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**STUDIES OF NUCLEAR STRUCTURE USING
NEUTRONS AND CHARGED PARTICLES**

Final Progress Report

1 September 1997-31 August 1998

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TUNL XXXVII

PROGRESS REPORT

1 SEPTEMBER 1997-31 AUGUST 1998

TRIANGLE UNIVERSITIES NUCLEAR LABORATORY

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Introduction

The Triangle Universities Nuclear Laboratory (TUNL) – a collaboration of Duke University, North Carolina State University, and the University of North Carolina at Chapel Hill – has had a very productive year. The following reports cover parts of the first and second year of a three-year grant between the U.S. Department of Energy and the three collaborating universities.

During the current grant period TUNL physicists have achieved several major successes:

- **Neutron-neutron scattering length:**

The neutron-neutron scattering length a_{nn} was determined from our neutron-deuteron breakup data and, for the first time, an accurate value was obtained that agrees very well with the “two-body” result extracted from the π^- - d capture reaction. The analysis of our new π^- - d data measured at LANL also supports the earlier results obtained for a_{nn} from this reaction.

- **Meson-exchange currents:**

Additional measurements of the $^2\text{H}(\vec{p}, \gamma)^3\text{He}$ and $^1\text{H}(\vec{d}, \gamma)^3\text{He}$ reactions at very low energies have added significantly to our understanding of these reactions. From the 9 observables measured we determined the astrophysical S factor, the asymptotic D- to S-state ratio for ^3He , and the quartet-to-doublet M1 cross-section ratio, which provides a precision test of MEC effect treatments in three-nucleon calculations.

- **Double-beta decay:**

We have successfully installed a coincidence apparatus consisting of two large HPGe detectors and a NaI annulus veto shield to study double-beta decay transitions to excited 0^+ states. The observed background of 0.1 counts per keV^2 per year corresponds to a sensitivity for half-life time measurements of 10^{22} years.

- **The tensor force in the nucleon-nucleon interaction:**

By scattering longitudinally polarized neutrons from a longitudinally polarized proton target we determined the nucleon-nucleon tensor force from the analysis of our $\Delta = \Delta\sigma_L - \Delta\sigma_T$ total cross-section difference measurements between 5 and 20 MeV. Our high-accuracy data suggest that the tensor force is considerably larger than predicted by meson-exchange based nucleon-nucleon potential models.

- **Parity nonconservation in the nuclear interaction:**

We have analyzed a large number of our transmission and capture measurements performed at LANSCE. PNC effects were observed for almost all nuclei studied. The previously observed sign correlation in ^{232}Th is confirmed with greater statistical significance, but the signs of the other parity violations appear to be randomly distributed.

- **Astrophysical S factor:**

We have continued our measurements of $(\vec{p}, \gamma)$ reactions on p -shell nuclei in order to extract accurate astrophysical S factors.

- **^6Li D state:**

We have used $(^6\bar{L}i, d)$ reactions to determine the asymptotic D/S state ratio η for ^6Li to very high precision. Our result is the most accurate value obtained to date and it is considerably smaller than theoretically predicted.

- **Chaos in the nucleus:**

With the Compton-suppression spectrometer and the excellent beam energy resolution of ~ 200 eV, we continued our studies of resonances in the $^{29}\text{Si}(p, \gamma)^{30}\text{P}$ reaction in order to obtain a complete level scheme of ^{30}P . The measured elastic scattering and capture spectra limit the quantum numbers of both initial (resonant) and final states. The complete level scheme will not only provide a definitive study of the statistical properties of eigenvalues and transition-matrix elements in light nuclei, but will also clarify the effect of symmetry breaking on these quantities.

- **Neutron-proton scattering length and three-nucleon forces:**

The comparison of our accurate results obtained for a_{np} from the neutron-deuteron breakup reaction with the value measured in free neutron-proton scattering clearly shows that three-nucleon force effects are less important in three-nucleon scattering systems than previously thought.

- **Proton-deuteron scattering at low energies:**

We made scattering measurements of protons from deuterons and vice versa at center-of-mass energies of 430 and 666 keV. These experiments show that the discrepancy between rigorous 3N calculations and data for $A_y(\theta)$ and $iT_{11}(\theta)$ approaches the stunning value of 50% at the lowest energy, while the tensor analyzing powers are rather well described.

- **Sub-Coulomb α -transfer reactions:**

We have measured cross sections for the $^{12}\text{C}(^6\text{Li}, d)$ and $^{12}\text{C}(^7\text{Li}, t)$ reactions to the bound 6.92 and 7.12 MeV states in ^{16}O at sub-Coulomb energies. These measurements will provide new constraints on the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction rates.

- **Globular clusters:**

We have completed two studies relevant to the anomalous abundances of Na and Al observed in globular-clusters. Our new reaction rates may account for the observed Na-O anticorrelation, but it seems unlikely that these stars are producing Al at the expense of Mg, which suggests a primordial origin for this effect.

- **Holifield Radioactive Ion Beam Facility:**

Our first series of radioactive-beam measurements planned for HRIBF have been developed using stable beams. We are presently awaiting delivery of the first ^{17}F beam.

- **Polarized target:**

The TUNL dynamically polarized proton target was converted into a polarized deuteron target and the first $\vec{n}\text{-}\vec{d}$ total cross-section difference data $\Delta\sigma_L$ were obtained.

- **Low-Energy Nuclear Astrophysics laboratory:**

We have begun construction of the Low-Energy Nuclear Astrophysics (LENA) laboratory at TUNL. This state-of-the-art facility is designed to produce intense beams of protons with energies up to 1 MeV for measurements of astrophysically-interesting reactions.

- **Polarized ion source:**

Studies of intense (~ 5 mA) beams of ~ 0.5 eV hydrogen ions, emerging in a magnetically confined, 5 mm diameter column with electrons from ECR heated plasmas, have shown that these beams are extremely promising for providing a highly efficient ionization of polarized atoms by charge exchange.

- **Charged-particle parity violation studies:**

A 2π α -particle detector system with 64 segments consisting of 4 large silicon strip detectors is being used for charged-particle parity-violation studies in the $^{31}\text{P}(p,\alpha)^{28}\text{Si}$.

- **Gas-jet target:**

We are installing a windowless high-density recirculating gas-jet target that we acquired from the University of Erlangen.

- **Focal-plane detector for Enge split-pole spectrometer:**

We improved the reliability of our new focal-plane detector that dramatically enhances our high-resolution spectroscopy capabilities.

- **Nuclear data project:**

We completed the review "Energy Levels of Light Nuclei $A=20$ ". A preliminary version for $A=5$ has been completed and distributed. The review of $A=6$ is underway. We also increased our World Wide Web (WWW) service. Energy Level Diagrams in the style of Fay Ajzenberg-Selove for $A=4-20$ are available as well as a short version

of the Table of Isotopes which has information about $A=1-20$ nuclei. We added abridged versions of Fay Ajzenberg-Selove's most recent evaluations of $A=5-10$, and they are available online. We are currently working to make modified versions of all her compilations available online.

TUNL seeks to be on several of the nuclear physics research frontiers identified in the 1996 NSAC Long Range Plan. The TUNL research program focuses on the following areas:

- Precision test of parity-invariance violation in resonance neutron scattering at LANSCE/LANL.
- Parity violation measurements using charged-particle resonances in $A=20-40$ targets at TUNL.
- Chaotic behavior in the nuclei ^{30}P and ^{34}Cl from studies of eigenvalue fluctuations in nuclear level schemes.
- Search for anomalies in the level density (pairing phase transition) in $1f-2p$ shell nuclei.
- Chaotic behavior in the nucleus ^{166}Ho from studies of amplitude correlations in neutron resonances.
- Nuclear astrophysics, using the refurbished Enge split-pole spectrometer, the Low-Energy Beam Facility, a new 200 keV accelerator for high-intensity unpolarized beams, and the KN accelerator (all at TUNL); facilities at HRIBF, Argonne, and Caltech; and the HIGS facility presently under construction at Duke's FELL. Emphasis is placed on the following topics:
  - abundance anomalies in globular clusters
  - explosive nucleosynthesis in novae
  - evolution of massive stars
  - origin of galactic radioactivity
  - the solar neutrino problem
- Neutrino studies at KamLAND and ORLAND.
- Few-body nuclear systems, with specific experiments to address:
  - radiative-capture reactions on hydrogen isotopes to investigate non-nucleonic degrees of freedom
  - the role of three-nucleon forces in the 3N and 4N continuum using hadronic and electromagnetic probes

- the strength of the tensor force in the NN interaction
  - search for “scaling” in the three-nucleon continuum
  - the $A_y(\theta)$ and iT_{11} puzzles in 3N scattering
  - the quark structure of nucleons in experiments at Bates and JLAB
- Study of double- β decay to excited 0^+ states
- High-spin spectroscopy and superdeformation
- Nuclear Data evaluation for $A=3-20$ for which TUNL is now the international center. Extensive services are provided through our WWW site and are constantly being improved.

Developments in technology and instrumentation are vital to our research and training program. We continued our innovative work in:

- polarized beam development
- polarized target development
- new cryogenic systems
- new detectors
- new polarimeters for charged particles and γ rays
- improving high-resolution beams for the KN and FN accelerators
- development of an unpolarized Low-Energy Beam Facility for radiative capture studies of astrophysical interest.

