this cross section can not be explained by the Meyerhof vacancy-sharing model since the conditions required for application of this theory are not satisfied in our work. First, the direct ionization cross section is much too big relative to the cross section for vacancy transfer from the 2p molecular orbital. Second, vacancy sharing applies to the outgoing part of the collision and the electron capture to the L and higher shells of the projectile is too large. As the ratio $Z_1/Z_2 \rightarrow 1$ the zero thickness K electron ejection cross sections are less well described by the CPSSR+ECR theory as expected. The abstract appeared in the 1979 progress report TUNL XVIII.

c. REC

A short paper on radiative electron capture entitled, "Radiative Electron Capture by Cl Ions Incident on C and Cu Foils", by J. A. Tanis, S. M. Shafroth, J. E. Willis and J. R. Mowat has been accepted for comments in Phys. Rev. A and will be published in January 1981.

In this paper we point out that in order to compare measured REC cross sections with theory one not only needs to extrapolate to zero target thickness but also it is useful to obtain the effective K shell binding energy directly from the experimental spectrum rather than by estimating it as is usually done. The effective K shell binding energy (E_K) can be found from the spectrum using the approximate formula: $E_{REC} = E_K + \left(\frac{m_e}{M}\right)E$ where E_{REC} is the centroid energy of the REC peak and $\left(\frac{m_e}{M}\right)E$ is the kinetic energy of a free electron in the projectile frame of reference. This is approximately valid since the electrons giving rise to the REC peak are loosely bound, i.e.,

$$\frac{v_e}{V} \ll 1$$

where v_e is the bound target electron velocity and V is the projectile velocity. Using these techniques we find that the 4 outer electrons contribute to the REC peak for C targets and the 11 outer electrons contribute in the case of Cu targets.

This work as well as a measurement of the angular distribution of REC and a three component model target thickness analysis were presented in a poster session at Stirling, U.K. The angular distribution of REC radiation was measured for 40 and 60 MeV Cl^{19+} on $140 \mu g/cm^2$ Cu. After doing a channel-by-channel absorption correction and

normalizing to Cu K_α radiation (assuming it to be isotropic) we found a distribution which agrees more nearly with a $\sin^2 \theta / (1 - \beta \cos \theta)^4$ distribution than a $\sin^2 \theta$ distribution as would be expected if retardation effects are included. Our measured angular distribution showed a forward-backward asymmetry, particularly for the 65 degrees to 115 degrees ratio as well as for the 45 degrees to 135 degrees ratio. The REC intensities at extreme forward and backward angles, 25 degrees and 155 degrees are very weak and do not show this asymmetry, but this is probably because the spectra are primarily due to captured electrons having momenta with components transverse to the incident Cl beam. This experiment is being repeated in view of the discrepancy with theory.

One of us (J.A.T.) has done a three-component target thickness analysis of REC and has shown that about 20% of the REC radiation at 80 MeV Cl^{10+} on C is due to capture into projectiles with a fully stripped K shell for 20 $\mu g/cm^2$ thick C foils. It is difficult to check this because the expected energy increase (170 eV) from REC into single K vacancy projectiles is not resolved in our spectra, due to the momentum distribution of the captured electrons and multiple ionization broadening. Some of this was also presented in a poster session at the Sixth Conference on The Applications of Accelerators in Research and Industry, Denton, Texas, Nov. 3-5, 1980.

3. X-Ray Angular Distribution Experiments

(M. Clark, S. Hurst, S. M. Shafroth,
J. Swenson, J. E. Willis, S. L. Varghese)

"Angular Distribution of Pb L X-rays Excited by 3 MeV Protons" by M. Clark, S. Hurst, S. M. Shafroth, J. Swenson, J. E. Willis and S. L. Varghese was presented at Denton, Texas and has been written for publication in IEE Proceedings. The summary follows:

"We have measured the angular distribution of Pb L α and L β x-rays in the case of lead where the targets were typically 100 $\mu g/cm^2$ thick with a 400 $\mu g/cm^2$ layer of silver evaporated on each side. Spectra were obtained at 25, 45, 65, 90, 115, 135 and 155 degrees and ratios of Pb L x-rays to the isotropic Ag K_α x-rays were taken. The most readily interpretable case is the L α since this transition involves only the L III subshell. After correcting for x-ray absorption in the target assuming it to be layered (i.e., neglecting diffusion of the Ag in the Pb) we find a small deviation from isotropy, which is expected due to enhanced depopulation of M=0 substates at small impact parameter collisions. The velocity dependence of the alignment parameter A_2 has been calculated using PWBA and screened as well as unscreened wave functions. Our results for A_2 agree with these calculations. Further work is under consideration."

Table F3-1 gives the results of this work and compares with theory. It can be seen that we agree with the unscreened hydrogenic wave function PWBA calculations of Scholer and Bell.

TABLE F3-1

Experimental and Theoretical Values for The L III Subshell Alignment, A_2 , for LI X-rays Emitted In The Dipole Decay of 3 MeV Proton Excited Lead

(a)	(b)
A_2	A_2
-0.11(5)	-0.17

- (a) Present value
 (b) PWBA calculation with unscreened hydrogenic wave functions (A. Scholer and F. Bell 1978 Z. Phys. U. 286, 163-168.)

4. Dielectronic Recombination (S. M. Shafroth, J. E. Willis, M. Clark, J. Swenson, J. Tanis, E. Strait, R. Mowat)

a. Coincidence Measurements

In the case of interest here dielectronic recombination (DIREC) occurs when a fast moving ion in charge-state q captures an electron from a target gas atom in such a way that one of the ion's K electrons is excited to the L shell for example. This is followed by emission of a K X-ray. The first part of this process is the time-reversed Auger effect. This process is represented schematically in Fig. F4-1. DIREC is thought to be an important energy loss mechanism in thin high temperature plasmas, such as are found in Tokamaks and stellar atmospheres. Measurements of DIREC cross sections are difficult due in part to the presence of similar processes occurring simultaneously such as collisional excitation and ionization. In order to study this and other processes such as radiative electron capture we have constructed a beam line which incorporates post stripping so that high charge states can be obtained. It is illustrated in Fig. F4-2. The highly stripped, magnetically analyzed beam is then tightly collimated (0.002 rad), passed through an interaction region consisting of a windowless gas cell and then electrostatically analyzed to establish its charge state. X-rays arising from the interaction region are detected with a semiconductor detector. Coincidences between X-rays and charge-changed beam are recorded and the dielectronic recombination (DIREC) cross section is inferred. The experimental arrangement is illustrated in Fig. F4-3.

DIELECTRONIC RECOMBINATION

FOR EXAMPLE, FOR A He-LIKE PROJECTILE ION

SIGNATURE FOR DIELECTRONIC RECOMBINATION:

EMISSION OF A K X RAY IN COINCIDENCE
WITH A SINGLE CAPTURE EVENT

Fig. F4-1. Schematic illustration of projectile dielectronic recombination.

Fig. F4-2. Floor plan of TUNL showing the post stripper foil and high charge state beam analyzer.

Fig. F4-3. Experimental arrangement for DIREC experiment.

S^{13-16+} Coincident capture cross sections (σ_{CAPRAD}) for 70 MeV projectiles incident on Ar gas are shown in Fig. F4-4.

Fig. F4-4. Coincident S K X-ray cross section with one or two electron capture vs incident projectile charge state (q).

Fig. F4-5 shows the ratio of K-capture radiation to single and for S^{15+} single and double capture. In the case of S^{16+} nearly all capture (single plus double) results in K radiation, but for S^{13+} the ratio is 0.0004. Fig. F4-6 shows the fraction of S K X-rays arising from capture to the total number of K X-rays (capture plus ionization). Thus for S^{13+} 17% is due to DIREC while for S^{16+} 70% is due to single capture to states with $n \leq 2$ and the rest is presumably due to double capture.

To the extent that the radiative processes studied here simulate the same processes for free electrons in a plasma, the results may be used to test theoretical calculations of radiative loss rates in plasmas and to provide experimental estimates of these radiative losses. A paper has been submitted to Physical Review Letters entitled "Dielectronic Recombination in S+Ar Collisions". The abstract follows:

Two distinct electron capture processes which result in projectile K X-ray emission are DIREC and capture into high n states ($n \geq 2$). In the case of incident S^{13+} the only coincident process is DIREC. However for the case of He-like S^{14+} a 10% 2^3S_1 (1s2s) metastable component can account for most of the cross section since a K vacancy is present initially. The cross section at $q=15$ for both single and double capture as well as that for bare S^{16+} are of course primarily due to capture into $n \geq 2$ states. The fact that these measurements are done in coincidence suggests that we are observing a single electron capture process rather than a Coulomb ionization interaction between projectile electron and Ar nucleus followed by double electron capture.

Fig. F4-5. Ratio of coincident S K x-ray cross sections to projectile one or two electron capture cross sections vs incident charge state (q).

"Dielectronic recombination is observed for 70 MeV S + Ar collisions. In addition, radiation following capture into high n states without accompanying excitation is measured for charge states $q = 14+$ to $16+$. The results are used to determine the fraction of capture events which result in K-shell radiation. Possible applications to radiative loss processes in fusion plasmas and stellar atmospheres are discussed.

Fig. F4-6. Ratio of coincident S K x-rays yield to total S K x-ray yield for single and double electron capture vs incident charge state (q).

b. X-Ray Satellites and Signatures of Dielectronic Recombination

L x-ray satellites arise when a transition to the K shell occurs in the presence of one or more inner shell vacancies. The exact energy of the satellite depends on the coupling of the unpaired electrons. We are studying the feasibility of determining more detailed information about the electron configurations involved in transitions following DIREC using the ARL spectrometer. To this end a differentially pumped gas target for use with the curved crystal x-ray spectrometer has been designed. Using the VAX computer at TUNL, Hartree-Fock calculations have been done of transition energies of highly ionized Fe^{q+} , which can be compared with recent measurements at the Princeton Tokamak, by K. Hill *et al.*, formerly of TUNL.

5. Electron Spectroscopy

- a. Resonant Raman Auger Electrons (J. Swenson, P. Peters, S. M. Shafrath, M. Clark, J. E. Willis)

In order to obtain at least 10,000 times the monochromatic x-ray intensity available from our x-ray tube, we decided to try searching for shifted resonant Auger electrons at the Cornell synchrotron. Targets of Co, Ni, Cu and Tb (all 5 g/cm²) were prepared for this purpose. The vacuum chamber which houses the spectrometer was modified significantly. First, an externally positioned target ladder was installed. Second, the chamber was milled so that the spectrometer position could be accurately determined with respect to the synchrotron x-ray beam. Third, the entire spectrometer and pumping system was modified so as to fit into a lead lined hutch (3'x3'x3') at the Cornell synchrotron. Fourth, an independently biased hot filament assembly was built to fit in the spectrometer vacuum chamber so that the spectrometer and electronics could be tested immediately before going to Cornell as well as on arrival. This permitted experimental determination of the spectrometer constant, the energy resolution and in principle the spectrometer efficiency. Detailed calculations concerning focal properties of the spectrometer were done to obtain the optimal location for entrance and exit apertures. Unfortunately, although the spectrometer was working when we left for Cornell, it did not work properly on arrival. Possible reasons may be residual magnetic fields and insufficient time to pump the chamber down since we opened it frequently on arrival.

As a result of that run we have made several modifications and have ordered a new fast diffusion pump for the spectrometer. We have done considerably more theoretical and experimental work studying the spectrometer using the hot wire electron source. A paper was presented at the Chapel Hill meeting of SESAPS, Nov. 1980 by Swenson on this work.

b. Electronics

A Kepco OPS 5000 high speed programmable power supply serves to supply the plate voltage of the spectrometer. It programs linearly with input signal from 0 to 5000 volts. This allows the spectrometer to analyze up to 10 keV electrons. (The spectrometer constant $C=E_0/V_p=2$ where V_p =plate voltage.) The supply can be floated to 1000 volts so that the maximum electron energy observable is 12 keV.

To program this supply, J. Swenson and J. Willis designed and built a control circuit consisting of an up/down counter with programmable upper and lower limits, a 10 bit digital to analog converter and an adjustable gain, biased amplifier. With this circuit one can set a voltage window anywhere in the 0 to 5000 volt range, sweep over any or all of that window, choosing one of 5 different conversion gains which sets the number of volts per step in a scan.

To take data, logic circuitry has been incorporated into the system so that an event (the detection of an electron) and the corresponding plate voltage may be stored in a multichannel analyzer (MCA). A single channel analyzer (SCA) serves to supply the event pulse

which tells the MCA to read the number present in the up/down counter and increment that memory location by one. Each number in the counter represents a plate voltage for a given setting of the control circuit so by calibrating the system a meaningful electron energy spectrum may be stored. Retrieval of the spectrum is accomplished by printing out the number of counts in each channel on a teletype or paper tape, by displaying on an oscilloscope, or by plotting the spectra using an X-Y plotter.

This system is designed so it can be interfaced with a microprocessor so that voltage programming and data acquisition and analysis may be done automatically and far more efficiently.

We are now in the process of interfacing the spectrometer to the new Vector Graphics computer so that we will have a portable, stand-alone data taking system for use at Cornell or Chapel Hill. In order to do low yield experiments such as studies of metastable Auger electron emitters we are designing a cylindrical mirror analyzer (CMA).

6. Lead K X-ray Production by 2-30 MeV Protons
(J. E. Willis, M. Clark, J. Swenson, S. M. Shafroth,
A. W. Waltner)

X-ray spectra have been recorded using nA proton beams from the TUNL Cyclo-Graaf and FN tandem from 2-30 MeV in 2 MeV steps to obtain cross section data for Pb K electron ionization. One problem at the higher energies was that (p,n) reactions gave rise to radioactive Bi which in some cases decays back to Pb by K electron capture and thus gives rise to Pb K x-rays which must be subtracted from the total Pb K x-ray yield to obtain the Coulomb ionization cross section.

7. X-Ray Identification of Fusion Reaction Products

A short paper entitled, "X-Ray Identification of Fusion Reaction Products Implanted in Al Foils Following ^{16}O and ^{19}F Bombardment of ^{59}Co Foils" by A. W. Waltner, S. L. Varghese, J. E. Willis and S. M. Shafroth has been published in Nuclear Instruments and Methods 120 (1980) 189-192. The abstract has appeared in TUNL XVIII.

8. Delayed X-Ray Emission (J. R. Mowat, K/ R. Huddle,
S. Matney, S. M. Shafroth, M. Clark, J. Swenson)

Two runs totaling three days' time were devoted to the study of delayed x-ray emission by fast, foil-excited ions. This work was partially supported by the Atomic, Molecular, and Plasma Physics Program of the National Science Foundation through a grant to NCSU.

An experiment to measure inner shell vacancy lifetimes involved the use of a gas-flow position-sensitive soft x-ray proportional counter (PSPC) built at NCSU. This detector was oriented with its sensitive length parallel to the beam, set up to view an extended length of beam downstream from the foil, and collimated so that only x rays emitted at 90 degrees to the beam were detected. With this arrangement there is a correspondence between the position in the detector at which an x ray is registered and the point along the beam from which the x ray is emitted. The position spectrum thus acquired is an exponential decay corresponding to the actual decay in flight of excited ions. Sulphur ions from the sputter source were used for the TUNL experiment. When compared with similar data taken at NCSU with a carbon ion beam, the new S data revealed that the position resolution is a function of the x-ray energy. The final interpretation of the experimental decay curves awaits the completion of experiments now underway at NCSU that are designed to systematically study this broadening effect.

A second experiment used the PSPC to take x-ray spectra. This time the detector was collimated to allow viewing only a point several centimeters downstream from the exciter foil, but with acceptance angles up to 45 degrees. Because of the doppler shift there is a correspondence between the position in the detector at which an x ray is registered and the (lab) energy of the detected x ray. The 45 degrees span of angles translates into an energy dispersion of 10 eV for carbon K x rays (rest frame energy near 285 eV) emitted by 10 MeV ions. This bandwidth includes several low ionization stages. The position spectrum has a smooth sine-squared distribution due to geometrical effects. When a suitably chosen material is placed in the path of the emitted x rays, structure will be introduced on that smooth distribution that reveals the characteristic absorption features of the material. Given the known energies of these features, the beam velocity, and the geometrical relation between emission angle and point of detection, the (ionic rest frame) energy of the emitted x ray can be determined. Only a limited amount of data was taken because of poor ion source performance, but two spectra were obtained which display the anticipated structure.

G. OTHER EXPERIMENTS

1. Heavy Ion Induced Neutron Producing Reactions (S. Shafroth, C. R Gould, S. A. Wender, J. Dave)

A preliminary study of Heavy-Ion Induced neutron-producing reactions was undertaken with the goal of producing well collimated fluxes over a wide energy range. Since negative Q reactions produce fast neutrons which, near threshold, are contained in narrow kinematic cones, it may be possible to place detectors close to samples but outside the neutron flux. With this geometry it may be possible to study neutron capture gamma reactions with GeLi detectors or neutron induced x-rays using semiconductor detectors. On the other hand, positive Q value reactions such as $7\text{Li} + d$ ($Q=15.0$ MeV) produce high energy neutrons. These positive Q value reactions might provide an alternative to tritium reactions for producing high energy neutrons.

In order to make this study a gas cell was constructed and installed on the neutron time-of-flight beam line. The gas cell was positioned over the center of rotation of the neutron detector. Beams of ^{160}D , ^{7}Li , ^{11}B , ^{12}C were obtained from the sputter source. The $^{160}\text{D} + n$ ($Q=-1.624$ MeV) time-of-flight spectra were observed for ^{160}D energies of 22.5 MeV at 0, 20 and 40 degrees. At 40 degrees no neutrons were detected since the maximum angle for the neutron emission in this case is 35 degrees. We also observed 18 and 36 MeV $^{11}\text{B} + d$ $^{12}\text{C} + n$ ($Q=+13.732$ MeV) without time-of-flight since the beams were not intense enough to pulse and bunch. Finally we mapped out the neutron cone for the $^{7}\text{Li} + p$ $^{7}\text{Be} + n$ reaction at a ^{7}Li incident energy of 24 MeV without time-of-flight. The cone was very well defined so the neutron flux of interest dropped by more than a factor of two in $1/2$ degree at 40 degrees as expected. This was followed by a gas-out run to obtain the background which was about $1/3$ of the counts in the cone. In the future we plan to have up to 1 microamp of ^{7}Li beam rather than 60 namp and a more sensitive time pick-off detector, so that time-of-flight spectra can be obtained.

H. WORK DONE ELSEWHERE

1. Medium Energy Nuclear Physics (R. E. Anderson)

During the present contract year R. E. Anderson has participated in medium energy nuclear physics experiments which were undertaken at LAMPF.

The excitations of giant resonance states in ^{118}Sn were observed with both π^+ and π^- projectiles at $T_\pi = 130$ MeV. Prominent peaks were observed in all cases at excitation energies consistent with the expected locations of the giant quadrupole resonance (GQR) and the giant dipole (GDR)/giant monopole (GMR) resonances. In addition, the low energy octupole resonance (LEOR) was quite strongly excited. Clear differences were seen in the π^+ and π^- spectra near 16 MeV excitation. This is the region where contributions from the GMR (an isoscalar excitation) and from the T-lower component of the GDR (an isovector excitation) are anticipated. The simplest explanation for these differences may be that the T-lower and T-upper components of the GDR overlap and isospin mixing of these levels takes place. Since the π^+ and π^- probes are sensitive to such effects, differences in the spectra would be expected on that basis. However, the absolute magnitudes of the π^+ and π^- excitations of the GQR are different also, and simple kinematic considerations (largely coulomb in origin) can account for only one-half of the observed effect. By comparison, the GQR state in ^{40}Ca was observed in both π^+ and π^- scattering. In that case the kinematic corrections completely accounted for the observed difference. Thus more complex effects than isospin mixing may be present in the ^{118}Sn data.

Differences were also noted in regions where higher lying isovector transitions have been theoretically predicted. We hope to investigate these regions more thoroughly in later runs.

Isovector transitions were also observed in the (π^+, π^0) reaction on $^{42,44,48}\text{Ca}$, since these isotopes are well suited for a detailed study of the isovector term $U_1(\vec{t}_\pi \cdot \vec{t})$ in the pion-nucleus optical potential. Data for the $^{40}\text{Ca}(\pi^+, \pi^0)$ reaction were also obtained in order to determine the shape of the quasifree scattering spectrum.

The experiment was performed with the LAMPF π^0 spectrometer, and the isobaric analog states are clearly visible at angles near 0° . Preliminary analysis of the data indicate a substantial deviation from the expected $(N-Z)/A^{-4/3}$ dependence which is theoretically predicted.

Finally, data have been obtained for π^- elastic scattering at $T_\pi = 21, 30, \text{ and } 50$ MeV for a series of nuclei $^{12,13}\text{C}, ^{16}\text{O}, ^{40,48}\text{Ca}$,

90Zr, and 208Pb. Some additional data were acquired at 40 MeV. It is my hope that, in addition to testing existing theories of elastic and charge exchange scattering, these data sets will also be useful in addressing the question of neutron radii for 40Ca and 48Ca.

2. Laser Spectrometer for Precise Energy Measurements of 10-120 keV D- and T- Ions (G. G. Ohlsen, Ronald E. Brown, Nelson JarmI, R. A. Hardekopf [LASL], S. E. King, F. D. Correll [LASL], and D. A. Clark [University of New Mexico])

Design and development of a precision laser spectrometer for energy measurement of low energy deuteron and triton beams was carried out in conjunction with the fusion cross section program at Los Alamos Scientific Laboratory. The abstract of a talk given on the subject is below.

"A program is underway at LASL to measure the cross sections for the basic fusion reactions $D(d,3He)n$, $D(d,t)p$, $T(d,\alpha)n$, and $T(t,\alpha)2n$ in the 10-100 keV. Because of the rapid variation of these cross sections with energy, the accurate measurement of the ion beam energy is one of the most critical parts of the measurement. We are constructing a laser-based time-of-flight system for this purpose. A negative ion beam of D- or T- is illuminated over a length of 1 mm or less with a 250 ps, 1 mJ pulse of photons from a Nd: YAG laser ($\lambda=1.06 \mu$). The charged particles are deflected and the burst of neutral atoms formed by photodetachment is allowed to drift 2 meters to a fast detector. Flight times for the atoms of interest vary between 600 and 2400 ns. An energy determination to within 0.03% is sought; therefore, both flight time and path length will need to be measured to comparable accuracy. The experimental problems and system status will be discussed."

3. Work Done at Los Alamos National Laboratory (S. A. Wender, D. M. Drake [LASL])

- a. NaI Spectrometer

A 6" x 10" NaI crystal with a NaI anti-coincidence shield was assembled for use in high energy neutron capture experiments. A computer code was written to acquire data which allowed the sorting of events coincident between the center crystal and the shield according to the energy deposited in the shield. This technique permitted the separation of the full-energy, first-, and second-escape peaks into separate spectra.

b. $^{12}\text{C}(n,\gamma)^{13}\text{C}$ Reaction

The $^{12}\text{C}(n,\gamma)^{13}\text{C}$ reaction was investigated from $E_n = 7.0$ to 16.8 MeV as a test of the detector system. The inverse of this reaction has previously been studied. [1] In addition it will be interesting to compare the results of this study with the $^{12}\text{C}(p,\gamma)^{13}\text{N}$ reaction which has also been investigated.

c. $^{208}\text{Pb}(n,\gamma)^{209}\text{Pb}$

The asymmetry, $A(\theta) = \frac{N_{55} - N_{125}}{N_{55} + N_{125}}$, has been measured for the $^{208}\text{Pb}(n,\gamma)$ reaction. A non-zero asymmetry would indicate the presence of non E1 radiation. Calculations predict that at incident neutron energies above 20 MeV, the effects of isovector quadrupole radiation may be allowed. Experiments are continuing to measure the asymmetry.

d. Bunching System for Vertical Van de Graaff Accelerator (S. A. Wender, J. Tesmer [LASL])

The bunching system for the vertical Van de Graaff accelerator was working poorly. This was due to the fact that the output tank circuit was not resonant at the proper frequency. This problem was eliminated by adding a small timing capacitor in parallel with the bunching tubes and adjusting it for resonance.

REFERENCES (Section H3)

1. J. G. Woodworth, K. G. McNeill, J. W. Jury, P. D. Georgopoulos and R. G. Johnson, Can. J. Phys. 55 (1977) 1704

I. APPLICATIONS

1. Plant Studies Using the Radioactive Tracer C-11 (C. E. Nelson,* E. G. Bilpuch, J. D. Goeschl,** B. R. Strain***)

The 4 MeV Van de Graaff continues to be used for the production of C-11 for real time studies of carbon transport and allocation in plants. The C-11, in the form of ^{11}CO , is produced via the $^{12}\text{C}(^3\text{He}, ^4\text{He})^{11}\text{C}$ reaction and is transported continuously to the plant growth chambers, located in the Duke University Phytotron, by an enclosed conduit, where it is oxidized to form $^{11}\text{CO}_2$. Several 1-3 week experimental runs were completed during 1980 in an effort to further explore the possibilities of these real time studies.

A typical, initial experiment has consisted of supplying an extended (2 hr.) square wave of $^{11}\text{CO}_2$ to a portion of a leaf (Fig. 11-1). Note that the light intensity and total CO_2 concentration (approximately 320 ppm) in a flowing air stream through the leaf chamber remains constant before, during, and after the $^{11}\text{CO}_2$ tracer pulse. Several of the ^{11}C uptake and transport parameters can be calculated by analyzing the leading edge, the near steady-state portion, and trailing edge of the wave as it accumulates in the leaf or passes various positions on the petiole, stem, roots, etc.

Once the base line behavior of a given plant is known, more elaborate experiments can be conducted and analyzed. An example of such an experiment is shown in Fig. 11-2 where a portion of the stem was chilled to temporarily stop transport to the root sinks. In this particular plant about 85% of the carbon exported from the lowest leaf was being transported to the roots as shown by the difference in amplitude and velocity between detectors 3 and 6 up to 100 min.

When the stem was chilled the ^{11}C count rate below the "Cold Block" (4 and 5) decayed with a 20 min half-life indicating a near complete stoppage. Meanwhile the tracer began to accumulate above the Cold Block (3); this was accompanied by an apparent increase of transport upward (past 6).

A preliminary example of the daily changes in storage vs. export of photosynthates and the direction of carbon allocation in soybeans is illustrated in Fig. 11-3.

These studies will be expanded to a full time basis beginning 1 March 1981, supported by a \$300,000 two-year grant now under negotiation with the Division of Environmental Biology of the National Science Foundation.

Fig. 11-1. Numbers refer to position of detectors on the plant and corresponding data output.

1. Labeled leaf ($^{11}\text{CO}_2$) applied to 5 cm^2 area).
- 2 and 3. Petiole of labeled leaf.
- 4, 5, and 6. Stem below labeled petiole.

0 to 28 min Calibration of detectors

30 to 58 min $^{11}\text{CO}_2$ supply vented until it reaches a relatively steady-state, meanwhile leaf is supplied with air flow with 350 ppm unlabeled CO_2 .

58 to 138 min $^{11}\text{CO}_2$ supplied to leaf.

- D. Difference between calculated decay of ^{11}C (20.5 min half-life) and measured decay indicates the amount of ^{11}C photosynthates available for export.
- R. Remaining count rate = rate of ^{11}C photosynthate storage (e.g. in starch) in the leaf.
- T. Purging or turnover time of the mobile ^{11}C photosynthate pool.
- C. The amplitude of these curves (when corrected for half-life, specific activity, and volume of transport tissue) is a function of the concentration of photosynthates.

The mean speed of the transport stream can be calculated from the arrival time of the ^{11}C front by appropriate curve fitting routines and correction for change in pulse shape during transit.

Fig. 11-2. Numbers refer to position of detectors on the plant and corresponding output data.

1. Labeled leaf ($^{11}\text{CO}_2$ applied to 5 cm^2 area).
2. Petiole of labeled leaf.
3. Stem below petiole but above Cold Block.
- 4 and 5. Stem below Cold Block.
6. Stem above labeled petiole.
- CB. Cold Block (10°C during "on").

$^{11}\text{CO}_2$ was applied to leaf at 52 min. From 52 min to 100 min leaf approaches steady-state and ^{11}C arrives at various positions along the transport system.

At 100 min the CB was chilled to 10°C . Downward transport was nearly stopped as indicated by the approx. 20 min half-life decay (no. 4 and 5), and ^{11}C began to accumulate above the cold block (no. 3). Upward transport of ^{11}C photosynthate increased by approx. 50% (no. 6).

At 156 minutes the C B. was warmed to room temperature, note rapid resumption of downward transport and decrease in upward transport.

Fig. 11-3. Temporal tracer profiles at positions on the stem (UP) 6 cm above, and (DOWN) 10 cm below the 4th node of a soybean seedling with 7 fully expanded leaves.

FOOTNOTES (Section 11)

- * Departments of Radiology and Physics, Duke University
- ** Biosystems Division, Texas A and M University
- *** Department of Botany, Duke University

J. DEVELOPMENT AND INSTRUMENTATION

1. FN Tandem Accelerator (F. O. Purser, R. L. Rummel, E. P. Carter)

a. Charging Belt Problems

During this contract period, the charging belt for the tandem was replaced due to a gradual decrease in terminal voltage stability. Belt lifetime of less than 9000 hours was somewhat less than our normal experience averaging better than 10,000 hours.