We submitted a proposal to DOE to develop an intense beam of polarized γ rays. This High-Intensity Gamma-ray Source (HIGS) will utilize the facilities of the Duke Free-Electron Laser Laboratory (DFELL). The DFELL currently includes a 500 MeV LINAC injector, a 1.1 GeV electron storage ring, and the OK-4 undulator. It is possible to tune the electron beam in a manner which allows the FEL photons produced by one electron bunch to backscatter from a second electron bunch, all within the ring. This leads to an intense beam of almost 100% polarized γ rays whose energy can be readily tuned from about 2 MeV to greater than 200 MeV. Furthermore, beam energy spreads of less than 1% can be obtained by purely geometrical collimation. In order to achieve the full range of energies, it will be necessary to upgrade the energy of the injected beam to 1.2 GeV and to make modifications in the electron beam optics in the FEL storage ring.

Funds for upgrading the injected beam energy to 1.2 GeV, which will allow us to produce γ rays up to about 220 MeV, will constitute the major part of the proposal.

In the development of polarized targets we successfully converted the dynamically polarized proton target at TUNL into a vector polarized deuteron target.

With respect to innovative detector and target developments, we have installed a unique detector system to study double-beta decay transitions to excited states. We are improving our recently installed focal-plane detector for the Enge spectrometer, and are testing a recirculating gas-jet target.

The Nuclear Data Evaluation project for nuclei $A=3-20$, which was moved to TUNL in 1990, continues not only to benefit our local research, but is also providing an important service to the international nuclear physics community.

The TUNL seminar program continues with characteristic vigor (32 invited speakers), supplemented by 20 in-house lectures on TUNL instrumentation and safety procedures and 7 lectures on Advances in Physics. A related program, the Triangle Nuclear Theory seminars, is also beneficial to TUNL faculty and students.

The talents and enthusiasm of the 18 faculty members, 11 research staff and post-doctoral associates, and 30 graduate students from the three Triangle universities are responsible for the successes of our research program. We also benefit from collaborations with Tennessee Technological University, North Georgia College and State University, North Carolina A&T State University, Shaw University, North Carolina Central University, State University of New York-Geneseo, Idaho State University, Gettysburg College, China Institute of Atomic Energy and Tsinghua University (Beijing), Jagellonian University (Cracow), and Istituto Nazionale di Fisica Nucleare (Pisa).

The TUNL Advisory Committee - Drs. David Balamuth (University of Pennsylvania), Baha Balantekin (University of Wisconsin), James Friar (Los Alamos National Laboratory), Gerald Garvey (Los Alamos National Laboratory), and Steven Vigdor (Indiana University) - continues to provide valuable advice on the research program.

The research summaries presented in this progress report are preliminary. They should not be referenced in other publications. If you wish to know the current status of a project, please contact the person whose name is underlined in the author list.

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Izzo, J.	NCSU
Jackson, M.	Duke
Jaye, C.	Shaw Univ.
Kirkwood, B.	UNC
Liu, A.	St. Mary's College
Mahar, K.	Tennessee Tech. Univ.
Monk, V.	UNC
Perdue, B.	North Georgia
Pierce, B.	Duke
Puryear, J.	NCSU
Ram, A.	Duke

Reisner, W.	Reed College
Schieber, D.	UNC
Seagroves, S.	UNC
Sieman, J.	UNC
Sorrenti, M.	Duke
Spencer, T.	NCSU
Staples, N.	NCA&T
Stoute, N.	NCSU

1 Fundamental Symmetries in the Nucleus

1.1 Parity-Mixing Measurements

1.1.1 Parity Violation with Polarized Epithermal Neutrons (The TRIPLE Collaboration) - General

B.E. Crawford, G.E. Mitchell, N.R. Roberson, S.L. Stephenson¹, and other members of the TRIPLE Collaboration²

The nucleon-nucleon force consists of the strong parity conserving (PC) interaction and the weak parity nonconserving (PNC) interaction. The PNC interaction has a strength of order 10^{-7} relative to the PC interaction. The weak interaction can be detected by measurement of appropriate pseudo-scalar observables. Resonances formed with polarized low-energy neutrons show strong PNC effects. The weak interaction causes the mixing of nuclear levels of the same spin and opposite parity. In heavy nuclei the combination of statistical and kinematic enhancements amplify the PNC effects by 10^4 to 10^6 in the helicity dependence of the neutron cross section.

The TRIPLE collaboration uses the high-flux epithermal neutron beam available at the Manuel Lujan Neutron Scattering Center (MLNSC) at the Los Alamos Neutron Scattering Center (LANSCE) to study the neutron-nucleus weak interaction. The longitudinal asymmetry is measured for neutron energies up to several hundred eV. The analysis treats the PNC matrix elements as random variables. Our initial results for ^{238}U and ^{232}Th yielded root-mean-squared PNC matrix elements with values $M \approx 1$ meV, in agreement with theoretical estimates. The ^{232}Th data showed an unexpected result – all of the longitudinal asymmetries had the same sign, instead of the expected random signs. All of the many attempts to explain the ‘sign effect’ as a general feature of the weak neutron-nucleus interaction failed. The early data are summarized in two review articles [Bow93, Fra93].

Following these initial results, we developed a new large-area, high-polarization proton target for polarizing the neutron beam, a new neutron detector for transmission experiments with large samples, and a large solid angle pure CsI detector for capture experiments with isotopic samples. With the new experimental system, we first performed transmission measurements on ^{238}U and ^{232}Th (repeating our initial measurements), obtained new transmission data on natural In and Ag, and performed a capture measurement on ^{113}Cd (with

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a preliminary version of the capture detector). Following these measurements the focus was on targets in the mass $A \approx 100$ region. The motivation was to determine the mass dependence of the weak neutron-nucleus effective interaction. Transmission measurements were performed on natural Nb, Rh, Pd, Sb, Xe, I, and Cs, and capture measurements on the separated isotopes $^{104,105,106,108,110}\text{Pd}$, ^{107}Ag , and ^{121}Sb .

The most important result is that the sign correlation in the ^{232}Th longitudinal asymmetries was confirmed. Excluding ^{232}Th , the new data (combined with a few older measurements) yield longitudinal asymmetries which have approximately 38 plus values and 25 negative values (the sign of the 0.7-eV resonance in ^{139}La is arbitrarily taken as positive). This suggests that the sign correlation observed in ^{232}Th is specific to that nuclide, and is not a general feature of the weak nucleon-nucleus interaction. This result has led to a number of new, local doorway state models.

We have also improved the analysis in several ways. Initially the PNC longitudinal asymmetries were determined with an empirical single-level code. There were several difficulties: (1) a multi-level analysis is often required, (2) the shape of the background flux can be appreciably distorted (by strong neighboring s -wave resonances) from the typical smooth energy dependence, (3) the observed resonance shape is dominated at higher energies by the asymmetric beam energy resolution function, (4) the effects of Doppler broadening and the beam energy resolution cannot be simulated by one symmetric convolution. We have written a multi-level code that addresses all of these (and other) concerns. The data are now being reanalyzed with this new code. In addition, the determination of the rms PNC matrix element M from the longitudinal asymmetries has been extended to include targets with spin and to situations where only partial spectroscopic information is available. The status of the data and analysis for each target is summarized in the next section.

An overall perspective on these results is given in a forthcoming review article [Mit99], where we consider parity violation in the compound nucleus as an example of the breaking of a discrete symmetry by a weak interaction in a chaotic system.

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1.1.2 Parity Violation with Polarized Epithermal Neutrons (The TRIPLE Collaboration) - Status of Experiments and Analysis

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²³²Th – Thorium was remeasured in transmission with the improved experimental system. For all practical purposes thorium is monoisotopic. The data have been reanalyzed with the new comprehensive code. Analysis of 24 *p*-wave resonances from 8 to 300 eV yields 10 statistical significant PNC effects, all of which have the same sign. A paper on ²³²Th has been published in Phys. Rev. C.

²³⁸U – The uranium target was remeasured in transmission with the improved system. Since the target was depleted to 0.2% ²³⁵U, the target was essentially ²³⁸U. The data have been reanalyzed with the new code. Analysis of 24 *p*-wave resonances yields five PNC effects. The value of *M* is very close to that obtained in the earlier measurement. A paper on ²³⁸U has been published in Phys. Rev. C.

¹¹⁵In – Natural indium (95.7% ¹¹⁵In and 4.3% ¹¹³In) was studied in transmission. An enriched ¹¹⁵In target was also studied with the capture detector. These measurements significantly improved the neutron spectroscopy for ¹¹⁵In [Fra93]. In addition the group at IRRM, Geel has now studied an enriched ¹¹⁵In target, with an emphasis on resonance spin determination. Preliminary analysis of 36 *p*-wave resonances yielded seven PNC effects. These data are being reanalyzed with the new code utilizing the new spin assignments.

¹⁰⁷Ag – Natural silver (51.8% ¹⁰⁷Ag and 48.2% ¹⁰⁹Ag) was studied in transmission. An enriched ¹⁰⁷Ag target was studied with the capture detector. These measurements significantly improved the neutron spectroscopy for ¹⁰⁷Ag [Low97]. The group at IRRM, Geel, has studied this same enriched target with an emphasis on the resonance spin determination. Analysis yields eight PNC effects. These results are being prepared for publication.