The replacement belt supplied by HVEC showed extreme "stretchiness" and during one adjustment of its position on the driving pulley, the belt dropped suddenly and unexpectedly. Approximately 1/4" of the lower edge was cut away by support structures before the drive motor could be stopped. After opening the tank (and cleaning up the debris) it was discovered that rather severe inclinations of both pulleys were required to keep the belt positioned. We have continued to run in this configuration.

The terminal voltage stability with this belt is normal at voltages of 2 MV or less. Above this voltage, as charge density is increased, stability rapidly deteriorates until at 7 MV on the terminal voltage fluctuations are about twice normal. HVEC has informed us that the type of rubber used in belt construction has been changed, the older type no longer being available from Dupont. If the stability experienced at TUNL proves to be a characteristic of the new rubber compound, high-resolution studies at higher beam energies are going to be considerably more difficult than in the past. A new belt has been ordered from HVEC and is scheduled for delivery in January.

b. Standby Filament Station

Barium-coated nickel gauge filaments used in our two duoplasmatron, direct-extraction ion sources require several hours of outgassing after installation in the source before stable operation is achieved. A separate filament station has been placed in use which allows replacement filaments to be pre-outgassed and then stored under an argon atmosphere. After installation in the source, the new filaments reach stable operation as soon as the base vacuum recovers resulting in a saving of several hours of beam time.

2. Injector Cyclotron

- a. Pulsed Ion Source (F. O. Purser, T. B. Clegg, S. A. Wender, C. Howell, A. W. Lovette, R. L. Rummel, E. P. Carter)

The usefulness of the Cyclo-Graaff beam for time-of-flight experiments has been limited by the very short pulse separation times (40 ns for protons, 80 ns for deuterons) imposed by the cyclotron's duty cycle. Since a substantial portion of the experimental programs at TUNL now make use of neutron time-of-flight techniques, interest has increased in extending the availability of these techniques to the full Cyclo-Graaff energy range. An independent development of beam bunching methods for use with the TUNL Lamb shift polarized ion source, described elsewhere in this report, offers an attractive way to reduce the repetition rate of the cyclotron output pulses without accepting the drastic beam current losses required by any brute force chopping technique.

Beam bunching techniques now in routine use with the polarized ion source approach an efficiency of 90% in compressing the d.c. beam into bursts of approximately 2 ns FWHM at frequencies of 2.0 and 4.0 MHz. We propose to inject into the cyclotron a pre-bunched beam phased to match the cyclotron's R.F. phase acceptance at a basic frequency of 2.5 MHz or 5.0 MHz. Lower repetition rates can be produced through the use of a beam chopper. The resulting pulse separation times and average beam currents will be immediately useful for most neutron time-of-flight purposes. In addition, successful completion of the present plan will point naturally to future injection of polarized ion beams into the cyclotron, thus extending TUNL's capability in this important area.

Work is proceeding on this project in three distinct areas with convergence and installation tentatively scheduled for early summer, 1981.

(1) Ion Source

The emittance, energy spread, and stability of the present cyclotron ion source are inadequate for this development. This source will be replaced by a duoplasmatron, direct-extraction, negative ion source similar to those previously constructed at TUNL and incorporating their successful features. All associated power supplies are to be highly stabilized to provide both good energy stability and stable arc conditions to minimize time-incoherent energy spread in the output. Beam currents on the order of 100 μ A D.C. are expected with an emittance of approximately 10 mm-mrad (at 50 keV) in both planes.

The importance of minimizing the time-incoherent energy spread from the ion source can be seen in Fig. J2-1. Curve A is the calculated maximum voltage ramp required to produce a time focus at a distance of 3 meters for various injection

Fig. J2-1. Calculations showing relation between voltage ramp amplitude, beam injection energy, and resulting pulse length.

voltages. Curves B and C are calculated minimum pulse lengths achievable at the time focus using a ramp alone with incoherent beam energy spreads of 3.0 and 10.0 eV respectively, again plotted versus injection energy. In order to keep the overall energy modulation in the injected beam below about 1 keV, we plan to transport the beam a distance of approximately 3 m. at an energy of 5 keV, followed by acceleration to full injection energy. The major portion of the time focussing will occur during the low-energy portion of the injection channel. Curves B and C would indicate that, for these parameters, ultimate pulse lengths of 1.3 ns and 4.2 ns for 3 eV and 10 eV energy spreads are possible. In the latter case, auxiliary bunching would be required to further bunch the beam to fit the 2.0 ns R.F. phase acceptance of the cyclotron.

Fig. J2-1 demonstrates obvious trade-offs between injection energy and ramp voltage which can be made to compensate partially for the effect of source energy spread. These will be made empirically once the system is assembled. Allowance is being made for the possible necessity of including auxiliary bunching as well as the voltage ramp to obtain the desired time focus.

Construction of the mechanical source assembly is complete. All required power supplies are on order with deliveries now scheduled for March, 1981 when operational testing can begin.

(II) Bunching Electronics

The linear voltage ramp for the cyclotron pulsed source will require higher voltages than needed for the polarized ion source. A new ramp has been designed and is being tested. Completion and final testing require power supplies whose delivery is also scheduled for March, 1981.

Necessary electronics equipment for auxiliary R.F. bunching is also being constructed. If not required for the cyclotron source, it will serve as backup equipment for the polarized source systems.

(III) Beam Transport

Transport of low energy beams for appreciable distances in the environment of the cyclotron's external magnetic field places moderate constraints on the transport system. Additional complications arise because of the necessarily chromatic nature of the bunched beam. As presently designed, the beam pipe for the injection system will be fabricated from soft iron to serve as a magnetic shunt for the stray fields present. For several critical regions where fields are strongest, additional magnetic shielding will be supplied.

Initial calculations with a standard beam optics program have been based on a lens system of two einzel and one electrostatic quadrupole triplet. More exact calculations await the acquisition of an optics program capable of handling electrostatic lenses exactly and incorporating the effect of space charge. Such a program is being obtained from ORNL.

The effect of the induced beam energy spread upon the system optics will be affected greatly by the final emittance of the ion source. Several options to compensate for this effect are under study.

A bunching frequency of 2.5 MHz will provide a pulse separation time of 400 ns useful for most TOF experiments. To provide longer pulse separation times, an auxiliary chopper system has been incorporated in the design. In addition to allowing flight times of 800 and 1600 ns, although with attendant beam loss, this chopper serves to eliminate the approximate 10% of the beam not bunched by the system.

Components of subsidiary systems such as vacuum, remote control, cooling, and beam diagnostic devices are either on hand or expected in January, 1981.

b. Cyclotron Maintenance and Development
(F. O. Purser, R. L. Rummel, E. P. Carter)

(i) Crowbar Circuit Modification

We have at times in the past experienced difficulties with prolonged "crowbarring" of the oscillator anode supply. With the dee voltage regulator operating in the closed loop mode transients introduced by multipactoring coupled to the very high Q of the tank circuit tend to drive the instantaneous dee voltage to unsustainable levels causing a repeat crowbar. A modification to the circuit based on a suggestion by the Cyclotron Corporation has completely eliminated the problem. Briefly, the modification forces the oscillator to come back on after a crowbar in a non-feedback mode at a slightly lower dee voltage. After a 30 millisecond delay, the circuit resumes closed-loop operation. Installation of this modification removes the stability problems in dee voltage and frequency previously associated with these intermittent crowbar episodes.

(ii) Major Maintenance

During the past report period all cyclotron vacuum systems, the dee voltage regulator, anode power supply, and the electrostatic deflector have undergone major overhauls with subsequent

Improvement in acceleration and extraction efficiencies.

3. 3 MeV Laboratory Development (C. R. Westerfeldt, R. O. Nelson, K. B. Sales, G. E. Mitchell, E. G. Bilpuch)

In an effort to reduce the amount of high-resolution time scheduled on the tandem accelerator, and also to improve the performance of the 3 MeV accelerator, we have decided to upgrade the 3 MV KN machine. If the design goal of 4 MV is reached, we will be able to perform a majority of the planned high resolution experiments on this accelerator--where there are minimal scheduling problems.

The upgrading procedure will consist of three separate projects. The first is the installation of a new (stainless steel electrode) accelerator tube, purchased from HVEC. At present one can run as high as 3.5 MV with no machine instabilities; it is anticipated that the new tube will allow operation at or above 4 MV. It would be preferable to use the present N + CO₂ gas mixture to reach these voltages; however, if needed a small amount of SF₆ will be added to the present mixture.

The second project is external to the accelerator. This project involves upgrading the electrostatic analyzer and associated electronics for operation at higher energies. The present analyzer-homogenizer system is designed for operation up to 3.3 MeV with the limiting factor the available inner plate voltage on the electrostatic analyzer. At present, the outer plate is biased at ground, and a (closed loop) correction signal is supplied to the outer plate and also to the target rod. The inner plate RF power supply has a range of 0 - 30 kV negative. In this configuration, the molecular hydrogen beam (HH⁺) which enters the analyzer is accelerated (by 0 - 30 kV), and one therefore must account for this energy shift in the determination of resonance energies. The "improved" design will involve a second RF power supply, which will apply a positive potential on the outer plate, with a magnitude equal (but opposite in sign) to the inner plate supply. In this configuration the analyzer is "balanced" and the energy correction term vanishes. This design also demands less of the RF supplies; they will be running at approximately half of their former voltages. The trade-off in this procedure is that now one must couple the correction signal to a plate operating near 15 - 20 kV! There are at least two approaches to this problem. One is to simply couple the correction signal through a high voltage capacitor to the outer plate. This has been tried and in fact does work. However, this approach does not address the problem of correcting for d.c. drift in the RF supplies. The only solution is to feedback directly to the supplies. A second approach is to use an op amp, which floats at the outer plate potential, and is optically coupled to the outer plate driver. This system should be able to handle both a.c. and d.c. correction signals.

The third project has been underway since last year. This involves the development of a terminal stabilizer for the KN accelerator. This fast feedback system would transmit a correction signal, from the electrostatic analyzer or from a pair of beam line slits, through a fiber-optic link to the terminal-mounted amplifier. This closed loop system will (hopefully) remove the 1 - 2 kV beam-energy fluctuations which are not removed by the corona feedback system. This should help to stabilize the beam on target and reduce the demands on the analyzer-homogenizer system. A prototype amplifier should be installed in the machine within the next few months.

4. Polarized Ion Source Development

The Lamb-shift polarized ion source was the most heavily scheduled ion source in the laboratory for the past twelve months, scheduled for 180 days during the 1980 calendar year. Generally it has operated reliably and well with accelerated beam currents of 200 nA d.c. or 150 nA (pulsed) routinely available. Accelerated d.c. currents as high as 380 nA and pulsed currents over 200 nA have been obtained.

Twice during the past year major problems developed, causing unscheduled downtime. In April the polarized source frame, normally isolated and biased at -50 keV, started arcing to ground. Secondary problems developed from surge currents produced by sparks. Several weeks of trouble ensued until the source of the arcing was located in the beam acceleration structure inside the vacuum system. A thorough cleaning, careful reassembly and alignment of the accelerating lens structure finally solved the problem. In December, a ceramic ring which insulates the duoplasmatron from the polarized source frame cracked causing several days of lost beam time before it could be replaced.

As in the past development work is severely handicapped by lack of experienced, available personnel and by limited access to the source because of the heavy experimental demand. Nevertheless, some work has continued on all development phases during the past year.

- a. Polarized Beam Pulsing (S. A. Wender, C. Howell, C. Floyd, T. B. Clegg, J. Rauber)

The three-stage bunching system has continued to be extremely successful in providing pulsed, polarized beams for experimental use. Deuteron beams pulsed at 4MHz are used to produce pulsed, polarized neutrons via the $D(d,n)$ reaction for neutron scattering or capture-studies. Proton beams pulsed at 4MHz and 2MHz are used to initiate (p,n) reactions. A recent publication [1] and invited conference paper [2] describe the system and its uses. Projects are underway to improve the system performance and reliability and to investigate other possible applications in the laboratory.

The main improvement is a new circuit design for producing the voltage ramp applied to the duoplasmatron. The goal here is to raise the overall bunching efficiency and improve the overall time resolution. The other major investigation utilizes a new beam line extending along the main axis of the polarized source to study the polarized beam pulse timing produced by the three-stage bunching system. The main goals here are (1) to determine if there are significant effects on pulse timing depending on the duoplasmatron operating parameters and (2) to determine the overall bunching efficiency at 17 keV rather than the 50 keV. This lower energy is interesting because it is the beam injection energy for our cyclotron.

(1) New Voltage-Ramp Circuit

In the three-stage bunching system, a voltage linear in time of approximately 100 volts peak-to-peak is applied to the anode of the positive-ion duoplasmatron. This is generated by charging the capacitance of the source with a constant voltage up to some maximum, and then discharging it. The initial circuit used to modulate the source consisted of a bank of five transistor switches and was basically the same design as constructed at Los Alamos, [3] with only slight modifications. This circuit had problems. First, the waveform produced when beam was extracted from the source had substantial ringing and the voltage flyback time was 50 ns. Both effects contributed to reduce the overall bunching efficiency. Second, the transistors had a limited current rating and often required replacement. Thus, a new circuit has been constructed which uses high-power FETS (1RC 332) capable of carrying peak currents up to 7 A at 400 V. The waveform produced with this circuit is superior, and the circuit is rugged and should be more reliable. The resulting waveform in Fig. J4-1 demonstrates a flyback time of approximately 50 ns, with

Fig. J4-1. Oscilloscope trace of actual voltage ramp waveform during source operation. Vertical scale is 20 V/div. Horizontal scale is 50 nsec/div.

substantially reduced non-linearities. Preliminary tests with this new design show that when only the duoplasmatron ramp voltage is applied, the beam burst width is reduced from 80 ns with the old circuit to 45 ns with the new circuit. This proves that a large fraction of the energy spread of 22 eV FWHM previously observed for the beam from the polarized source is attributable to the non-linearities. The new measurements allow us to infer that the inherent energy spread of the beam coming from the duoplasmatron is approximately 12 eV FWHM.

(II) Beam Pulsing Diagnostics

The new diagnostic beam line for the polarized source contains two bunching elements capable of operating in a double-drift mode [4] for protons and deuterons with pulse repetition rates of 4MHz (5MHz) at energies of 50 keV (17 keV). An RF amplifier, a tank circuit for the fundamental frequency buncher, and circuits for phase control of the buncher and ramp, have been constructed and tested. The tank circuit and the electronics for the second harmonic buncher are under construction. The electronics will be useful later for the cyclotron injection project. The goals of the investigations using the new beam line are several:

- 1) We need to learn how to measure accurately time profiles of beam bursts of 17 to 50 keV beams. There are two immediate questions to be answered, both relevant to the proposal to inject pulsed beams into our cyclotron and both requiring this technique. First, for unpolarized beams, we need to apply a voltage ramp waveform to the duoplasmatron of one of our present direct extraction sources to see if we can, by this simple technique, bunch the beam to a true profile of ~ 2.5 ns FWHM needed to fit into the phase acceptance of our injector cyclotron. Second, for polarized beams for which the intrinsic energy spread is larger, we need to determine if with a voltage ramp and double-drift buncher we can achieve the same 2.5 ns FWHM for the 17 keV injection energy of the cyclotron.