¹⁰⁹Ag – The combination of measurements described above identified new resonances in ¹⁰⁹Ag. In addition, neutron capture has been studied with an enriched ¹⁰⁹Ag target at IRRM, Geel. Analysis yields four PNC effects. These results are being prepared for publication.

¹⁰⁵Pd – Natural Pd was studied in transmission and in capture. A number of PNC effects are observed, most of which are in ¹⁰⁵Pd, which has a much higher level density than the even Pd isotopes. Preliminary analysis indicates seven PNC effects.

¹⁰⁶Pd – An enriched ¹⁰⁶Pd target was studied with the capture detector. Analysis yields one PNC effect. The combination of this capture measurement and the transmission

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measurement for natural Pd made significant improvement in the neutron spectroscopy for ^{106}Pd . A paper on the neutron spectroscopy for ^{106}Pd and ^{108}Pd has been published in Phys. Rev. C.

^{108}Pd – An enriched ^{108}Pd target was studied with the capture detector. Analysis indicates one PNC effect.

Note – Since natural Pd is a mixture of many isotopes, other enriched isotopic targets ($^{104,110}\text{Pd}$) were also studied with the capture detector to aid in isotopic identification of new resonances.

^{113}Cd – An enriched ^{113}Cd target was studied with the capture detector. Analysis yielded three PNC effects. A paper on these results has been accepted for publication in Phys. Rev. C.

^{93}Nb – Natural niobium (100% ^{93}Nb) was studied in transmission. No PNC effects were observed. However, the absence of effects yielded an upper limit for the rms matrix element and consequently a limit for the weak spreading width. These results are being prepared for publication.

^{103}Rh – Natural rhodium (100% ^{103}Rh) was studied in transmission. Four PNC effects were observed.

^{117}Sn – An enriched ^{117}Sn target was studied with the capture detector. Six PNC effects were observed.

Sb – Natural (57.25% ^{121}Sb and 42.75% ^{123}Sb) antimony was studied in transmission. An enriched ^{121}Sb target was studied with the capture detector. Five PNC effects were observed in ^{121}Sb and one PNC effect in ^{123}Sb .

^{127}I – Natural iodine (100% ^{127}I) was studied in transmission. Seven PNC effects were observed.

^{133}Cs – Natural cesium (100% ^{133}Cs) was studied in transmission. One PNC effect was observed.

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1.1.3 Parity-Violation Tests with Charged Particles

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The neutron resonance parity-violation experiments (see preceding sections) have been performed at the $3p$ and $4p$ neutron strength function maxima near $A = 100$ and $A = 230$. Parity-violation tests in light or medium mass nuclei would be of special value to determine the mass dependence of the weak spreading width. Since the neutron resonance measurements are not feasible in light nuclei, we are performing parity-violation experiments using charged particles.

High-resolution (p,p) and (p,α) resonance data from TUNL exist for the targets ^{23}Na , ^{27}Al , ^{31}P , ^{35}Cl , and ^{39}K . For 331 resonance pairs with the same J and different π , the values of $A_z(\theta)$ and $A_x(\theta)$ were calculated for the (p,p_0) and (p,α_0) reactions. We focus on A_z and the (p,α_0) reaction. Perturbed reduced-width amplitudes were obtained using first-order perturbation theory; internal mixing was assumed. Differential cross sections were then calculated for a longitudinally polarized proton beam using experimentally determined resonance parameters. Since the longitudinal analyzing power $A_z(\theta)$ is proportional to the parity violating matrix element V , the ratio A_z/V is a convenient measure of the relative enhancement.

The results depend dramatically on energy, angle, and the specific resonance parameters. These calculations are described in two recent papers [Shr94, Mit96]. Of course, the true quantity of interest is A_z , not the enhancement factor A_z/V . Although the determination of V is the goal of the measurement, an estimate for the average value of V can be obtained by assuming a value for the weak spreading width $\Gamma_W = 2\pi|V|^2/D(J)$, where $D(J)$ is the local average level spacing for resonances with spin J . Assuming that the weak spreading width is equal to the value obtained in the TRIPLE measurements for heavy nuclei yields an estimate for V_{rms} for each resonance pair. These estimates are usually between 50 and 150 meV, with values for A_z ranging from 10^{-3} to 10^{-7} . Measurements at the 10^{-4} level would provide significant new information – this level of sensitivity is our initial goal.

From our calculations for the enhancement one can estimate the time required to measure V at a given level for a particular pair of resonances. Incorporating beam intensity, target thickness, solid angle, and detector efficiency into a constant k , then for a figure-of-merit $\beta = \left[\left(\frac{A_z}{V} \right)^2 \frac{d\sigma}{d\omega} \right]$, the time required to determine V at a level V_0 is $t_0 = k/[\beta(V_0)^2]$. One can invert this procedure and ask what limit is set on V if one measures for a time t_0 and no parity violation is observed. We focus on the target ^{31}P . For the eight resonance pairs with the largest values of the figure of merit β , the limits placed on V by a null result

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after one day of measurement would average about 25 meV. This limit would constrain Γ_W to be much less than the value measured in heavy nuclei. Therefore, even a set of null results would be quite important.

These experiments require stability of the polarized beam energy, position, and polarization direction. We have examined the possible sources of systematic errors in these experiments, and evaluated monitoring and control methods for these systematic errors. These methods (for performing precision measurements of parity violating asymmetries in charged-particle resonances) are discussed in a recent publication [Wil97].

A recently installed stripper bias amplifier has reduced the energy fluctuations due to accelerator voltage fluctuations significantly – equivalent to terminal voltage fluctuations of approximately 30 V. An improved slit feedback steering system has been constructed to provide the necessary improvements in beam position stability. Since the counting rates are a concern, a large solid-angle detector is of particular value. The sign of the parity violation often changes with angle, making a segmented detector essential. There are a number of examples where the difference in the net effect for a single detector and a segmented detector is two orders of magnitude.

We have constructed an array of silicon strip detectors that subtends approximately 80% of 2π at backward angles. The detector array is segmented by 16 in polar angle θ and 4 in azimuthal angle ϕ , for a total of 64 individual detector elements. Sixteen-channel preamplifiers provide energy and timing outputs, with the energy signals going directly to charge-integrating analog-to-digital converters. Gates for the ADC's are generated from the timing signals by constant-fraction discriminators. By using short shaping times (300 ns) and gates (75 ns), pulse pile-up is kept to a minimum at high counting rates.

Typical operating conditions involve polarized protons (polarization 80%, beam current 0.5 μ A) on a ^{31}P target (10 mg/cm² with a 2 mg/cm² carbon backing). In tests of individual detector strips, the detectors performed very well, with good energy resolution and low pile-up. We then scaled up the data acquisition to 64 simultaneous channels, and again the system performed very well. A sample spectrum is shown in Figure 1.1-1 for one of the detector strips. Results for 16 spectra are shown in Figure 1.1-2. Preliminary measurements have now been performed with both transverse and longitudinally polarized beams. The next steps are to quantify the systematic errors arising from remnants of transverse polarization in the longitudinally polarized beam, effects due to different characteristics of the polarized beam in different helicity states, etc.

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Figure 1.1-1: Counts versus ADC channel for a single detector strip at 145 degrees. The left most peaks correspond to elastic protons scattered from Carbon and Phosphorous. The proton counts have been reduced by a factor of 30. The large peak is from alpha particles.

Figure 1.1-2: Counts versus ADC channel for all 16 detector strips in one of the four 16-strip arrays. The spectrum from each strip is offset (successively) by 512 channels in order to fit the spectra from all 16 strips into one combined spectrum. An angular dependence in the α cross section is apparent. From left to right the angles of the detectors range from 112 degrees to 165 degrees.

1.2 Quantum Chaos in Nuclei

1.2.1 Transition-Strength Distributions

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Because of the stringent data requirements for energy-level statistics, other signatures of chaos in quantum systems are highly desirable. One approach which has been used is the examination of transition-strength distributions; these have been studied within the framework of several models [Alh92, Mer93], and it has been suggested that the strengths follow a $\chi^2(\nu = 1)$ distribution if the system is chaotic and a $\chi^2(\nu < 1)$ distribution if the system is regular. We began our study by examining the distribution of reduced transition probabilities calculated for the nuclide ²²Na using the shell-model code OXBASH. A large number of B(M1) and B(E2) values were examined, and the distributions were consistent with a χ^2 distribution with $\nu = 1$ [Ada97].

Next, we applied the techniques developed for ²²Na to experimental data from ²⁶Al [Ada84, End88, End88b]. We found that the reduced transition probability distributions were no longer described by a χ^2 distribution [Ada98] and suggested that this might be a manifestation of the broken isospin symmetry. Unfortunately, there is at present no theoretical guidance on this particular aspect of transition distributions, and the question of why these distributions do not follow a χ^2 distribution remains open.