- 2) The new beam line should allow us to investigate the bunched beam performance of the polarized source at the present 50 keV injection energy with less intrusion on the ongoing accelerator experiments. We need to continue to optimize parameters of the voltage ramp and will attempt to reduce the capacitance of the duoplasmatron and anode-plate assembly. Our preliminary tests indicate this will be crucial for reducing the flyback time of the voltage ramp and therefore the overall bunching efficiency.

- 3) There are several indications that the beam-pulse timing on target after acceleration is longer than we would expect to be achieved by our system, based on measurements of our beam energy spread, and we do not completely understand why. We will compare pulse timing both before and after acceleration to try to isolate the source of this discrepancy.

- b. New Polarized Source Systems for Spin-State Selection and Spin Precession
(T. B. Clegg, R. L. Varner, and J. L. Bowsher, R. K. Murphy, A. W. Lovette)

The new polarized source spin filter, cryopumping system, and vacuum system described in last year's progress report have been assembled and tested. The main 575G magnetic field, the d.c. and r.f. electric fields for the cavity, and the coil around the spin filter to provide ± 10 G for rapid spin-state switching have been checked and are operational. The cryopumping hardware has been assembled and cooled to 15 degrees K without difficulty. Final testing of the hydrogen heat pipes to be used with the cryopumping system is underway. Work is concentrating now on the design, construction, and assembly of the fast-spin-flip hardware mentioned last year.

The fast-spin-flip hardware, which has been designed, will accommodate three basic modes of polarized source operation.

(1) For polarized deuteron beam experiments utilizing the $m_J = +1/2$, $m_I = 0$ or $m_I = -1$ hyperfine states of the $D(2s)$ atom (states 2 or 3), the present mode of operation will continue. Here the spin-filter selects metastable atoms in a single hyperfine state and argon ionization must occur in a non-zero magnetic field. Similarly, for polarized proton operation in the $H(2S)$ state with $m_J = +1/2$, $m_I = +1/2$ (state 1) when the experiment requires accurate knowledge of the beam polarization through the quench ratio, one should operate the system as is done now with a small magnetic guide field in the argon region.

(2) For polarized proton or deuteron operation in state 1, for which accurate quench-ratio determination of the beam polarization is not needed but for which rapid spin-reversal is desired, a new coil is being provided between the spin filter and argon charge-exchange region to precess the electron magnetic moment in the metastable atom through ± 90 degrees. The atoms then emerge into the argon charge-exchange region, which because of the cryopumping is well-defined and which because of extensive magnetic shielding has magnetic fields of < 0.01 G. Thus the atom will be ionized maintaining the spin direction it obtained in the precession coil. Since the precession coil will be mounted so it can rotate around the beam axis, complete freedom of spin-axis orientation will be provided in this mode. This will facilitate orienting the incident beam polarization along the beam direction at the target, as will be needed for some experiments with the cryogenic polarized target now under construction (see Section J6).

(3) For polarized proton operation where the maximum beam intensity is desired, a SONA transition [5] will be accomplished by turning off the fast-spin-flip coil and by operating the axial magnetic field in the argon region opposite to that of the spin-filter field. The axial magnetic field crossover through 0G will be

accomplished by a static magnetic shield. This mode of operation should be most useful for the high-resolution studies of narrow resonances (see Section D1).

The exact design of the fast-spin-flip coil was chosen after we made magnetic field measurements of a scale model and used these results in a computer calculation to solve the equations of motion of a precessing electron along each path through the magnetic field. The individual-path results were then folded with the radial beam intensity profile to obtain an estimate that there will be ~2% depolarization produced during the 90 degrees spin precession. Interchange between ± 90 degrees precession should be possible at frequencies up to 1kHz allowing a "fast flip" of the beam quantization axis at the target. The actual coil design is adapted from that being used in the LAMPF polarized ion source. [6]

Installation of all this hardware on the polarized source is planned as soon as all systems are debugged.

- c. A Microprocessor Based Interlock and Control System for the Polarized Source (M. C. Wright, C. Carmen, A. Knott, N. R. Roberson, S. E. Edwards, T. B. Clegg)

A microprocessor based interlock and control system is being developed for the polarized ion source. The design will allow software rather than hardware changes to accommodate future interlock requirements. Devices or systems to be monitored will be sensed by switches that open-circuit when a failure condition exists. Such an event then produces an optical signal to the microprocessor. Software logic determines the response required by this failure and other optical signals return to banks of relays which turn off systems in the proper order. Failures can also be detected by monitoring readings on the high voltage frame digital voltmeter.

The microprocessor will also serve as the communications channel through which control and readout of polarized source systems will be accomplished. Two CRT terminals, one at the source and the other in the control room, will display the current status of the system and a log of actions taken by the microprocessor. The user can request the status of any device and can turn any device on or off from either terminal. The main lab computer can also perform any of these operations.

Development of the Motorola 6800 microprocessor based system suffered a serious setback in February when we learned that the MPL Language Cross Compiler supplied by Motorola occasionally generated incorrect code. Motorola said that they were aware of the problems with the compiler but had no plans to fix them. We were then forced to expand

the microprocessor system so that software could be developed on the system itself. We purchased an eight inch floppy disk, another 16K bytes of memory, the FDOS disk operating system, and the Software Dynamics SD Basic Compiler, from Midwest Scientific, the supplier of the original system. The software, which was 90% completed and debugged in the MPL language, was rewritten into the Compiled Basic language.

As we began debugging the Basic software, we realized several important facts:

- 1) The form of the basic language used by the SD compiler bears little resemblance to standard Basic, or any other language.
- 2) The SD Basic language is not well suited for the problem at hand.
- 3) Modifications to the software are difficult and time consuming due to the primitive nature of FDOS.
- 4) FDOS is not a standard operating system.
- 5) The Motorola 6800 microprocessor and SS50 system bus are not being widely used in the industry for similar applications.

It has in recent months become clear to us that the most widely used and supported microprocessor based computer systems use the Z80 microprocessor, the S100 system bus, and the CP/M operating system. All major computing languages, including ANSI Standard Fortran, are available for these systems. We decided that, in the long run, the advantages of using standard hardware and software were sufficient to justify switching to a Z80 based microprocessor system. Most of the external interfacing hardware that we have designed and assembled will work without modification on a Z80 system.

We have ordered the "System B" manufactured by Vector Graphics Inc. The system includes a Z80 microprocessor, 64K of memory, dual five inch floppy disk drives, a memory mapped video terminal, 3 serial ports, 2 parallel ports, and the CP/M operating system. In addition we have ordered 2 boards from Crememco that contain 8 parallel ports each that provide the interface to the sense and control lines. There are presently 8 Vector Graphics computers in the Duke physics department and 2 in the UNC physics department. The large number of identical computer systems in the department will be very helpful in developing the software for the Polarized Ion Source system. A library of subroutines and other useful information is available from the other

Vector Graphics users in the department. The original MPL language software is currently being rewritten into ANSI Standard Fortran. The CP/M operating system is very similar in syntax and function to the operating system used on the main computer for the laboratory, the Digital Equipment Corporation VAX 11/780.

The sense and control hardware for the low voltage frame of the polarized source has been installed and tested. During the summer the fiber optics communication system for the high voltage frame sense and control lines was significantly redesigned and rebuilt in order to improve its reliability and noise immunity. The high voltage sense and control hardware is now ready for installation. Assembly of the high voltage frame digital voltmeter has been completed but it has not yet been tested. The hardware constructed for communication between the microprocessor and the old main lab computer, the DDP-224, is now obsolete and will be replaced by a simple RS-232 serial interface. The microprocessor and the VAX will each consider the other to be an ordinary CRT terminal. We hope to have the system in operation by the summer.

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5. Sputter Ion Source

- a. Beams Obtained (J. Willis, E. N. Strait, M. W. Clark, J. Swenson, S. A. Wender, R. L. Rummel, F. O. Purser, S. M. Shafroth)

A General Ionex, Hiconex 834 Sputter Ion Source has been installed and made operational at TUNL. Table J5-1 shows the beams obtained up to this time (August, 1980).

Table J5-1

Beams Obtained

Ion	Current (μ a)	Cone	Mode	Comment
Li^-	0.05	LIF	Reflection	
BeO^-	0.3	Be	Transmission	
BO^-	1	10B0	Ref.	0 Sprayed on
C^-	1	C	Trans.	
C^-	10	C	Ref.	
O^-	3	PbS	Ref.	
F^-	30	CaF	Ref.	
Na^-		NaF	Ref.	Unstable (not useable)
S^-	3	PbS	Ref.	
TI^-	0.03	TI	Trans.	
VO^-	0.1	VO	Trans.	
Cu^-	0.1	Cu Alloy		
SI	2	Sj	Ref.	

b. $\text{C}_1^-/\text{C}_2^-$ Ratio Study

Using program DOUBLE and a carbon reflector core we tried to study this ratio as a function of Cs beam energy (extractor volts) and obtained some indication that the ratio of $\text{C}_1^-/\text{C}_2^-$ increased from 1.6 to 2.0 as the extraction voltage was varied between 11 and 20 kV. However, on repeating the data the next day, we did not obtain reproducible results and so dropped this project.

c. Heavy Ion Bunching

The ability to produce pulsed heavy ion beams should

facilitate many intriguing experiments both in nuclear and atomic physics. At its present location in the low energy transport system, the double-drift bunching system is ideally suited for this purpose. The present bunching structure contains bunching tubes of 27 cm and 11 cm. When both drift tubes are driven together, the length (38 cm) is correct for protons at 50 keV. When the 27 cm drift tube is used alone, it is the correct length for deuteron at 50 keV. If we adjust the injection energy of the heavy ion source between 50 keV and 80 keV these three combinations of drift tubes allow the bunching of mass ions 1 to 3, 9 to 40, and 48 to 160 AMU. Other ions close to this mass will also be bunched but will require greater voltages. If pulsed beams of ions far from these masses are required, new drift tubes would have to be constructed.

Bunching tests have been performed for beams of ^{12}C , ^{19}F . Results of tests for ^{12}C are shown in Fig. J5-1. We measure an efficiency of 65% and a time width (FWHM) of 2 ns. These results are similar to those obtained for light ions. If further reduction of bunching is required, chopping will be necessary to match the phase acceptance of the double drift bunching system.

Fig. J5-1. Plot of number of ^{12}C nuclei detected after elastic scattering from a gold foil versus time.

6. Cryogenically Polarized Target Facility (C. R. Gould, D. G. Haase, T. B. Clegg, W. J. Thompson, R. L. Walter)

A proposal to construct a cryogenically polarized target facility was submitted and funded during the past year. The proposal was developed to take advantage of the substantial beams of polarized neutrons that are now available to TUNL. The thrust of the initial research is toward a better determination of the effective spin-spin force in nuclei.

The simplest way to measure a spin-spin cross section is via transmission of a polarized beam through a polarized target. The technology for producing high intensity polarized beams has advanced considerably over the last five years. [1] At the same time the only polarized nuclei that have been studied in any detail have been holmium and cobalt, where hyperfine interaction effects are large.

Recently commercial ^3He - ^4He dilution refrigerators have become available which are capable of cooling to temperatures of about 10 mK in magnetic fields of 7 T or more. As a result, it is now possible to consider experiments with polarized targets other than cobalt and holmium. Fig. J6-1 summarizes information on isotopic abundance, energy of first excited state, and vector polarization, f_1 , for nuclei suitable for brute force nuclear orientation (BFNO). Taking 20% as a lower limit for polarization, we find twenty nuclei which can be obtained in reasonable quantities and for which BFNO is feasible.

Pulsed polarized neutron beams are routinely available at TUNL at energies from 2 to 30 MeV. Typical beam polarizations, P are about 60% from the $2\text{H}(d,n)$ reaction, for example. The absolute accuracy of a polarized beam--polarized target experiment scales as $(P*f_1)^2$ (where f_1 is the target vector polarization) and we expect that the high neutron beam polarizations available at TUNL will allow us to improve substantially on the statistical accuracy of previous spin-spin cross section measurements.

Measurements with two different geometries, transverse spin and parallel spin, can determine the relative strengths of the central and tensor spin-spin potentials. [2] By studying nuclei with different A -values we can determine if there is any dependence of the effective spin-spin interaction on nuclear structure. Core polarization is known to have a substantial effect on the form factor of the spin-spin interaction [3] so A -dependent effects may well be present.

The targets ^{27}Al , ^{51}V , Cu , ^{93}Nb , ^{115}In , and ^{209}Bi are particularly suitable for first experiments. They are relatively easily polarized, can be obtained in the form of wire (thus minimizing eddy current heating effects), and cover a broad range of mass values. Data acquisition procedures will be similar to those used in other spin-spin cross section measurements. [4,5]

Fig. J6-1. Nuclei suitable for brute-force nuclear orientation. The symbol denotes the natural abundance and the vertical axis gives the energy of the first excited state. The horizontal axis plots $f_1 \times T/B$ in %, where T is the absolute temperature in mk, B is the magnetic field in Tesla, and f_1 is the vector polarization in %.

The system is built around the model 430 dilution refrigerator of S.H.E. Corporation, with a two-bore magnet from American Magnetics Corporation. The Model 430 has been tested under no load conditions to provide temperatures of less than 6 mK outside the mixing chamber and a cooling power in excess of 1 microwatt at 10 mK. Our design goal is for a magnetic field of 7T at a temperature of 10 mK.

A sketch of the proposed cryostat is shown in Fig. J6-2.

Fig. J6-2.

The system consists of the following components:

1. Dilution refrigerator insert - this is the standard Model 430 insert as described above. The sample holder is thermally anchored to the mixing chamber which sits above the superconducting magnet.
2. Sample holder - the scattering sample is in the form of a bundle of thin wires and is attached to a rigid Vespel plastic support screwed into the dilution refrigerator mixing chamber. The holder and plastic spacers position the sample at the center of the superconducting magnet. Thermal conduction is provided by soldering the sample to a bundle of thin copper wires (coil foil) attached to the mixing chamber.