A recent study by Hamoudi *et al.* [Ham98] has added an additional question. They study B(M1) and B(E2) distributions in shell-model calculations for $A = 60$. The B(E2) distributions agree with a $\chi^2(\nu = 1)$ distribution, but the B(M1) distribution sometimes deviates from that behavior. In particular, they observe that “a significant deviation from the GOE statistics is observed for self-conjugate nuclei ($T_z = 0$).” Since we did not observe such a dependence in the $A = 22$ system, this may suggest a mass-dependence for the transition strength distribution. As part of our experimental study of ³⁴Cl, we have calculated B(M1) and B(E2) matrix elements for positive-parity states in ³⁴Cl using OXBASH. We shall study the distributions of these matrix elements to test whether the behavior is consistent with or different from behavior in the ²²Na system.

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1.2.2 Energy-Level Statistics

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One means of studying chaos in quantum systems is examination of the energy-eigenvalue statistics. This dates back to the conjecture [Boh84] that quantum analogs of classically chaotic systems are described by the gaussian orthogonal ensemble (GOE) of random matrix theory. Subsequent studies have confirmed this conjecture in general and also shown that quantum analogs of classically regular systems obey Poisson statistics.

Testing eigenvalue distributions requires data of extremely high quality, since incomplete or impure data bias the results [Shr92]. Resonance states in a variety of nuclides have yielded data of sufficient quality to apply these tests, and the data show excellent agreement with the GOE for a variety of tests [Haq82, Boh85, Shr87, Lom94]. The conclusion from these tests is that nuclei above the particle separation energy are generally chaotic. A remaining question is whether nuclei may be chaotic even near the ground state or whether there is a transition from regular to chaotic behavior as the excitation energy increases. However, data to address this question are sparse. The only nuclide with data known sufficiently well over the entire range from the ground state into the resonance region is ²⁶Al; level spacing distributions in this case lie between the GOE and Poisson limits [Shr90]. Near the ground state, data from different nuclides have been combined and suggest a mass dependence of the level spacing distribution, ranging from GOE behavior for light masses to Poisson behavior for heavy masses [Shr91].

To further examine this question, we are studying the (p,γ) reaction with the goal of establishing nearly complete level schemes in two additional nuclides, ³⁰P and ³⁴Cl. The study of ³⁰P is advanced, while the ³⁴Cl measurements are just beginning. The first step in our studies was to identify all resonant states by collecting ²⁹Si(p,γ) excitation functions with ultrahigh resolution proton beams and NaI detectors. Sixteen previously unknown

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states in ^{30}P were identified, and (p,γ) strengths were determined for the first time for 46 resonances [Fra92, Vav97].

Next, branching ratios were measured for 45 $^{29}\text{Si}(p,\gamma)$ resonances with $E_p < 2.51$ MeV (above this energy, the increasing level density made measurements more difficult) [Wal96, Vav97]. The γ -ray strengths were combined with proton widths [Nel83] to yield γ -ray widths, which were then combined with the branching ratios to give reduced transition probabilities for many of the transitions. These transition probabilities were compared to the recommended upper limits (RULs) of Endt [End93] to help assign spins J , parities π , and isospins T for each state. For a number of states, this resulted in the unique $J^\pi; T$ assignment required for a complete level scheme. However, for a number of states, some ambiguity remained.

Our next step has been to measure $^{29}\text{Si}(p,\gamma)$ angular distributions. These can provide the desired information in several ways. One is that the observed distribution may not be consistent with a given choice of initial and final state quantum numbers. If so, this limits possible $J^\pi; T$ assignments. These measurements also can determine γ -ray mixing ratios for specific transitions, which then allow more detailed comparisons with RULs that are available from branching ratios alone. Angular distributions have been measured thus far for 27 resonances whose $J^\pi; T$ assignment is ambiguous or which feed a state with an ambiguous assignment. Both primary and secondary γ rays are used in the analysis. Several resonances remain to be studied in this way.

At this point it is clear that the angular distributions will not eliminate all of the ambiguities. We are considering the use of polarized beam measurements to help with such cases. As a test we expect to measure elastic scattering with a polarized beam at a few resonances in the near future.

As stated earlier, the ^{34}Cl measurements are just beginning. The first step there is identification of resonance states in $^{33}\text{S}(p,\gamma)$ excitation functions and determination of their γ -ray strengths.

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2 Internucleon Reactions

2.1 Neutron-Proton Interaction

2.1.1 Measurements of Spin-Dependent $\vec{n} - \vec{p}$ Total Cross Sections

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We have recently completed a series of measurements of the spin-dependence of the $\vec{n} - \vec{p}$ total cross section in the transverse ($\Delta\sigma_T$) and longitudinal ($\Delta\sigma_L$) configurations. Measurements of $\Delta\sigma_T$ and $\Delta\sigma_L$, when combined with the known $n - p$ total cross section, allow a model-independent extraction of the three phase shifts, $^1S_0$, $^3S_1$, and ϵ_1 , which characterize the NN interaction at low energy (see Sect. 2.1.2).

The measurements utilized a newly developed dynamically polarized proton target. The target material was propanediol chemically doped with EHBA Cr(V) complex and had a nominal thickness of 0.06 b^{-1} . The target was maintained at 0.5 K by a ^3He evaporation refrigerator in a 2.5 T magnetic field. Dynamic polarization allows for rapid reversing of the target polarization, an important consideration when measuring small asymmetries. Proton polarization of order 60% was routinely achieved, measured with NMR and with low-energy neutron transmission.

The beams of polarized neutrons were produced as secondary beams from charged-particle reactions. The $^3\text{H}(p,n)^3\text{He}$ reaction was used below 5 MeV neutron energy, and the $^2\text{H}(d,n)^3\text{He}$ reaction was used at higher energies. The polarized ion beams were produced by the TUNL ABPIS, and the spins were flipped at a rate of 10 Hz.

The transmitted neutron flux at 0° was counted by a 5 in. diameter liquid scintillator. Pulse-shape discrimination was used for neutron selection. A small liquid scintillator placed after the neutron production cell monitored the incident neutron flux.

Results of the TUNL measurements of $\Delta\sigma_T$ and $\Delta\sigma_L$ are shown in Figure 2.1-1. Also included in the figure are recent Prague measurements and the Nijmegen phase-shift predictions. The cross-section results follow the trend of the Nijmegen predictions. However, deviations are apparent which imply values of ϵ_1 systematically larger than potential-model predictions. See Sect. 2.1.2 for a detailed comparison of ϵ_1 predictions with our experimental results.

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Figure 2.1-1: Plot of $\Delta\sigma_L$ (top panel) and $\Delta\sigma_T$ (bottom panel) data in the energy range 0 to 25 MeV. The Nijmegen phase-shift prediction is shown. The TUNL data are shown as asterisks with the Prague measurement shown as a triangle. The error bars are the sum in quadrature of the statistical and systematic uncertainties.

2.1.2 Extraction of the Mixing Angle ϵ_1 for n - p Scattering

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The individual spin-dependent n - p total cross-section differences $\Delta\sigma_L$ and $\Delta\sigma_T$ have been previously measured at TUNL ([Wil93, Rai97, Wal98]). The observable $\Delta = \Delta\sigma_L - \Delta\sigma_T$ is sensitive to the phase shift ϵ_1 which characterizes the strength of the NN tensor interaction at low energy, and relatively insensitive to other phases.

The mixing parameter ϵ_1 was determined from the experimental data through a single-energy χ^2 minimization of the quantity Δ . The quantity

$$(\Delta(\epsilon_1) - \Delta_{exp})^2 \quad (2.1)$$

was minimized through varying ϵ_1 , where Δ_{exp} is the experimental determination of the observable at the energy of interest. The quantity $\Delta(\epsilon_1)$ is the observable calculated from the phase shifts obtained from the Nijmegen partial-wave analysis. $\Delta(\epsilon_1)$ was calculated using

$$\begin{aligned} \Delta = & \frac{-2\pi}{k^2} \sum_{J=0}^{\infty} \left\{ (2J+1)(\sin^2 \delta_{J,J} - \sin^2 \epsilon_J) \right. \\ & - \cos 2\epsilon_J [(J-1)\sin^2 \delta_{J,J-1} + (J+2)\sin^2 \delta_{J,J+1}] \\ & \left. - 3\sqrt{J(J+1)} \sin 2\epsilon_J \sin(\delta_{J,J-1} + \delta_{J,J+1}) \right\}, \end{aligned} \quad (2.2)$$

where the $\delta_{J,\ell}$ are the phase shifts for the (J, ℓ) state. The phase $\delta_{J,J+1}$ is the only nonzero phase with $J = 0$. For the minimization, Eq. 2.2 was evaluated using $J \leq 6$. The minimization began with the Nijmegen partial-wave prediction for ϵ_1 , and this phase was varied until a minimum for Eq. 2.1 was reached.

The results of the minimization are shown in Figure 2.1-2. The determination of ϵ_1 at 19.71 MeV was performed without $\Delta\sigma_T$ experimental data. Again, a χ^2 minimization was carried out, but with respect to $\Delta\sigma_L$, using the following equation:

$$\begin{aligned} \Delta\sigma_L = & \frac{-2\pi}{k^2} \sum_{J=0}^{\infty} \left\{ (2J+1)(\sin^2 \delta_{J,J} - \sin^2 \delta_J) \right. \\ & + \cos 2\epsilon_J [\sin^2 \delta_{J,J-1} - \sin^2 \delta_{J,J+1}] \\ & \left. - 2\sqrt{J(J+1)} \sin 2\epsilon_J \sin(\delta_{J,J-1} + \delta_{J,J+1}) \right\}. \end{aligned} \quad (2.3)$$

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Figure 2.1-2: Plot of Δ data in the energy range 0 to 25 MeV. The Nijmegen phase-shift prediction is shown. The TUNL data are shown as asterisks with the one Prague measurement shown as a triangle. The error bars are the sum in quadrature of the statistical and systematic uncertainties.

Figure 2.1-3: Plot of ϵ_1 in the energy range 0 to 60 MeV. Shown are the Bonn B meson-exchange potential model, the Nijmegen and VPI phase-shift predictions and the TUNL, Erlangen, Bonn, PSI and Prague experimental determinations. The error bars are the sum in quadrature of the statistical and systematic uncertainties.

Figure 2.1-3 shows a plot of the TUNL experimental determinations of ϵ_1 alongside the previous data, potential-model and partial-wave predictions.

The low values of ϵ_1 measured by the groups at Erlangen and Bonn between 10 and 20 MeV are not supported by our new data. Also, our values of ϵ_1 follow the trend of the potential-model predictions but are systematically higher. This is in agreement with the results of the Bonn and PSI analyses at 25 and 50 MeV, respectively. However, our data do not support the 1998 phase-shift analysis of the VPI group which predicts values of ϵ_1 different from the potential models even below 10 MeV.

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[Wal98] J. R. Walston, Ph.D. thesis, North Carolina State University, 1998.

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2.1.3 On the $^3S_1$ - $^3D_1$ Mixing Parameter ϵ_1 Discrepancy Near $E_n = 15$ MeV

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Very recently, the Bonn group [Clo98] reported the results of a new measurement of the polarization-transfer coefficient $D_t(133^\circ)$ in $\vec{n} + p \rightarrow n + \vec{p}$ scattering at $E_n = 16.1$ MeV. The extracted value obtained for the $^3S_1$ - $^3D_1$ mixing parameter ϵ_1 in n - p scattering turned out to be negative, in agreement with the earlier measurement of $D_t(133^\circ)$ by the same group at $E_n = 17.4$ MeV [Ock91], but in disagreement with theoretical models and nucleon-nucleon (NN) phase-shift analysis predictions as well as with the TUNL results [Wal98] and a value published by the Prague group [Bro97], both based on the analysis of $\vec{n} + \vec{p}$ total cross-section difference measurements. Because the Erlangen/Tübingen result [Sch88] for ϵ_1 at $E_n = 13.7$ MeV based on the analysis of a $\vec{n} + \vec{p}$ $A_{yy}(90^\circ)$ measurement is also negative, we investigated the sensitivity of the observables measured in the experiments referred to above to various NN interactions that are important at these low energies.

Table 2.1-1 summarizes our results obtained at $E_n = 17$ MeV for 10% changes of the Nijmegen NI93 [Sto93] $^1S_0$ and $^3S_1$ NN phase shifts. Clearly, the observables A_{yy} , D_t , $\Delta\sigma_T$ and $\Delta\sigma_L$ are all very sensitive to $^1S_0$ and $^3S_1$. The observable $\Delta = \Delta\sigma_L - \Delta\sigma_T$, on which the TUNL ϵ_1 results are based, is not sensitive at all to singlet phase shifts and the sensitivity to $^3S_1$ is very small. Since the n - p total cross section σ_{tot} is very accurately known, $^1S_0$ and $^3S_1$ cannot be changed independently. Therefore, we also show in Table 2.1-1 results where we increased $^1S_0$ by 10% and lowered $^3S_1$ by 10%. As can be seen, this approach changes σ_{tot} by only 0.3% and the observed large sensitivity of $A_{yy}(90^\circ)$ could explain the

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small value found for ϵ_1 in the Erlangen/Tübingen analysis, but not the Bonn result based on $D_t(133^\circ)$. However, the close agreement of the individual TUNL $\Delta\sigma_T$ and $\Delta\sigma_L$ results [Wal98] with theoretical expectations rules out even small variations of $^1S_0$ and especially of $^3S_1$. Therefore, if the theoretical values for ϵ_1 are correct, the Erlangen/Tübingen result for $A_{yy}(90^\circ)$ cannot be reconciled, unless higher partial waves play an unexpectedly large role. The same statement holds for the Bonn results.

Table 2.1-1: Sensitivity (change in percent) of neutron-proton observables (first column) at $E_n = 17$ MeV to a 10% increase of the phase-shift parameter $^1S_0$ (second column), and a 10% decrease of $^3S_1$ (third column), and to the combined effect of a 10% increase of $^1S_0$ and a 10% decrease of $^3S_1$ (fourth column). For comparison, the last column gives the sensitivity to a 10% increase of the mixing parameter ϵ_1 . The minus (positive) sign indicates the percentage decrease (increase) of the value for the observables of interest.

Observable	$^1S_0 \times 1.10$	$^3S_1 \times 0.90$	$^1S_0 \times 1.10$ $^3S_1 \times 0.90$	$\epsilon_1 \times 1.10$
$A_{yy}(90^\circ)$	23.4-	13.2-	44.8-	2.9+
$D_t(133^\circ)$	30.4-	24.1+	0.8-	1.6+
$\Delta\sigma_T$	27.9-	6.7-	39.4-	2.1-
$\Delta\sigma_L$	135-	17.8-	271	12.0+
$\Delta = \Delta\sigma_L - \Delta\sigma_T$	0	0.8-	0.8-	10.0+
σ_{tot}	2.3+	2.0-	0.3+	0

Table 2.1-2: Same as Table 2.1-1, but for p -wave NN phase shifts.

Observable	$^3P_0 \times 1.10$	$^3P_1 \times 1.10$	$^3P_2 \times 1.10$	$^3P_0 \times 0.98$ $^3P_1 \times 0.95$ $^3P_2 \times 1.05$	$^1P_1 \times 1.10$
$A_{yy}(90^\circ)$	0.4+	0.4+	0.1+	0.3-	0
$D_t(133^\circ)$	0.8-	1.4-	0.4+	1.2+	0.4+
$\Delta\sigma_T$	0.6+	0	0	0.1-	1.2+
$\Delta\sigma_L$	1.5-	1.6+	0.2+	0.4-	3.0-
$\Delta = \Delta\sigma_L - \Delta\sigma_T$	1.9+	1.7+	0.1-	0.1+	0
$A_y(63^\circ)$	18.2-	13.6+	9.8+	0.2+	0.2+

Table 2.1-2 summarizes the sensitivity to the p -wave NN phase-shift parameters $^3P_0$, $^3P_1$, $^3P_2$, and $^1P_1$. As can clearly be seen, these phase-shift parameters have no sizeable influence on the observables of interest. The ^3P_j sensitivity is extremely small, especially

for ${}^3P_j$ combinations that do not alter the analyzing power $A_y(63^\circ)$ (fifth column). The sensitivity to d - and f -wave NN phase shifts is even smaller.

We conclude from our sensitivity study that unknown instrumental effects must be responsible for the negative ϵ_1 values reported by the Erlangen/Tübingen and Bonn groups near $E_n = 15$ MeV.

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 [Wal98] J. R. Walston, Ph.D. thesis, North Carolina State University, 1998, and references therein.

2.1.4 Results of the TUNL Neutron-Proton Scattering Length Experiment

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A complete meson-exchange description of the reaction dynamics in few-nucleon systems requires the consistent inclusion of exchange diagrams for two-nucleon (2N) and multi-nucleon interactions. Though the need for multi-nucleon diagrams is generally accepted, they are usually ignored at low energies, even in the most sophisticated calculations [Glö96]. The reasoning behind this general practice is that the estimated size of the influence of multi-nucleon forces on observables is normally smaller than the accuracy of experimental data and does not warrant the enormous increase in computational complexity caused by their inclusion. Even in the three-nucleon (3N) system, which is the most theoretically developed few-nucleon system studied at low energies, multi-nucleon forces are usually neglected. In the case of the 3N system, the only multi-nucleon force is that involving three nucleons, i.e., the 3N force. The decision to neglect 3N forces is certainly sound since these calculations [Glö96] predict with high precision most data using only 2N interactions. However, in the midst of the impressive success of the parameter-free rigorous 3N calculations using

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2N interactions, there are some significant and persistent discrepancies between calculations and experimental data. Some of these discrepancies are suggestive of the actions of 3N forces and provide fairly convincing evidence that the dynamics of the 3N system is too complicated to be represented using iterated pairwise interactions alone [Fri83]. One long-standing failure of 3N calculations is the triton binding energy problem. Rigorous calculations made with realistic 2N potential models fail to predict the triton binding energy by about 800 keV out of 8 MeV. The most credible fix of this problem has been the inclusion of 3N interactions [Gib88]. Most 3N forces arise from the neglect of the nucleon substructure in meson-exchange models. Using a chiral Lagrangian, van Kolck [vK94] estimated the effective shift in the strength of the 2N potential due to 3N-force contributions to be about 5%. This amount is sufficient to account for the additional attraction needed to correctly bind the triton and is consistent with meson-exchange 3N-potential models [Fri83]. Van Kolck's results were also in agreement with the observation that 2N potentials with a weaker than normal tensor force component, and consequently a stronger central potential, predict a more tightly bound triton than those with a standard tensor-force strength [Mac89]. Another example of a discrepancy that may be due to 3N forces is the difference in the $^1S_0$ neutron-neutron (nn) scattering length (a_{nn}) determined from the $^2\text{H}(\pi^-, nn\gamma)$ reaction (-18.5 ± 0.3 fm [Mil90]) and the value obtained from kinematically-complete neutron-deuteron (nd) breakup (-16.73 ± 0.47 fm [Šla89]) experiments, where there are three nucleons in the exit channel.