3. Superconducting magnet - a split coil superconducting magnet immersed in a bath of liquid helium at 4.2 K will produce the 7 Tesla magnetic field at the sample. The magnet and its container will hang from the main liquid helium bath of the cryostat dewar. The magnet is oriented with its axis horizontal and the sample holder is inserted through a 1.5" diameter vertical radial access hole. The incident beam then may reach the sample through a horizontal radial access, for a B perpendicular to the beam experiment, or through the axial magnet hole, for B parallel to the beam. The switch between the two orientations is simply made by rotating the cryostat 90 degrees with respect to the beam. This arrangement is quite similar to that commonly used in demagnetization refrigeration cryostats. The magnet is built into the dewar system so that the incident and transmitted beams do not pass through liquid helium or nitrogen. All isothermal radiation shields surrounding the sample will be made of thin walled aluminum or stainless steel to reduce neutron absorption and reflection.

4. Dewar system - the cryostat and magnet will reside in a custom-designed dewar and cryostat support system for mounting on the axis of the beam line. The lower vacuum shroud and isothermal shields are all removable to allow direct access to the magnet and mixing chamber without removal of the entire dewar system. Only the outer shield need be thick enough to withstand an external pressure of one atmosphere, although it is convenient to have the liquid nitrogen shield leak tight in order to use exchange gas during precooling.

The dilution refrigerator is inserted into the liquid helium chamber from the top and is connected at the top and bottom of that container with 4 inch diameter stainless steel bellows. The lower vacuum seal is made with an indium O-ring. The dilution refrigerator will be vertically positioned by means of a mechanical lift and position stops located at the dewar top. This vertical positioner will also allow simple sample removal and replacement at room temperature, without adjustments to the magnet.

5. Thermometry - Because of the importance of the temperature to the determination of the polarization much of the development time for the cryostat will be put into thermometry. The current National Bureau of Standards practical temperature scale in the 10 mK region is based on noise thermometry, nuclear orientation and the magnetic susceptibility of cerium magnesium nitrate (CMN). Normally one would use one of these devices as the primary thermometer for the cryostat and some type of resistance sensor for the secondary or working thermometer. The high magnetic fields at the sample in the proposed cryostat make CMN and resistance thermometry unworkable. We propose to use nuclear orientation thermometry as the primary standard for temperature measurement [6] and capacitive temperature sensors (CTS) as secondary thermometers where practicable.

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7. High Sensitivity Pulsed Beam Pick-off System
(C. Howell, H. Futzner, G. Honore, S.A. Wender)

Many pulsed beam experiments involve low beam currents. In these cases the timing pulses derived from our usual capacitive pick-off unit (CPU) may become unreliable. In order to produce a more reliable timing pulse with low intensity beams, we have investigated two techniques which involve the detection of secondary electrons knocked out of a thin foil as the beam pulse passes through.

In the first technique [1] a current pulse is detected directly from the foil as the secondary electrons are accelerated away with a bias voltage. In the second technique, [2] the secondary electrons are accelerated towards a channel electron multiplier (CEM) and an amplified electron current pulse is detected at the output of the CEM. Fig. J7-1 shows a schematic diagram of the CEM system.

Fig. J7-1.

Preliminary tests of these two systems indicate that the first technique is about as sensitive as the present CPU, while the CEM method is much more sensitive and reliable. We therefore feel that the CEM technique will now enable us to perform pulsed beam experiments with low beam currents. Because of the success with the CEM it has been installed on the polarized ions source test beam line to evaluate the pulsing and bunching system on the polarized ion source.

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K. COMPUTER RELATED DEVELOPMENT

1. New Computing Facilities (S. Edwards, C. Gould, J. Holzweig, S. King, S. Lau, R. Poore (LASL), R. Roberson, S. Wender)

- a. Overview

In March 1980 we took delivery of a VAX 11/780 computer system from Digital Equipment Corporation. The new computer replaces both the on- and off-line DDP-224 computers at TUNL and will be used for both data acquisition and analysis.

The system configuration is shown in Fig. K1-1. The VAX is a 32 bit machine. We currently have 1.25 MB of main memory with a floating point accelerator, three 67 MB RM03 disc drives, two TU45 75 ips tape drives and support for 16 terminals. We will shortly add support for 16 more terminals, and plan to add another 1 MB of memory in the near future. The data acquisition is via CAMAC and is controlled by an MBD-11, the micro programmable branch driver developed at LAMPF. Graphics displays are via Tektronix 4010 or 4014 terminals connected to a common hard copy unit. The VAX is housed in an individually air conditioned room, separate from the old computers. The DDP-224 computers will be phased out over the coming year as the data acquisition facilities on the VAX become available.

The VAX has been heavily used since it was installed and has proven to be a very reliable and powerful machine. Execution times for computer bound jobs are of the order of one third those on the IBM 370/165 at TUCC. At present 60 users are known to the system. At peak times we support about 12 to 16 processes in interactive or batch mode.

The first data were stored in the VAX in early July following completion of a device driver for the MBD. We then began work on a general data acquisition system XSYS. XSYS is similar in structure to the Z system at the Los Alamos Tandem accelerator [1] and is based on the event analysis language EVAL [2]. XSYS is written almost exclusively in Fortran. We use VMS system services and the VMS executive routines wherever possible. We were able to store, display and analyze data with XSYS in early September, and have continued to improve the system since that time. Further development awaits completion of CAMAC interface hardware presently being built. We expect that most experimenters will be running on the VAX by July 1981.

The following sections provide some preliminary information on the XSYS and EVAL programs and describe the CAMAC interface

Fig. K1-1. Computer facility at TUNL, built around a 32 bit minicomputer with a large main memory, two DMA based data acquisition channels and a multiuser time shared operating system.

and the MBD device driver.

b. Data Acquisition And Analysis
System XSYS

XSYS consists mostly of stand alone Fortran modules which communicate with each other via a permanently resident global section of memory. The global section contains all the data arrays, buffers and control information associated with a particular user. A data acquisition or a data analysis program consists of a series of XSYS commands with parameters. The commands can be entered one at a time from the VMS DCL command line, or can be stored in an indirect command file for automatic sequential execution. Each XSYS command invokes a single executable Fortran image which runs and then in general exits back to the VMS command language. There is no XSYS monitor and the XSYS commands are activated as if they were VMS DCL commands.

Commands exist for defining, storing, manipulating, clearing, dumping, reading back and displaying spectra, as well as for starting and stopping runs and reading scalers. If a user wants to carry out operations not in the present XSYS library of commands, he writes his own Fortran program. A template routine is provided for this purpose. It contains all the Fortran statements needed for mapping and communicating with the XSYS global section.

During an experiment the data flows from the ADC through CAMAC into the MBD, and from the MBD into a buffer in the VAX via DMA transfer. The MBD interrupts the VAX when the buffer, typically 2048 words long, is filled. This interrupt wakes a hibernating sub process which then sorts the data. The data are double buffered in the VAX, so the MBD is filling another buffer while the VAX is sorting the first. There is a sort sub-process for each active MBD channel. The sorting algorithm for each sub process is determined by the EVAL code written by the user. In general this code will be different for each of the eight possible MBD channels. The data flow during analysis of an event tape is the same, except that the VAX buffers are filled from tape instead of from CAMAC. Scalers are also handled by a special sub process. They can be read when the sub process is woken by the system timer, or on demand by the user.

The user displays his spectra on the Tektronix terminals using a Fortran program XDIS built around the GRZ package from Western Electric. XDIS has provisions for background fitting, area calculations, counts per channel output and has commands to permit arbitrary horizontal and vertical scaling. Unlike a normal XSYS program, the display routine stays resident and has the graphics terminal permanently allocated to it.

c. EVAL

EVAL [2] is an event analysis language used for sorting ADC data or for sorting data from event tapes. Sorting multi-parameter data consists of many repetitions of a simple sorting algorithm. This normally consists of some sequence of numeric manipulations, with various spectra being incremented based on the results. EVAL provides a language which is broad enough to allow these algorithms to be easily specified but which is simple enough to allow a compiler to generate code which executes very quickly. The program also provides a simple mechanism for interfacing with the XSYS data structures containing the appropriate spectrum and gate arrays.

EVAL is written totally in Fortran. Macro is used only to branch to the EVAL code stored in a Fortran Common block. The executable code is built up using byte instructions. The present VAX implementation is an outgrowth of the MODCOMP Fortran version of EVAL written by Martin Neiman at LBL and R. Poore, J. Sunier and R. Hardekopf at the LASL Van de Graaff Laboratory.

All EVAL programs consist of a series of one-line statements which begin with a keyword. The keyword specifies the statement type. The following statement types are defined: DATA, SPEC, FORM, GATE, VARIABLE, OPTION, GET, INC, TINC, LDA, STA, SUB, ADD, MUL, DEV, CHS, FIX, FLOAT, INDEX, LSA, ASH, ROT, OR, AND, XOR. Branching is controlled by IF, ELSE, ENDIF statements and events are written to tape by a TAPE instruction.

The user writes his EVAL source code into a disk file. An XSYS command compiles it into executable code at the time the sort sub processes are created. The EVAL code has access to both the event buffers and to the user's spectra, so sorting proceeds automatically once data and interrupts are received from the MBD.

A sample EVAL program is given below. The program defines two spectra S1 and S2 and a gate G1. An event consists of all 16 bits of one 16 bit word (EVSIZ and FORMAT statements). If the event (F1) lies within the gate G1 then channel F1 of spectrum S1 is incremented. Otherwise channel F1 of spectrum S2 is incremented. The spectra S1 and S2 have been previously defined by an allocate memory command AMEM in XSYS. The gate condition G1 is also set by XSYS, usually from the display program XDIS. The compiled version of this code will be executed for every event in the buffer.

```
SPEC S1 1
SPEC S2 2
GATE G1 1 1
DATA EVSIZ 1
FORMAT F1 1 16 1
```

```
GET F1
IF G1      INC S1
          ELSE
          INC S2
ENDIF
END
```

d. MBD Device Driver

A VMS device driver has been written to support the MBD-11 on the UNIBUS channel of the VAX. The driver was developed under VMS version 1.6 and runs without modification under VMS 2.0. The driver supports the following QIO options:

- 1) Down line loading of MBD control memory from the VAX
- 2) Reading of MBD control memory back into the VAX
- 3) Execution of CAMAC FCNA commands by the VAX
- 4) DMA transfers between the MBD and the VAX
- 5) Forced time out of any MBD channel by the VAX

All of these options are supported by FORTRAN or MACRO QIO calls. Each MBD channel is treated as a single unit on a single controller. Device names for the MBD channels are CXA , CXB0 etc. The MBD is shut down and is in single cycle mode for the first three operations. The MBD is running and able to respond to LAMS only for operation four.

The first two options are for down line loading of MBD microcode and for reading it back. The VAX can write to or read from arbitrary regions of MBD control memory. MBD code is assembled in VAX MACRO, using the macro definitions developed at LAMPF for the PDP-11.[3]. The cross boundary check in the PDP-11 version of the MBD instruction macro's does not work in VAX MACRO, but otherwise the procedure for assembling MBD code on the VAX is identical to that used on PDP-11's. The down line loading is performed by a Fortran program which links to the

starting and ending locations of the object file generated by the MACRO assembler. The program loads and verifies the MBD code one word at a time. Under XSYS the MBD contains one reentrant program which runs all of the MBD channels.

The FCNA option is for testing CAMAC modules. The driver supports transfer of a single 24 bit word to or from the CAMAC crate. Q and X response checking are not implemented. We do not use this option in our present data acquisition system.

Option four is for data transfer to or from a particular MBD channel. This option requires the MBD to have been previously loaded with cooperating microcode. In XSYS we use one general purpose program in the MBD and this program controls all eight MBD channels. The word in the PDX register is the VAX address of the control buffer for the channel that is being started. One sixteen bit word is written into the PDX register before the channel initialisation latch is set. The first word of the buffer is a flag word to tell the MBD program what operation to carry out. For a DMA transfer, the MBD program picks up the word count and event buffer address for that channel and initiates the DMA transfer. When the transfer is complete, the MBD interrupts and the channel is shut down. The channel is not restarted until another QIO request is issued from VMS. Transfers are via the direct data path, one word at a time. Buffered data path transfers are not presently implemented.

The fifth option permits the VAX to force completion of outstanding QIO requests. It is used for stopping data acquisition in conjunction with the Camac interface hardware. The driver searches the VMS DDB list for MBD IO requests that are active and sets their time-out times to zero. When a device time out is detected by VMS, the driver sets the MBD into single cycle mode, thus shutting down all channels. All outstanding QIO requests terminate with a TIMEOUT error. This procedure leaves partially filled data buffers since the MBD DMA transfer has never completed. These buffers are sorted by restarting the MBD and forcing it to send completion interrupts for all channels.

e. Data Acquisition Interface

Our design goals for the data acquisition interface are to provide an easy-to-maintain and flexible coupling of the system ADC's, scalars, etc. to the computer, and to provide circuit speeds which do not significantly add to the dead time of the total system. An interface which will meet these goals, has been designed and will (1) allow, by the use of a single 8 x 15 push button panel, any arrangement of the available ADC's (up to 15) into single or multiparameter groups, (2) provide one word of buffering by transferring the ADC data into Camac input registers with subsequent resetting of the ADC's, and (3) provide fast transfer of the contents of data registers to the VAX memory via a programmable micro-processor (BI-Ra, Model MBD) connected to the VAX

Fig. K1-2. Diagram showing the connection of an ADC to a data input register.

Fig. K1-3. Diagram of the two plane selector matrix. The dots represent electrical connections.

Unibus.

Simplified diagrams for the ADC to Input data register transfer path are shown in Figs. K1-2 and K1-3. The "data ready" signal (top of Fig. K1-2) latches the 16 bits of data (ADC-13 bits, Router-3 bits) into the data register. The "data accepted" signal sets a flop which removes the DR signal and prevents future DR signals from reaching the register. A look-at-me (LAM) signal appears after latching occurs and signals that the data is available for transfer.

The generation of the CLAM (coincidence LAM's) and OLAM (OR LAM's) is shown in Fig. K1-3, which represents the two planes of the 8 x 15 push button panel. The crossed solid lines with dots indicate electrical connections and two dots joined by a dashed line are activated by a single push button. As an example, the configuration shown is for a two parameter grouping of ADC1 and ADC2 and a single parameter set-up for ADC3. We shall discuss the two parameter grouping. The CLAM1, CLAM2 and INTERRUPT 1 signals appear only when both LAM1 and LAM2 are present; that is, only after both ADC's have transferred data to the Input registers. The CLAM signals generate (See Fig. K1-3) ADC reset signals and release the ADC's to process the next event. The OLAM signal is the OR of LAM1 and LAM2 and therefore goes off only when the contents of both data input registers are transferred to memory. As seen in Fig. K1-2, the trailing edge of OLAM removes the block from the "data ready" signal and allows processing of the next event. Since the ADC's are free to accept new events during the actual transfer of the previous event to the computer memory, overall dead time is reduced.

The hardware on-off control will be a parallel output register mounted in the Camac crate. Each of the 8 Interrupt signals which are connected to the MBD can be gated by a bit in the output register. In addition, external stops from scaler presets, beam current gates, etc. are available. The combination of the forced time out Q10 option and the hardware on-off circuits will provide flexible control of the system.

REFERENCES (Section K1)

1. R. V. Poore et al., IEEE Trans. on Nucl. Sci. NS-26 (1979)708
2. A. Holm, IEEE Trans. on Nucl. Sci. NS-26 (1979)4569
3. R. F. Thomas, LA-5404-MS "Programming the MBD" (LASL 1973)

L. NUCLEAR THEORY AND PHENOMENOLOGY

1. Reciprocity Relation for Multi-Channel Coupling
Kernels (S. R. Cotanch, G. R. Satchler*)

A theorem, based upon time-reversal invariance, has been developed that established a definite symmetry relation between off-diagonal coupling interactions in a general coupled-channels theory. This result is scheduled for Jan. 1981 publication in Phys. Rev. C. The abstract follows:

"Assuming time-reversal invariance of the many-body Hamiltonian, it is proven that the kernels in a general coupled-channels formulation are symmetric, to within a specified spin-dependent phase, under the interchange of channel labels and coordinates. The theorem is valid for both hermitian and suitably chosen nonhermitian Hamiltonians which contain complex effective interactions. While of direct practical consequence for nuclear rearrangement reactions, the reciprocity relation is also appropriate for other areas of physics which involve coupled-channels analysis."

FOOTNOTE (Section L1)

* Oak Ridge National Laboratory

2. Polarization Effects in Heavy Ion Transfer Reactions
(H. Hasan, G. Tungate)

The work described here, while not in the main stream of the research program at TUNL is a natural continuation of the theoretical and experimental studies of heavy ion transfer reactions performed by the authors at Oxford and Heidelberg.

Differential cross sections for heavy ion transfer reactions can be calculated using a semiclassical approach based on the DWBA. [1] The transfer amplitudes calculated in this analysis show a strong dependence on the kinematical matching conditions as discussed by Brink. [2] These amplitudes depend also on the orientation of the orbital angular momentum of the transferred particle in both the projectile and the residual nucleus. In a polarized 7Li beam the orientation of the 7Li spin results in a partial orientation of the orbital angular momentum of the "valence neutron". Experiments with a polarized 7Li beam which look at reactions in which the "valence neutron" is transferred to the target nucleus can show large analyzing powers which are sensitive to the

kinematical matching conditions. Experimental data for the reaction $58\text{Ni}(7\text{Li}, 6\text{Li})59\text{Ni}^*$ going to several states in 59Ni have shown that the vector analyzing power is sensitive to the Q -value of the reaction. [3] The analysis of Ref. [3] shows only the vector analyzing power for a grazing collision as a function of the Q -value. The current work is aimed at using the techniques of Ref. [1] to calculate the transfer amplitudes and to use these to evaluate the vector and tensor analyzing powers as a function of the scattering angle and reaction Q -value.

A computer code for calculating the transfer amplitudes has been installed at the TUCC computer and is currently being tested. Preparation of a subroutine to calculate the analyzing powers from the transfer amplitudes is also underway.

REFERENCES (Section L2)

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2. D. M. Brink in : Nuclear Physics With Heavy Ions And Mesons, Les Houches Lectures (1977) (North-Holland Amsterdam)
3. G. Tungate et al., Physics Letters 95B (1980) 35
3. Polarized Triton Elastic Scattering at 17 MeV
(W. J. Thompson, R. A. Hardekopf, R. F. Haglund, Jr.,
G. G. Ohlsen, L. R. Veaser [LASL])

Differential cross-section and analyzing-power angular distributions for (t, t) with polarized tritons at 17 MeV for scattering from nuclei with $40 \leq A \leq 208$ in the angular range from 20 to 160 degrees were measured. The data were analyzed using the optical model to fit both observables simultaneously. The analyzing-power data delimit the real potential well parameters much more precisely than do cross-section data alone. The spin-orbit potential is less well defined, but has an average spin-orbit well depth of 6.2 ± 1.5 MeV, with geometric parameters similar to those for nucleons. The spin-orbit volume integrals are about a factor of three greater than predicted from simple folding models.

An account of this work has been published in Physical Review C.

4. Polarization of Nuclei (W. J. Thompson)

A pedagogical article describing polarized beams, polarized targets, the use of nuclear polarization in tests of symmetry principles, the spin dependence of nuclear interactions, the determinations of nuclear shapes of polarized nuclei such as the deuteron, 6Li and 7Li , and the applications of polarized beams to the determination of nuclear structure, was written for the McGraw Hill Yearbook of Science and Technology, 1980.

Apparatus and data from TUNL were featured in the article.

5. Elastic Scattering Potentials for Nucleons and Composite Particles (W. J. Thompson)

A review of optical-model potentials for elastic scattering of polarized neutrons, protons, deuterons, tritons, 3-helium, and 6,7-lithium from targets with $A \geq 6$ and in the bombarding energy range 4 to 1000 MeV has been prepared. Emphasis was placed on polarization phenomena leading to better understanding of the spin-dependent terms in optical potentials. Recent advances in microscopic theories of nucleon scattering and folding models of composite scattering were surveyed. This review was presented as an invited paper at the Fifth International Symposium on Polarization Phenomena in Nuclear Physics in August 1980.

6. Energy Dependence of The Nucleon Spin-Orbit Potential (W. J. Thompson)

The energy dependence observed for the depth of the nucleon spin-orbit potential was investigated by considering the consequences of non-locality in the nucleon-nucleus interaction. For low bombarding energies a simple relation between the energy dependences of the spin-orbit and central well depths was predicted. The relations were found to be in good agreement with empirical values, with the spin-orbit well depth varying less rapidly than the real central well depth. A short report on these results was published in Journal of Physics G: Nuclear Physics.

7. Statistical-Model Calculations of Neutron-Induced Reactions (R. Y. Cusson, H. W. Meldner [L.L.L.])

The code NIFTE written to study neutron induced reactions on medium to heavy nuclei is being superseded by a new one which conserves total angular momentum and does full optical model calculations. The new code NIFTNG utilizes Peter Fu's (ORNL) code TNG as a starting point. The new code includes realistic multiple barrier fission channels with or without discrete levels in the barrier region, and can still be used in medium nuclei where fission channels are closed. Applications to the reaction $^{56}\text{Fe} + n$ studied at TUNL are underway, as well as to actinide burnup in Laser Induced Fusion of pellets.

8. Proton Radiative Capture Calculations (J. M. Lafferty, Jr., S. R. Cotanch)

Calculations of direct E1, E2, and M1 radiative capture have been performed for the reaction $^{11}\text{B}(p,\gamma)^{12}\text{C}^*$ in the energy (lab) region 5-70 MeV. Relative contributions of the spin- and nonspin-flip

terms in the Hamiltonian have been calculated. Gauge invariance of the Hamiltonian leads to spin-orbit corrections to the EL and ML processes which have also been treated. Effects due to nonorthogonality of the wavefunctions have been calculated. These calculations have been carried out both in the long wavelength approximation and using the exact form of the EM-transition operators. In addition calculations have been performed to test the validity of Siegert's theorem. A description of this work is to be published in Nuclear Physics.

9. An Extended Computer Code for Radiative Capture Reactions (J. M. Lafferty, Jr., S. R. Cotanch)

The code PARCAP, [1] which computes direct electric radiative capture processes, has been extended to compute electric spin-flip transitions and magnetic spin- and nonspin-flip transitions. Gauge invariance of the Hamiltonian when spin-orbit interactions are included leads to additional electric and magnetic transition corrections and these effects are also treated. In addition, the code calculates electric transitions using a form of the electric nonspin-flip operator which may be more appropriate for continuum capture processes (does not use Siegert's theorem). The generalized code exists in two versions, PARCAPA and PARCAPB. PARCAPA treats the transitions in the long wavelength approximation and PARCAPB treats the transitions exactly. In the near future the code will be extended to calculate polarized capture processes. The two versions of the code are available to all TUNL personnel.

REFERENCES (Section L9)

1. J. M. Lafferty, Jr. and S. R. Cotanch, TUNL 1979 Annual Report.
10. Atomic Excitation Effects on Nuclear Reactions
(W. J. Thompson, J. Wilkerson, T. B. Clegg, J. Feagin,
E. J. Ludwig, E. Merzbacher)

The effects of excitation of an atom on the reaction of its nucleus with a projectile are of interest because of the insight into the mechanisms of atomic and nuclear collisions these effects can provide. We demonstrated atomic-excitation effects on nuclear reactions in which the interaction time is shorter than atomic periods, so that the collision can be approximated as sudden with respect to atomic motions. Atomic-excitation effects arising from sudden nuclear recoil were revealed by broadening of the very narrow isolated resonance (~ 1 keV) in $^{12}\text{C}(p,p)^{12}\text{C}$ at a proton energy near 14.23 MeV.

The excitation functions of the analyzing power and differential cross section were measured simultaneously at four proton

scattering angles. The TUNL Lamb-shift polarized-ion source was used with the high-energy-resolution system to produce 50 nA of polarized proton beam on target with an average polarization of 88% and an energy resolution FWHM of 850 ± 40 eV, as deduced in the analysis of the excitation functions. The excitation functions are shown in the Fig. L10-1.

In the resonance analysis we used a Breit-Wigner resonance with helicity amplitudes to describe the non-resonant scattering. Doppler broadening in the graphite microcrystallite target was deduced from the phonon spectrum for similarly-prepared graphite, beam straggling in the target, as well as the atomic-excitation broadening, were included in the analysis. A resonance width of 1010 ± 20 eV (lab frame) was deduced thereby, in agreement with the measurement of the decay of the state in ^{13}N , whereas a width of 1610 ± 20 eV is deduced if atomic-excitation effects are ignored.

Measurement of the corresponding spectrum of atomic excitations is a challenge to atomic physicists and would provide data for further study of the interplay between atomic and nuclear physics. A report on this work has been published in Physical Review Letters and will be part of a more extensive review of atomic-excitation effects on nuclear reactions which is in preparation.

Fig. L10-1. Excitation functions for $^{12}\text{C}(p,p)^{12}\text{C}$ across the lowest $T=3/2$ state. Fits to the data include the atomic excitation effects.

11. A Program for Perspective Views of Three-Dimensional Surfaces (W. J. Thompson, E. A. Olszewski [UNC at Wilmington])

We have written a FORTRAN program, TDPL0T3, which constructs either monoptic or stereoptic perspective projections of three-dimensional surfaces described in spherical-polar or cylindrical coordinates. Hidden-line elimination is very efficient in TDPL0T3. It also features a cubic-interpolation routine which generates additional perspective points so that a smoother display of the surface may be constructed without needing additional input data or hidden-line search time. The program has been written in modular structures, using ASA

FORTRAN 77. Graphical output may be displayed on incremental or vector graphics devices.

A description of the algorithms used and of the program have been accepted for publication in Computer Physics Communications, which also distributes copies of the FORTRAN program TDPL0T3 as catalogue number ABVL.

APPENDIX I

A. PUBLISHED JOURNAL ARTICLES December 1979-January 1981

1. Angular Distribution Theory for Particle-Capture-Gamma Reactions, R. G. Seyler and H. R. Weller, Phys. Rev. C20 (1979) 453
2. Corrections to Literature Expressions for Angular Distributions of Gamma Reactions Initiated by Polarized Particles, R. G. Seyler and H. R. Weller, Atomic Data and Nuclear Data Tables 23 (1979) 99
3. Polarization Transfer in the $2\text{H}(p,n)2\text{p}$ Reaction at $\theta=0^\circ$, P. W. Lisowski, R. C. Byrd, R. L. Walter and T. B. Clegg, Nucl. Phys. A334 (1980) 45
4. Analyzing Power Measurements for n-p Scattering between 13.5 and 16.9 MeV, W. Tornow, P. W. Lisowski, R. C. Byrd and R. L. Walter, Nucl. Phys. A340 (1980) 34
5. The Analyzing Power $A_y(\theta)$ for the $9\text{Be}(p,n)9\text{B}$ Reaction, G. Mack, R. C. Byrd, P. W. Lisowski and R. L. Walter, Nucl. Phys. A345 (1980) 241
6. Inelastic Proton Amplitudes for f-Wave Resonances in 55Co , W. A. Watson III, E. G. Bilpuch and G. E. Mitchell, Zeitschrift für Physik A294 (1980) 153
7. Correlations for Reduced-Width Amplitudes in 49V , B. H. Chou, G. E. Mitchell, E. G. Bilpuch and C. R. Westerfeldt, Phys. Rev. Lett. 45 (1980) 1235
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9. Study of the Structure of the Low-Lying Levels of 29Si Via The $28\text{Si}(d,p\gamma)$ Reaction and Multi-step Reaction Calculations, H. Clement, R. N. Boyd, C. R. Gould and T. B. Clegg, Nucl. Phys. A339 (1980) 285
10. A High Efficiency Buncher System for Polarized Beams, S. A. Wender, C. Floyd, T. B. Clegg and W. R. Wylie, Nucl. Instr. and Meth. 174 (1980) 341
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12. J-Dependent Effects in Tensor Analyzing Powers for the (d,α) Reaction, S. A. Tonsfeldt, T. B. Clegg, E. J. Ludwig, Y. Tagishi and J. F. Wilkerson, Phys. Rev. Lett. 45 (1980) 2008

13. Polarized Proton Capture on ^{13}C , J. D. Turner, N. R. Roberson, S. A. Wender, H. R. Weller and D. R. Tilley, Phys. Rev. C21 (1980) 525
14. Polarized Proton Capture on ^{30}Si , C. P. Cameron, R. D. Ledford, M. Potokar, D. G. Rickel, N. R. Roberson, H. R. Weller and D. R. Tilley, Phys. Rev. C22 (1980) 397
15. Evidence for a 2^+ Resonance in ^4He at 40 MeV, R. C. McBroom, H. R. Weller, S. Manglos, N. R. Roberson, S. A. Wender, D. R. Tilley, D. M. Skopik, L. G. Arnold and R. G. Seyler, Phys. Rev. Lett. 45 (1980) 243
16. Capture Reactions with Protons, Neutrons and Alpha Particles, H. R. Weller and N. R. Roberson, Rev. Mod. Phys. 52 (1980) 699
17. Systematics of Target and Projectile K X-ray Production and Radiative Electron Capture for 20-80 MeV $\text{Cl } q^+$ Ions Incident on 25-200- $\mu\text{g}/\text{cm}^2$ Cu Targets, J. A. Tanis, W. W. Jacobs and S. M. Shafroth, Phys. Rev. A22 (1980) 483
18. Evolution of Projectile Double K Vacancy Fractions with Target Thickness in Ion-Atom Collisions, J. A. Tanis, S. M. Shafroth, J. E. Willis and J. R. Mowat, Phys. Rev. Lett. 45 (1980) 1547
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22. Energy Dependence of the Nucleon Spin-Orbit Potential, J. A. Ramirez and W. J. Thompson, Journal of Physics G: Nuclear Physics 6 (1980) L-113
23. Pressure Monitoring System for Tritium Gas Target, L. W. Seagondollar and P. M. Thambidurai, Nucl. Instr. and Meth. 173 (1980) 603
24. X-Ray Identification of Fusion Reaction Products Implanted in Al Foils Following ^{16}O and ^{19}F Bombardment of ^{59}Co Foils, A. W. Waltner, S. L. Varghese, J. E. Willis and S. M. Shafroth, Nucl. Instr. and Meth. 170 (1980) 189
25. Reciprocity Relation for Multi-Channel Coupling Kernels, S. R. Cotanch and G. R. Satchler, Phys. Rev. C23 (1981) 566
26. Measurement and Lane Model Analysis of Cross Sections for the $^{13}\text{C}(p,n)^{13}\text{N}$ and $^{15}\text{N}(p,n)^{15}\text{O}$ Reactions, R. C. Byrd, C. E. Floyd, K. Murphy, P. P. Guss, R. L. Walter and S. R. Cotanch, Nucl. Phys. A351