In this work we use the amplification features of the nucleon-nucleon (NN) scattering length to set an empirical upper limit on the size of the effective shift in the $^1S_0$ neutron-proton (np) potential due to the aggregate of all 3N-force contributions in the nd system. In our study we determine the $^1S_0$ a_{np} from absolute cross-section measurements of the np final-state-interaction (np FSI) in nd breakup. The measurements are made at an incident neutron energy of $E_n = 13.0$ MeV for three production angles ($28.0^\circ, 35.5^\circ, 43.0^\circ$) of the np pair. All measurements were made at TUNL using the shielded neutron source on the 20° beam line off the first analyzing magnet. A value of a_{np} is determined at each angle from a single-parameter χ^2 analysis of the cross-section data. The measured cross sections are compared to Monte-Carlo simulations which include the energy resolution and the finite geometry of our experimental setup. The simulations are made using rigorous Faddeev calculations as input. In order to produce cross sections that correspond to different values of a_{np} , a modified version of the Bonn-B (OBEPQ) NN potential [Mac89] was used that permitted adjustment of the σ - nucleon coupling constant to give different values for a_{np} . The comparison of our results to the highly accurate value of a_{np} obtained from free np scattering sets a limit on the effective shift in the strength of the $^1S_0$ np force due to the aggregate of all 3N-force diagrams.

The analysis of our data is complete, and the results are shown in Table 2.1-3. As can be seen, there is no significant angle dependence in the value of a_{np} obtained from our data. The main sources of the ± 0.8 fm systematic uncertainty are the uncertainties in absolute neutron

detection efficiency and the integrated target-beam luminosity. Combining the statistical and systematic uncertainties in quadrature, we obtain a final value for $a_{np} = -23.5 \pm 0.8$ fm. Our result is in agreement with the value of a_{np} (-23.749 ± 0.008 fm [Mil90]) obtained from 2N-scattering data and can be used to set an upper limit on the effective shift in the np $^1S_0$ potential strength due to 3N-force contributions.

Table 2.1-3: Results of TUNL a_{np} experiment.

Angle ($^\circ$)	a_{np} (fm)	Error (fm)
43.0	-23.6	± 0.3
35.5	-23.2	± 0.3
28.0	-23.7	± 0.3
Average	-23.5	± 0.2 (stat) ± 0.8 (syst)

The variation of the scattering length with the strength of the nuclear potential can be estimated using effective-range theory and low-energy approximations. The fractional change in the NN scattering length ($\frac{\delta a}{a}$) due to a shift in the NN potential strength ($\frac{\delta V}{V}$) is given by,

$$-\frac{\delta a}{a} = \frac{a}{b} \left(\frac{\pi}{2} \right)^2 \frac{1}{2} \frac{\delta V}{V} = -1.23 \frac{a}{b} \frac{\delta V}{V}. \quad (2.4)$$

In the above equations the b symbol is the effective range parameter. For the case of the $^1S_0$ np potential, $a/b = -23.8/2.7$, giving the result that $\delta a/a = -10.8(\delta V/V)$. Therefore, a 1% shift in the np potential strength results in about an 11% change in a_{np} . The modification of a_{np} in the nd system is $\delta a_{np} = a_{np}^{2N} - a_{np}^{3N} = -0.3 \pm 0.8$ fm. The corresponding effective shift in the np potential strength is $\delta V/V = 1.15 \times 10^{-3} \pm 3.07 \times 10^{-3}$. Setting the limit at the three-sigma level, the upper limit on the effective shift in the $^1S_0$ np potential strength due to 3N forces is $|\delta V/V| < 0.01$. This result is the first empirically determined limit on the relative strengths of the 2N and 3N forces. It is a factor of about five smaller than the value estimated by van Kolck [vK94] for the NN $^3S_1$ potential. Though these findings suggest an extremely small influence of 3N forces, caution is urged in the interpretation of these results. Since the relative contributions of 3N-force terms are likely to be strongly energy and geometry dependent, the findings reported here are most valid under similar conditions of this study, that is, in the nd continuum at energies around 9 MeV in the $c.m.$ system.

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2.2 Neutron-Neutron Interaction

2.2.1 Measurement of the $^1S_0$ Neutron-Neutron Scattering Length Using the $^2\text{H}(\pi^-, nn\gamma)$ Reaction: LAMPF E1286

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The violation of charge symmetry in the strong nuclear force is now well documented and has been found to have its origins at the quark level [Mil90]. Most observed charge-symmetry-breaking (CSB) effects can be explained as being primarily due to the differences in the masses of the d and u quarks with a minor contribution from their electromagnetic differences [Mil90]. These differences are reflected in the dispersion in the hadron masses and in the values of the ρ - ω and π - η mixing amplitudes within meson-exchange potentials [Mil90].

The difference between the nuclear force parts of the neutron-neutron (nn) and proton-proton (pp) $^1S_0$ scattering lengths, $a_{nn}-a_{pp}$, is one of the most direct measures of CSB, and therefore of the d - u quark mass difference. Measuring the scattering lengths to the accuracy needed to address charge-symmetry issues is challenging. The a_{pp} has been measured directly using two-nucleon scattering to a high experimental precision ($a_{pp} = -7.8063 \pm 0.0026$ fm) [Mil90]. However, there is a large theoretical uncertainty in the procedure for extracting the nuclear part ($a_{pp}^N = -17.3 \pm 0.4$ fm). The situation is different for a_{nn} ; the experimental and theoretical uncertainties are each around ± 0.5 fm and direct measurements using two-nucleon scattering are currently not viable. The standard technique is to use a reaction that emits two neutrons with low relative momentum and to measure the cross section for the final-state interaction (FSI) enhancement. The presently recommended value [Mil90] for a_{nn} is based on two measurements of the π^- - d capture reaction made at the PSI in Switzerland by the same group. The first was a measurement of the energy spectrum of the outgoing γ rays using a high-resolution and high-stability pair spectrometer [Gab84]. The second measurement was a kinematically complete measurement in which the γ rays were detected in coincidence with one of the outgoing neutrons [Sch87].

In this section we report our results for a_{nn} from the LAMPF E1286 $^2\text{H}(\pi^-, \gamma n)n$ ex-

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periment. Neutrons were detected by an array of 24 liquid organic scintillators, and the associated γ rays were detected in one arm of the LAMPF neutral meson spectrometer (NMS). Data were accumulated for both double-coincidences (DC) (the γ ray and one neutron were detected) and for triple coincidences (TC) (the γ ray and both neutrons were detected). For both types of data the momenta of all detected particles were measured, thereby fully determining the reaction kinematics in the case of the DC events and overdetermining the kinematics in the TC measurements. A total of 1.9×10^6 DC events and 5.7×10^4 TC events were stored on tape. The value of a_{nn} was determined from the shape of the measured neutron time-of-flight (NTOF) spectrum of the DC data.

Because the shape of the NTOF spectrum is strongly dependent on θ_3 , the NTOF spectra were analyzed for six cuts on θ_3 . The θ_3 angle is the supplement of the opening angle between the momentum vectors of the γ ray and the detected neutron. Each θ_3 cut was 0.05 radian wide, and the first cut started at $\theta_3 = 0$. The measured NTOF for the interval $0.05 < \theta_3 \leq 0.10$ radian is shown in Figure 2.2-1 in comparison to Monte-

Figure 2.2-1: a) The top plot is a comparison of the shape of the experimental NTOF spectrum with that of the Monte Carlo (MC) simulated TOF spectrum for a θ_3 cut between 0.05 and 0.1 radian. The spectra are for the entire neutron-detector array. b) The total χ^2 vs. a_{nn} .

Carlo (MC) simulations made with different values of a_{nn} . The theoretical cross sections used in the simulations were computed using the formula given by Gibbs, Gibson and Stephenson [Gib75]. The strong peak around channel 530 (a neutron energy of about 9 MeV) comes from quasifree $p\pi^-$ capture, and the broad enhancement around channel 800 (about 2.4 MeV) is due to the nn FSI. A value of a_{nn} was determined for each θ_3 cut from a χ^2 analysis implemented by comparing the NTOF spectrum to MC simulations (see the bottom of Figure 2.2-1). Our analysis was limited to θ_3 values less than 0.3 radians to keep the influence of the effective range parameter small. A θ_3 dependence in the values of a_{nn} would indicate a systematic problem with our technique.

Our results are summarized in Table 2.2-1. The uncertainties given in the table are statistical only. The main sources of systematic uncertainties come from uncertainties in the neutron detection efficiency (± 0.29 fm) and the finite-geometry modeling (± 0.31 fm). There is also a ± 0.30 fm theoretical uncertainty. Our final value is $a_{nn} = -18.50 \pm 0.05 \pm 0.44 \pm 0.30$ fm. The uncertainties are statistical, systematic and theoretical, respectively. Combining the present results with those from the two measurements done at PSI gives $a_{nn} = -18.59 \pm 0.27 \pm 0.30$ fm and makes the experimental error (± 0.27 fm) on a_{nn} slightly less than the theoretical uncertainty (± 0.30 fm) and gives a_{nn} to an accuracy similar to that of a_{pp} . Correcting for the nn magnetic interaction of 0.34 ± 0.01 fm [Mil90] and combining the experimental and theoretical uncertainties in quadrature, we obtain $a_{nn}^N = -18.9 \pm 0.4$ fm. We conclude that CSB in the nucleon-nucleon $^1S_0$ scattering lengths is $\Delta a_{CSB} = a_{pp}^N - a_{nn}^N = 1.6 \pm 0.6$ fm, which is consistent with a $d-u$ current quark mass difference of 4 MeV.

Table 2.2-1: Values of a_{nn} (fm) obtained with increasingly more complete MC simulations. The uncertainties are statistical only.

θ_3 Range (rad)	Finite Geometry	Finite Geom. + Scatt.	Full MC
0.00 to 0.05	-17.70 ± 0.15	-18.60 ± 0.15	-18.43 ± 0.12
0.05 to 0.10	-17.80 ± 0.15	-18.70 ± 0.15	-18.34 ± 0.09
0.10 to 0.15	-17.90 ± 0.15	-18.80 ± 0.15	-18.47 ± 0.09
0.15 to 0.20	-17.70 ± 0.15	-18.60 ± 0.20	-18.92 ± 0.13
0.20 to 0.25	-17.50 ± 0.25	-18.30 ± 0.20	-18.60 ± 0.22
0.25 to 0.30	-17.90 ± 0.45	-18.30 ± 0.25	-18.48 ± 0.24
Weighted average:	-17.75 ± 0.07	-18.61 ± 0.07	-18.50 ± 0.0492

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2.2.2 Results of the TUNL Neutron-Neutron Scattering Length (a_{nn}) Experiment

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The $^1S_0$ neutron-neutron scattering length (a_{nn}) is an especially sensitive parameter to the interaction strength between two neutrons with near-zero relative momentum [dT89]. The currently accepted a_{nn} value (-18.6 ± 0.3 fm) [Mil90] is derived exclusively from two π^-d capture-reaction experiments, in disagreement with the average of -16.73 ± 0.47 fm extracted from kinematically-complete $n-d$ breakup experiments [Šla89]. This discrepancy could be due to deficiencies in the older analyses of the $n-d$ breakup data and/or three-nucleon force (3NF) effects acting on the exit channel.

A kinematically-complete $n + d \rightarrow n + n + p$ breakup experiment at an incident neutron energy of 13.0 MeV was performed at TUNL to either resolve or understand the discrepancy between the values of a_{nn} extracted from the π^-d and kinematically-complete $n-d$ breakup experiments. The $n-d$ breakup events corresponding to two neutrons with nearly equal momentum in the exit channel (neutron-neutron final state interaction or $n-n$ FSI) were detected by triple coincidences between a deuterated scintillator target and two neutron detectors placed one behind the other at an angle θ_{nn} with respect to the incident neutron beam axis. The energies of the neutrons in the exit channel were determined by their time of flight from the deuterated scintillator target to their corresponding neutron detector. The energy of the proton was obtained from the pulse height of the signal it produced in the deuterated scintillator target. Having completed more than 2500 hours of data taking, we have achieved a statistical precision better than $\pm 5\%$ on the cross-section peak for the four $n-n$ FSI configurations studied ($\theta_{nn} = 20.5^\circ, 28.0^\circ, 35.5^\circ, 43.0^\circ$).

The data analysis was based on rigorous Faddeev calculations of the $n-d$ breakup differential cross sections using three realistic NN-interaction potentials: The Bonn-B [Mac87] and charge-dependent Bonn (CD Bonn) meson-exchange potentials [Mac96], and the Nijmegen I potential [Sto94]. Cross-section libraries were prepared for different values of a_{nn} and incorporated into Monte-Carlo simulations that calculate the $n-n$ FSI cross sections for the four $n-n$ FSI configurations including the energy-resolution, energy-spread and finite-geometry effects of the experimental setup. We extract values for a_{nn} for each $n-n$ FSI configuration by direct comparison between simulated cross sections obtained for different

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values of a_{nn} and experimental cross sections. A systematic dependence of a_{nn} on the production angle θ_{nn} would indicate the presence of a 3NF [Šla89].

Values for a_{nn} were extracted by means of χ^2 fits of Monte-Carlo calculated finite-geometry cross sections based on the three NN interactions to the experimental absolute cross-section data (see Table 2.2.2), obtaining an average $a_{nn} = -18.7 \pm (0.1)_{stat} \pm (0.6)_{syst}$ fm.

Table 2.2-2: The table on the left shows a_{nn} values extracted from each n - n FSI configuration using MC cross sections generated by the Bonn B, CD Bonn and Nijmegen I NN potentials. The systematic uncertainties originate from a $\pm 5\%$ systematic error in the experimental absolute cross sections. The table on the right shows a_{nn} values and associated errors extracted from the shapes of three n - n FSI cross-section curves.

$\theta_{nn} (^\circ)$	a_{nn} (fm)	Δa_{nn}^{stat} (fm)	Δa_{nn}^{syst} (fm)	$\theta_{nn} (^\circ)$	a_{nn}^{shape} (fm)	Δa_{nn}^{shape} (fm)
Bonn B				Bonn B		
20.5°	-18.9	± 0.2	± 0.6	20.5°	-19.0	± 0.7
28.0°	-18.8	± 0.2	± 0.6	28.0°	-18.3	± 0.9
35.5°	-17.7	± 0.4	± 0.6	35.5°	-18.8	± 1.2
43.0°	-18.8	± 0.4	± 0.7	CD Bonn		
CD Bonn				20.5°	-19.1	± 0.6
20.5°	-18.9	± 0.2	± 0.7	28.0°	-18.3	± 0.9
28.0°	-18.6	± 0.3	± 0.7	35.5°	-18.8	± 1.3
35.5°	-17.8	± 0.3	± 0.6	Nijmegen I		
43.0°	-18.6	± 0.4	± 0.6	20.5°	-19.1	± 0.6
Nijmegen I				28.0°	-18.4	± 0.9
20.5°	-19.2	± 0.2	± 0.8	35.5°	-18.9	± 1.3
28.0°	-18.8	± 0.3	± 0.7			
35.5°	-18.0	± 0.3	± 0.6			
43.0°	-18.7	± 0.4	± 0.6			

In addition, χ^2 fits of MC cross-section calculations were done to the *shape* of the experimental cross section with floating normalization (see Table 2.2.2) obtaining an average $a_{nn} = -18.8 \pm 0.5$ fm. Our values of a_{nn} are in agreement with the values quoted in Ref. [Mil90], resolving the π^- - d vs n - d breakup discrepancy.

Calculations were made to study the effect on a_{nn} of the Tucson-Melbourne (TM) 3NF [Coo79] with a form factor cutoff parameter $\Lambda = 4.856m_\pi$ and using CD Bonn for the NN part of the interaction (reproducing the binding energy of ^3H). As can be seen from Figure 2.2-2, the effect of the TM 3NF on a_{nn} diminishes considerably when compared to the case when $\Lambda = 5.8m_\pi$, consequently, for $\Lambda = 4.856m_\pi$ the effect of the TM 3NF on a_{nn} is not perceptible given the size of the error bars of the experimentally-determined a_{nn} values. Given the lack of a strong θ_{nn} angle dependence of a_{nn} we can conclude that 3NF effects

on these n - n FSI configurations are small and cannot be responsible for the π^- - d vs n - d breakup discrepancies observed in the past.

Figure 2.2-2: Comparison of the effect of the TM 3NF on a_{nn} ($\Delta a_{nn} = a_{nn}^{NN+TM3NF} - a_{nn}^{NN}$) with the difference between the experimentally-extracted a_{nn} and the currently accepted value $a_{nn} = -18.6$ fm.

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2.2.3 Progress of a_{nn} Measurement from a Kinematically Incomplete n - d Breakup Experiment

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We are collecting data for the measurement of the neutron-neutron (nn) scattering length (a_{nn}) from the neutron-deuteron (n - d) breakup reaction $n + d \rightarrow n + n + p$ in a kinematically incomplete geometry. The energy distribution of the protons near $\theta_p = 0^\circ$ is observed from the nd breakup reaction ${}^2\text{H}(n,p)nn$ for $E_n = 14$ MeV. The experiment is intended to resolve the inconsistency of a_{nn} values from similar experiments performed near 14 MeV [Hai77, Shi73] after re-analysis of the data using a realistic nucleon-nucleon potential in three-body calculations [Tor93, Wit88].

The experiment utilizes the Enge split-pole magnetic spectrometer at TUNL [Cha94] and a new multi-wire position sensitive proportional counter [Hal96] as the focal-plane detector. Improved performance of the TUNL Enge Spectrometer and significant design changes in the focal-plane detector [Hal97] have permitted development runs for study of systematic effects in the proton spectrum from the ${}^2\text{H}(n,p)nn$ reaction. The neutrons were produced by bombarding a deuterium gas target with a deuteron DC beam. The deuterium gas target was 2.12 mg/cm² thick (3.1 cm long with 4.0 atmospheres of pressure). The deuteron beam energy was 11.35 MeV and there was an average of 2.5 μA beam current on target.