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27. Radiative Electron Capture by Cl Ions Incident on C and Cu Foils, J. A. Tanis, S. M. Shafroth, J. E. Willis and J. R. Mowat, Phys. Rev. A23 (Comments) (1981) 366

APPENDIX I (Continued)

B. JOURNAL ARTICLES ACCEPTED FOR PUBLICATION

1. The $^{15}\text{N}(p,n)^{15}\text{O}$ Reaction Below 9.3 MeV, K. Murphy, R. C. Byrd, P. P. Guss, C. E. Floyd and R. L. Walter, Nucl. Phys. A (In press)
2. A Polarized Beam Study of The $^{207}\text{Pb}(d,t)^{206}\text{Pb}$ Reaction, J. E. Willis, T. B. Clegg, M. D. Kaitchuck, E. J. Ludwig and W. J. Thompson, accepted for publication in Nuclear Physics
3. Elastic and Inelastic Neutron Cross Sections for ^{10}B and ^{11}B , S. G. Glendinning, R. L. Walter, F. O. Purser, S. El Kadi, R. S. Pedroni, C. R. Gould, L. W. Seagondollar, A. G. Beyerle and P. Thambidurai, Nucl. Sci. and Eng. (to be published)
4. Building a Turing Machine, J. E. Willis, Byte, in press
5. A Program for Perspective Views of Three-Dimensional Surfaces, E. A. Olszewski and W. J. Thompson, Computer Physics Communications (to be published)

APPENDIX I (Continued)

C. JOURNAL ARTICLES SUBMITTED FOR PUBLICATION

1. Comparison of Analyzing Power and Polarization in the Reaction $^3\text{H}(p,n)^3\text{He}$: New Polarization Results Below 4 MeV, W. Tornow, R. C. Byrd, P. W. Lisowski, R.L. Walter and T. R. Donoghue, submitted to Nucl. Phys. A
2. Amplitude Correlations for Inelastic Proton Scattering from ^{48}Ti , B. H. Chou, G. E. Mitchell, E. G. Bilpuch and C. R. Westerfeldt, submitted to Zeitschrift für Physik
3. Statistical Tests Applied to Proton Resonances in ^{57}Co , W. A. Watson III, E. G. Bilpuch and G. E. Mitchell, submitted to Zeitschrift für Physik
4. Dielectronic Recombination in S + Ar Collisions, J. A. Tanis, S. M. Shafroth, J. E. Willis, M. Clark, J. Swenson, E. N. Strait and J. R. Mowat, submitted to Phys. Rev. Lett.

APPENDIX II

INVITED TALKS, CONFERENCE AND TECHNICAL REPORTS AND
BOOK CHAPTERS BY TUNL PERSONNEL

December 1979-January 1981

1. Double Differential Neutron Scattering Cross Sections for Fe, Cu, Ni and Pb between 8 and 12 MeV, A. Beyerle, C. Gould, W. Seagondollar, P. Thambidurai, S. El-Kadi, G. Glendinning, C. E. Nelson, F. O. Purser and R. L. Waller, "Proceedings of the International Conference on Nuclear Cross Sections for Technology", NBS Special Publication 594 (1980) p. 139
2. Elastic Neutron Scattering from ^{63}Cu , ^{65}Cu , ^{54}Fe and ^{56}Fe from 8 to 12 MeV, S. El-Kadi, R. Pedroni, G. Glendinning, C. E. Nelson, F. O. Purser, E. L. Walter, A. Beyerle, C. Gould and W. Seagondollar, *ibid.*, p. 143
3. Finite Geometry and Multiple Scattering Corrections for Neutron Cross Section Measurements, H. H. Hogue and A. Beyerle, *ibid.*, p. 504
4. Recent Modifications of the TUNL Fast Neutron Cross Section Facility, L. W. Seagondollar, A. G. Beyerle, C. R. Gould, F. O. Purser, S. El-Kadi, S. G. Glendinning and C. E. Nelson, *ibid.*, p. 537
5. Polarization Observables in (p,n) Reactions, R. L. Walter and R. C. Byrd, "The (p,n) Reaction and the Nucleon-Nucleon Force", ed. C. D. Goodman, S. M. Austin, S. D. Bloom, J. Rapaport and G. R. Satchler (Plenum, N.Y., 1980) p. 469
6. Self-Consistent Application of the Lane Model, R. C. Byrd, R. L. Walter and S. R. Cotanch, *ibid.*, p. 481
7. Scattering of Polarized Neutrons from ^{54}Fe and ^{65}Cu at 10 MeV, C. E. Floyd, P. P. Guss, K. Murphy, R. C. Byrd, S. A. Wender, R. L. Walter and T. B. Clegg, "Proc. 5th Int. Symp. on Polarization Phenomena in Nuclear Physics", Santa Fe, N.M., 1980 (to be published) p. 2.4
8. Neutron Scattering from ^{58}Ni and ^{208}Pb at 10 MeV, P. P. Guss, G. Tungate, C. E. Floyd, K. Murphy, R. C. Byrd, R. L. Walter and T. B. Clegg, *ibid.*, p. 2.5
9. The Analyzing Power for Elastic Scattering of 9.9, 11.9, and 13.9 MeV Neutrons from Ca, W. Tornow, E. Woye, G. Mack, C. E. Floyd, K. Murphy, P. P. Guss, S. A. Wender, R. C. Byrd and R. L. Walter, *ibid.*, p. 2.6
10. The Scattering of Polarized Neutrons from ^9Be Between 9 and 15 MeV, C. E. Floyd, P. P. Guss, R. C. Byrd, K. Murphy, S. A. Wender, W. Tornow, R. L. Walter, T. B. Clegg and W. J. Thompson, *ibid.*, p. 2.7

11. A Program of Systematic Measurement and Analysis for the Low-Energy Optical-Model Potential, R. L. Walter, R. C. Byrd, T. B. Clegg, E. J. Ludwig and W. J. Thompson, *ibid.*, p. 2.9
12. Use of Neutron Time-of-Flight Techniques in (p,n) A_y Measurements, R. C. Byrd, K. Murphy and R. L. Walter, *ibid.*, p. 3.43
13. Vector Analyzing Power for the $2\text{H}(d,n)^3\text{He}$ Reaction, P. P. Guss, K. Murphy, R. C. Byrd, C. E. Floyd, S. A. Wender, R. L. Walter, T. B. Clegg and W. R. Wylie, *ibid.*, p. 5.26
14. Small Angle Neutron Polarization for $2\text{H}(d,n)^3\text{He}$ at $E_d = 8$ MeV, W. Tornow, E. Woye, G. Mack, R. L. Walter, P. P. Guss and R. C. Byrd, *ibid.*, p. 5.27
15. The Analyzing Power $A_y(\theta)$ for $^{12}\text{C}(n,n_0,1)^{12}\text{C}$ from 9 to 16.8 MeV, E. Woye, W. Tornow, G. Mack, C. E. Floyd, P. P. Guss, R. K. Murphy, R. C. Byrd, S. A. Wender, R. L. Walter, T. B. Clegg and W. R. Wylie, *ibid.*, p. 5.43
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17. Comparisons of Polarizations and Analyzing Powers for the $^{11}\text{B}(p,n)^{11}\text{C}$ and $^{13}\text{C}(p,n)^{13}\text{N}$ Reactions, K. Murphy, R. C. Byrd, P. P. Guss, C. E. Floyd, R. L. Walter, S. A. Wender and T. B. Clegg, *ibid.*, p. 6.13
18. Status of Comparisons Between Polarization and Analyzing Power in (p,n) Reactions, R. C. Byrd and R. L. Walter, *ibid.*, p. 6.14
19. Analyzing Powers for (p,n) Reactions on Light Nuclei, K. Murphy, R. C. Byrd, C. E. Floyd, P. P. Guss, R. L. Walter, S. A. Wender and T. B. Clegg, *ibid.*, p. 6.15
20. Lane Model Constraints on Nucleon-Nucleus Scattering Potentials, R. C. Byrd, R. L. Walter and S. R. Cotanch, *ibid.*, p. 6.16
21. A Deuteron Vector and Tensor Polarimeter for $E_d=4-17$ MeV, T. B. Clegg, S. A. Tonsfeldt, E. J. Ludwig and J. F. Wilkerson, *ibid.*
22. An Upgrading Program for the TUNL Lamb-Shift Polarized Source, T. B. Clegg, S. M. Mitchell, R. L. Varner, W. R. Wylie, S. A. Wender, C. E. Floyd, R. K. Murphy and M. E. Wright, *ibid.*
23. Polarized Proton Scattering from Se Isotopes, R. L. Varner, J. F. Wilkerson, W. J. Thompson, Y. Tagishi, E. J. Ludwig, T. B. Clegg and B. L. Burks, *ibid.*
24. Measurement and DWBA Analysis of the $^{78}\text{Kr}(d,p)^{79}\text{Kr}$ Reaction, T. B. Clegg, B. L. Burks, R. R. Cadmus, Jr. and E. J. Ludwig, *ibid.*
25. Polarized Proton Beam Studies of Very Narrow Resonances, J. F. Wilkerson, W. J. Thompson, E. J. Ludwig and T. B. Clegg, *ibid.*

26. Atomic Excitation Effects in Nuclear Reactions Studied with Polarized Beams, W. J. Thompson, J. F. Wilkerson, T. B. Clegg, J. M. Feagin, E. J. Ludwig and E. Merzbacher, ibid.
27. A Test of Collective Effects in $\text{Se}(d,d)\text{Se}$, Y. Tagishi, B. L. Burks, T. B. Clegg, E. J. Ludwig, R. L. Varner, J. F. Wilkerson and W. J. Thompson, ibid.
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29. Polarized Proton Capture to the First Excited State of ^{60}Ni , K. Sparks, J. D. Turner, N. R. Roberson, D. R. Tilley and H. R. Weller, ibid.
30. Polarized Proton Capture to the First Excited State in ^{31}P , C. Fitzpatrick, C. P. Cameron, Hideo Kitazawa, N. R. Roberson, D. R. Tilley and H. R. Weller, ibid.
31. Polarized Proton Capture on ^{88}Sr , R. D. Ledford, C. Cameron, M. Potokar, N. R. Roberson, D. R. Tilley and H. R. Weller, ibid.
32. The Influence of Multiple Scattering Corrections of High Accuracy Neutron-Proton Analyzing Power Measurement at 16.9 MeV, W. Tornow and R. L. Walter, ibid.
33. Discrepancies in The Polarization of Elastically Scattered Neutrons from ^{12}C Around 16 MeV, W. Tornow, E. Woye and R. L. Walter, ibid.
34. Cryogenic Polarized Target Facility for Spin-Spin Neutron Total Cross Section Measurements, C. R. Gould, D. G. Haas, T. B. Clegg, W. J. Thompson and R. L. Walter, ibid.
35. Polarized Neutron Capture Studies in the Giant Resonance Region, H. R. Weller, Invited Talk, ibid.
36. Elastic Scattering Potentials for Nucleons and Composite Particles, W. J. Thompson, Invited Talk, ibid.
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46. Statistical Properties from High Resolution Proton Resonance Reactions, G. E. Mitchell, Invited Talk, published in "Theory and Applications of Moment Methods in Many-Fermion Systems", ed. B. J. Dalton, S. M. Grimes, J. P. Vary and S. A. Williams (Plenum Press, New York, 1980) p. 33
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APPENDIX III

ABSTRACTS OF CONTRIBUTED PAPERS PRESENTED AT AMERICAN
PHYSICAL SOCIETY AND OTHER MEETINGS*

1. Laser Spectrometer for Precise Energy Measurements of 10-120 keV D and T Ions, G. G. Ohlsen, Ronald E. Brown, Nelson Jarmie, R. A. Hardekopf, S. E. King, F. D. Correll and D. A. Clark, Bull. Am. Phys. Soc., 24 (1979) 822
2. TUNL Progress Report, J. E. Willis, et al., Proceedings of Society of Northeastern Accelerator Personnel, Oct. 1979
3. Isomeric Ratio of ^{44}Sc Resulting from $^{27}\text{Al}(^{19}\text{F}, p n)^{44}\text{Sc}$ Reaction, A. W. Waltner, J. R. Ashburn, S. M. Shafroth and J. Willis, Bull. Am. Phys. Soc. 25 (1980) 125
4. Atomic Excitation Moments for Narrow Resonance Line Shapes, G. B. Lipton, J. M. Feagin and W. J. Thompson, ibid., p. 128
5. Polarization for Neutron Elastic Scattering from ^{54}Fe , ^{65}Cu , and Pb at 10 and 14 MeV, C. E. Floyd, P. P. Guss, R. K. Murphy, S. A. Wender, R. C. Byrd, R. L. Walter and T. B. Clegg, ibid., p. 542
6. Double Differential Neutron Emission Spectra for Iron, A. Beyerle, S. El-Kadi, C. Gould, C. E. Nelson, F. O. Purser, W. Seagondollar and R. L. Walter, ibid., p. 543
7. Elastic Scattering of Pulsed Polarized Neutrons Produced in the $2\text{H}(d, n)^3\text{He}$ Reaction, R. L. Walter, C. E. Floyd, P. P. Guss, R. C. Byrd, S. A. Wender, T. B. Clegg, E. Woye, W. Tornow and G. Mack, ibid., p. 555
8. Measurements of Vector and Tensor Analyzing Powers for the $^{38}\text{Ar}(d, \alpha)^{36}\text{Cl}$ and $^{36}\text{Ar}(d, \alpha)^{34}\text{Cl}$ Reactions, T. B. Clegg, Y. Tagishi, J. F. Wilkerson, E. J. Ludwig, S. A. Tonsfeldt and W. Wylie, ibid., p. 555
9. Determination of Atomic-Excitation Effects on The $^{12}\text{C}(p, p)^{12}\text{C}$ First $T=3/2$ Resonance by Use of a Polarized Beam, J. F. Wilkerson, W. J. Thompson, T. B. Clegg, E. J. Ludwig and S. A. Tonsfeldt, ibid., p. 555
10. Vector Analyzing Power for the $2\text{H}(d, n)^3\text{He}$ Reaction, P. P. Guss, R. K. Murphy, R. C. Byrd, C. E. Floyd, S. A. Wender, R. L. Walter and T. B. Clegg, ibid., p. 556
11. Radiative Capture of Neutrons by ^3He , L. Ward, D. R. Tilley, S. A. Wender, N. R. Roberson, H. R. Weller and D. Skopik, ibid., p. 576
12. Studies of (p, n) Reactions in Light Nuclei, R. C. Byrd, R. K. Murphy, C. E. Floyd, P. P. Guss, R. L. Walter, S. A. Wender and T. B. Clegg, ibid., p. 592

13. A High Resolution Study of The $^{29}\text{Si}(p,p)$ Reaction, C. R. Westerfeldt, R. O. Nelson, E. G. Bilpuch, G. E. Mitchell and K. B. Sales, ibid., p. 596
14. High Resolution Proton Inelastic Scattering from $\ell=2$ Resonances In ^{49}V , B. H. Chou, G. E. Mitchell, C. R. Westerfeldt and E. G. Bilpuch, ibid., p. 596
15. High Resolution Proton Elastic and Inelastic Scattering on ^{56}Fe , W. A. Watson III, E. G. Bilpuch, C. R. Westerfeldt, G. E. Mitchell and K. B. Sales, ibid., p. 596
16. High Resolution Study of The $^{66}\text{Zn}(p,p)$ Reaction, K. B. Sales, G. E. Mitchell, E. G. Bilpuch and C. R. Westerfeldt, ibid., p. 596
17. Proton Capture to Excited States of ^8Be and ^{14}N , S. Manglos, H. R. Weller, N. R. Roberson, D. R. Tilley, S. A. Wender and S. L. Blatt, ibid., p. 603
18. Radiative Capture of Polarized Neutrons by ^{13}C , M. J. Jensen, D. R. Tilley, S. A. Wender, N. R. Roberson, H. R. Weller, ibid., p. 603
19. High-Lying $T=3/2$ States in ^{25}Al , ^{29}P , ^{33}Cl and ^{37}K , T. B. Clegg, J. F. Wilkerson, E. J. Ludwig, Y. Tagishi and R. T. Kouzes, ibid., p. 723
20. Proton and Neutron Radiative Capture, H. R. Weller, ibid., p. 775
21. K-Shell Binding Energies of Highly Ionized Projectiles Deduced from Experimental Studies of Radiative Electron Capture, S. M. Shafroth, J. E. Willis, J. A. Tanis and J. R. Mowat, Bull. Am. Phys. Soc. 26 (1981) 48
22. Zero-Degree $T(p,n)$ Breakup Cross-sections, P. Thambidurai, A. Beyerle, C. Gould, F. O. Purser, W. Seagondollar, and R. L. Walter, Annual Meeting of the Southeastern Section of the American Physical Society, Nov. 1980, Chapel Hill, N. C., Bull. Am. Phys. Soc. 26 (1981) 89.
23. Polarized Proton Capture to the First Excited State in ^{31}P , C. Fitzpatrick, C. P. Cameron, Hideo Kitazawa, N. R. Roberson, D. R. Tilley and H. R. Weller, ibid.
24. Direct Capture Calculation for The $^{11}\text{B}(p,\gamma)^{12}\text{C}$ Reaction, G. Mitev, J. Lafferty, H. Hasan, S. Cotanch and H. R. Weller, ibid.
25. Mott-Schwinger Interaction and The Scattering of Fast Neutrons, C. E. Floyd, R. L. Walter and W. J. Thompson, ibid.
26. Recent Experiments Involving the $^{27}\text{Al}(^{19}\text{F},X)^Y$ Reactions, A. W. Waltner, J. R. Ashburn, S. M. Shafroth, J. Willis, and M. Clark, ibid., p. 90
27. Thick vs. Thin Targets in the Comparison of Cross Sections Resonance Regions: The $^{15}\text{N}(p,n)^{15}\text{O}$ Reaction below 9.3 MeV, K. Murphy and R. C. Byrd, ibid.

28. Absolute Neutron Flux Measurement Using a Proton Recoil Telescope, S. E. King, N. R. Roberson and S. A. Wender, ibid.
29. Multiple Scattering and Finite Geometry Effects on Neutron Cross-Section and Analyzing Power Measurements, P. P. Guss and E. Woye, ibid.
30. Calculation of K_{α} X-ray Energies for Dielectronic Recombination Satellites in S^{9+} , Tom McAbee, ibid., p. 84
31. Search for Temperature Dependent X-Ray Fluorescence, M. Clark, P. Peters, C. V. Briscoe and S. M. Shafroth, ibid., p. 85
32. Properties of a Parallel Plate Electron Analyser, J. K. Swenson, ibid.
33. Measurement of Dielectronic Recombination Cross Sections at TUNL, J. A. Tanis, S. M. Shafroth, M. Clark, J. Swenson and J. E. Willis, ibid.

FOOTNOTE (Appendix III)

- * See also Appendix II.

APPENDIX IV

TUNL SEMINARS 1980

1. J. P. Delaroche, Bruyeres Le Chatel, France (1/24/80)
Fast Neutron Scattering from Tungsten Isotopes--Comparison
with Structure Calculations
2. Charles Glashauser, Rutgers University (1/31/80)
Proton Inelastic Scattering at 800 MeV
3. Hashima Hasan, University of Poona, Pune, India (2/7/80)
Semiclassical Analysis of Heavy Ion Transfer Reactions
4. Jack Rapaport, Ohio University (2/14/80)
Global Optical Potentials for Neutrons
5. Raymond Dewberry, Florida State University (2/21/80)
Some Results of (t,) Reactions in The Rare Earth Region
6. Ken Hill, Princeton Plasma Physics Laboratory (2/28/80)
X-Ray Diagnostics of Tokamak Fusion Plasmas
7. Garry Tungate, Duke University (3/13/80)
Experiments with Polarized ^7Li
8. N. Russell Roberson, Duke University (3/18/80)
Beginner's Guide to the VAX
9. Thomas Clegg, University of North Carolina (3/20/80)
Polarized Ion Sourcery
10. Constance Kalbach, Duke University (3/27/80)
"Truth or Consequences" Nuclear Energy and Our Responsibility for
Public Education
11. Vaclav Kostroun, Cornell University, Ward Reactor Laboratory
(4/3/80)
The Cornell EBIS: The Source of Low Energy, Multiply Charged
Ions for Atomic Physics Experiments
12. Roger Perkins, Los Alamos Scientific Laboratory, Inertial Fusion
Division, (4/10/80)
An Overview of Research at LASL and Technical Problems with
Fusion Diagnostic Techniques
13. Ron Jaszczak, Duke University Medical Center, Radiology
Department (4/17/80)
Single Photon Emission Computed Tomography

14. Yoshihiro Tagishi, University of Tsukuba, Ibaraki, Japan (5/15/80)
Studies of the (p,) Reaction with a Polarized Proton Beam
15. Herbert Vonach, Institute for Radiumforschung and Nuclear Physics, Vienna, Austria (5/20/80)
Study of Fast Neutron Reactions at The Nuclear Institute at Vienna
16. Ray Moreh, Nuclear Research Centre, Negev, and Ben-Gurion University of the Negev, Beer Sheva, Israel (5/22/80)
The Study of Molecular Orientation Using Nuclear Photon Scattering
17. John Tanis, Lawrence Berkeley Laboratory (5/27/80)
Atomic Collision Studies Related to Development of Neutral Beam Injectors for Fusion by Means of Magnetic Confinement
18. William Bertozzi, Massachusetts Institute of Technology and Bates Linac (5/29/80)
Electromagnetic Studies of Nuclei
19. J. Knudsen, Kent State University (6/5/80)
Large Volume Scintillation Detectors for Neutron Time-of-Flight Studies
20. Stephen M. Shafroth, University of North Carolina (6/12/80)
Double K-Vacancy Production in Ion-Atom Collisions
21. Wenzeslav Andrejtscheff, Rutgers University and The Institute of Nuclear Research and Nuclear Energy, Sofia, Bulgaria (6/20/80)
Systematic Behavior of B(E2) Values
22. Hubert Zankel, Institute for Theoretical Physics, University of Graz, Graz, Austria (6/26/80)
Approximate Coulomb Corrections in Two- and Three-Body Systems
23. Gary Mitchell, North Carolina State University
Review of Recent High Resolution Experiments at TUNL
24. Conrad Knight, Radiological Safety Office, Duke University (7/10/80)
Radiation Safety
25. Dieter Flick, Phillips-Marburg Universität, Marburg, W. Germany (8/21/80)
Nuclear Shapes from Heavy-Ion Polarization Experiments
26. Ray Poore, Los Alamos Scientific Laboratory (9/4/80)
Status Report on VAX Data Acquisition System
27. Jim McCarthy, University of Virginia (9/11/80)
Future Directions for The Study of Nuclei with Electromagnetic Interactions

28. Hans Paetz gen. Schleck, University of Köln, Germany (9/18/80)
Kinematically Complete Measurement of The Breakup Reaction
 $4\text{He}(d,p)n$ at $E = 18$ MeV
29. William J. Thompson, University of North Carolina (9/25/80)
Atomic-Excitation Effects on Nuclear Reactions
30. Terry Fortune, University of Pennsylvania (10/2/80)
The Structure of Neutron Rich Light Nuclei from (t,p) Reactions
31. Michael Danos, National Bureau of Standards (10/9/80)
Does The Existence of Quarks Change Our Notion of Nuclear Forces?
32. L. C. Biedenharn, Duke University, and Thomas Clegg, University
of North Carolina (10/16/80)
A Discussion of Recent Experiments on the Breakdown of Time
Reversal Invariance in the Interaction of Nuclear Particles
33. Peter Paul, State University of New York at Stony Brook
(10/23/80)
Are Heavy Ion Resonances Really Resonances?
34. Richard Anderson, University of North Carolina (11/13/80)
A Generalized Description for States in Odd-A Nuclei
35. Hideo Kitazawa, Tokyo Institute of Technology (11/20/80)
-production Cross Sections for Energetic Neutrons

APPENDIX V

GRADUATE DEGREES AWARDED - 1980

1. S. G. Glendinning, "Elastic and Inelastic Neutron Scattering Cross Sections for 10B, 11B, and 16O", Supervisor, E. G. Bilpuch
2. Bing-Hui Chou, "A Study of Inelastic Decay Amplitudes in 49V", Supervisor, G. E. Mitchell
3. K. B. Sales, "A High Resolution Study of Proton Resonances in 65Ga and 67Ga", Supervisor, G. E. Mitchell
4. W. A. Watson, "A High Resolution Study of Proton Resonances in 57Co", Supervisor, E. G. Bilpuch
5. A. G. Beyerle, "Double Differential Continuum Neutron Scattering Cross Sections in Iron and Nickel for Incident Energies of 7.5, 10.0 and 12.0 MeV", Supervisor, L. W. Seagondollar

APPENDIX VI

Articles Published, January 1980-December 1980
In Journal edited at TUNL by K. Way

Atomic Data and Nuclear Data Tables

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Correction to the Table of Differential
Polarization Coefficients for (Gamma,
Particle) Reactions

J. E. Monahan, R. J. Holt, and R. M.
Laszewski

Corrections to Literature Expressions for
Angular Distributions of Gamma Reactions
Initiated by Polarized Particles

R. G. Seyler and H. R. Weller

Multipole Operators in Semileptonic Weak and
Electromagnetic Interactions with Nuclei:
Harmonic Oscillator Single-Particle Matrix
Elements

T. W. Donnelly and W. C. Haxton

Thick-Target Measurements and Astrophysical
Thermonuclear Reaction Rates: Proton-Induced
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N. A. Roughton, M. R. Fritts, R. J.
Peterson, C. S. Zaidins, and C. J. Hansen

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Grotrian Diagrams for Highly Ionized Iron
FeVIII-FeXXVI

K. Mori, M. Otsuka, and T. Kato

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Electron Densities at the Nuclear Center and
Surface for "Mössbauer" Atoms: Obtained by
Relativistic Dirac-Fock Calculations

I. M. Band and V. I. Fomichev

Tables of $S_{nN}^{k,l,2}$ and s_{kn} for γ -Ray Perturbed
Angular Correlations with Quadrupole
Interactions

E. Dafni, R. Bienstock, M. H. Rafailovich,
and G. D. Sprouse

Tables of Linear-Polarization Mixing Coefficients
T. Aoki, K. Furuno, Y. Tagishi, S. Ohya,
and J.-Z. Ruan

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Differential Cross Sections for Ejection of
Electrons from Argon by Protons
M. E. Rudd, L. H. Toburen, and N.
Stolterfoht

Photoionization Cross Sections and
Photoelectron Angular Distributions for X-Ray
Line Energies into the Range 0.132-4.509 keV.
Targets: $1 \leq Z \leq 100$
I. M. Band, Yu. I. Kharitonov, and M. B.
Trzhaskovskaya

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New Catalogue of Recommended Alpha Energy and
Intensity Values
A. Rytz

Hartree-Fock Values of Some Atomic Integrals
Useful in Simplified LCAO-MO Calculations for
Molecules.
I. Atoms B, C, N, O, F
J. Wasilewski

Strengths of Gamma-Ray Transitions in $A = 45-90$
Nuclei
P. M. Endt

Erratum: Semiempirical Auger-Electron
Energies for Elements $10 \leq Z \leq 100$
F. P. Larkins

Erratum: Reduction of U_{15} Representations
Into SU_3 Irreducible Components
K. V. Krishna Brahman and R. D. Ratna Raju

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Calculations of Direct Coulomb M-Subshell
Ionization by Charged ParticlesDavid E. Johnson, George Basbas, and F. D.
McDaniel

Relativistic Radiationless Transition

Probabilities for Atomic K- and L-Shells

Mau Hsiung Chen, Bernd Crasemann, and Hans
MarkRecommended Standards for Gamma-Ray Energy
Calibration (1979)R. G. Helmer, P. H. M. van Assche, and C.
van der LeunAtomic Constants of Autoionization States of
Ions with $Z = 6, 8, 10-42$ in the Be
Isoelectronic Sequence

U. I. Safronova and T. G. Lisina

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Model Potential Method. $Z = 25-80$

L. N. Ivanov and E. P. Ivanova

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K. T. Cheng, Y.-K. Kim, and J. P. Desclaux