The proton spectrum from the ${}^2\text{H}(n,p)nn$ reaction at forward angles exhibits a sharp peak near the maximum proton energy. This enhancement is due to the nn final-state interaction (FSI) in the ${}^1\text{S}_0$ state. The height and shape of the FSI peak is a sensitive measure of the a_{nn} parameter [Tor96]. We have observed the nn FSI peak from the ${}^2\text{H}(n,p)nn$ reaction at $E_n = 14$ MeV and $\theta_p = 0^\circ$. We used a CD_2 solid target with a thickness of 14 mg/cm². Protons from the reaction were analyzed by the Enge spectrometer and their positions were detected by the focal-plane detector. Figure 2.2-3 is a sample position histogram of the detected protons. The foreground and the background (blank target ring) measurements are overlaid. The total data accumulation time for these histograms was 16 hours (10 hours on the foreground and 6 hours on the background measurement). Figure 2.2-4 is the background subtracted proton spectrum. Measurements have been made also with a thinner CD_2 target approximately 3 mg/cm² thick, and a narrower peak was observed. Analysis is underway and Monte-Carlo simulations are being developed to determine the contributions in the spectrum due to finite target-geometry effects.

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Figure 2.2-3: Position spectrum of protons measured in the foreground and background (normalized) of the $^2\text{H}(n,p)nn$ reaction.

Figure 2.2-4: Proton spectrum (foreground minus background) from the $^2\text{H}(n,p)nn$ reaction.

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2.3 Proton-Deuteron Scattering

2.3.1 Proton-Deuteron Elastic Scattering at $E_{c.m.}=432$ keV

C.R. Brune, B.M. Fisher, W.H. Geist, H.J. Karwowski, E.J. Ludwig, K.D. Veal, and M.H. Wood

During the past year we have performed measurements of the absolute p - d scattering cross section by comparison to the well-known p - p cross section. The results are shown in Figure 2.3-1 along with theoretical calculations done by the Pisa group [Kie97] utilizing the AV18 NN plus Urbana 3N potential. These data serve to normalize our previously measured relative cross sections and complete our measurements at this energy.

Figure 2.3-1: Absolute p - d cross section measured at $E_{c.m.} = 432$ keV (squares). The solid curve is a theoretical calculation using the AV18+UR potential.

With $\sigma(\theta)$, A_y , iT_{11} , T_{20} , T_{21} , and T_{22} data now in hand, a phase-shift analysis can be performed. Assuming that the AV18+UR phases are correct for the $l \geq 2$ partial waves, the S- and P-wave phase shift parameters can be determined within 0.5° or better. In general, the empirical phase shifts are in excellent agreement with the theoretical predictions. However, a few of the P-wave parameters differ significantly from theoretical predictions – a discrepancy which underlies the well-known “ A_y puzzle.” The A_y and iT_{11} data and various predictions are shown in Figure 2.3-2. Whether this discrepancy is due to inadequacies in the NN interaction, the 3N interaction, or other new physics is presently unknown, but this problem cannot be solved by considering standard 3N force models. A paper describing the A_y and iT_{11} measurements and their interpretation has recently been published [Bru98].

Empirically, the discrepancy is related primarily to just two p - d phase shift parameters: $^4P_{1/2}$ and $\varepsilon_{3/2}^-$. Using the AV18+UR results for the other phase-shift parameters, we find that agreement with our A_y and iT_{11} data is optimized if the absolute values of the $^4P_{1/2}$

Figure 2.3-2: Experimental A_y and iT_{11} for p - d scattering at $E_{c.m.} = 432$ keV (circles), along with theoretical calculations using the AV18 (solid curve) and the AV18+UR potentials (short-dashed curve). The long-dashed curve results from modifying the ${}^4P_{1/2}$ and $\epsilon_{3/2}^-$ phases as described in the text.

and $\epsilon_{3/2}^-$ parameters calculated assuming AV18+UR are reduced by 1.6% and increased by 15%, respectively. The A_y and iT_{11} calculated using these modified phase-shift parameters are also shown in Figure 2.3-2. These changes also lead to subtle but statistically significant improvements in the description of the tensor analyzing powers.

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2.3.2 Cross Section and Tensor Analyzing Powers for Proton-Deuteron Scattering at $E_{c.m.} = 0.667$ MeV

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Three-nucleon systems for which the scattering process can be calculated exactly provide fundamental tests of our understanding of nuclear interactions. Direct comparison of model calculations with experimental p - d and n - d scattering below the deuteron-breakup threshold shows generally very good agreement for cross sections and tensor analyzing powers [Kie97]. These calculations utilize the Pair-Correlated Hyperspherical Harmonic basis with realistic 2N and 3N potentials [Kie95]. There is, however, a large discrepancy between these calculations and the measurements of the vector analyzing powers, which is increasing with decreasing energy to reach 40% at $E_{c.m.} = 432$ keV [Bru98].

Two previous measurements [Koc69, Hut83] of the cross section at $E_{c.m.} = 667$ keV differ by as much as 4% at the forward angles. Our goal is to obtain a complete set of analyzing power and cross-section data at $E_{c.m.} = 667$ keV. By choosing this slightly higher energy and using the experimental techniques developed by our previous measurements, a greater accuracy of the data can be achieved. This data set will allow for a phase-shift analysis of p - d scattering and provide a more stringent test of the calculations. To date, the cross section, T_{20} , and T_{22} have been measured.

For the measurement of the $^1\text{H}(d,d)^1\text{H}$ scattering cross section, an unpolarized deuteron beam was produced by the DENIS source and accelerated by the FN tandem to $E_d = 2.0$ MeV. The 20° - 70° analyzing magnet established the beam energy and directed the beam into the 61-cm diameter scattering chamber. The targets employed for this experiment were ≈ 10 $\mu\text{g}/\text{cm}^2$ hydrogenated carbon foils. The relative cross section was obtained with two pairs of symmetrically-placed silicon detectors with angular separations of 10° . Deviations in beam position and target thickness were cancelled out with an additional two pairs of symmetrically-placed silicon detectors fixed in the reaction plane at $\theta_{lab} = 15^\circ$ and 42° . A plot of the relative cross section with respect to $\theta_{c.m.}$ is shown in Figure 2.3-3.

To obtain the absolute cross section, the $^1\text{H}(d,d)^1\text{H}$ yield at $E_d = 2.0$ MeV was measured relative to the well-known $^1\text{H}(p,p)^1\text{H}$ cross section [Ber90] at $E_p = 4.0$ MeV. The deuteron and proton beams were produced simultaneously by the DENIS source. The beams were switched on target by only changing the setting of the inflection magnet after the source and doubling the tandem terminal voltage. The beam position was easily reproduced for both beams since the magnetic rigidity is the same for proton and deuteron beams. The beam-switching procedure was repeated four times on four individual targets. The runs were short to keep the target deterioration small ($< 3\%$). The monitor detectors remained in their previous positions. The angular settings of 25° and 35° in the lab for the chamber detectors were chosen because the background under the peaks of interest is minimal, and

the lab cross sections are insensitive to angle. The analysis of the absolute cross-section measurement is in progress.

Furthermore, T_{20} and T_{22} angular distributions for $^1\text{H}(\vec{d},d)^1\text{H}$ scattering were measured. The polarized deuteron beam was produced by the TUNL atomic beam polarized ion source. As with the cross section, the experiments were conducted in the 61-cm scattering chamber, and the targets were $\approx 20 \mu\text{g}/\text{cm}^2$ hydrogenated carbon foils. The polarization of the beam was determined online at $E_d = 2.0 \text{ MeV}$ with a calibrated polarimeter [Ton80] which sat behind the scattering chamber and is based on the $^3\text{He}(\vec{d},p)$ reaction. The analysis of the data will be completed in the upcoming months.

Figure 2.3-3: Relative cross sections for p - d scattering at $E_{c.m.} = 667 \text{ keV}$. The solid curve is the calculations of Kievsky *et al.* The circles and squares are the experimental data normalized to the calculations by the most forward-angle data point. The errors are smaller than the symbols.

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2.3.3 The Energy Dependence of the Nucleon-Deuteron Analyzing Power Puzzle

*W. Tornow and H. Witala*¹

The recent p - d analyzing power $A_y(\theta)$ data of Brune *et al.* [Bru98] at $E_p = 650$ keV and their comparison to 3N calculations using the AV18 NN potential [Wir95] show that the discrepancy $(A_y^{exp} - A_y^{cal})/A_y^{exp}$ at the maximum of the $A_y(\theta)$ angular distribution is 0.41 compared to 0.38 at $E_p = 2.5$ MeV and 0.35 at $E_p = 3.0$ MeV [Kie96]. Clearly, the discrepancy between data and calculations decreases slowly with increasing energy. For n - d scattering the associated ratio stays fairly constant at 0.27 between $E_n = 3$ MeV and 14.1 MeV, although the experimental uncertainties are much larger in this case [Tor91]. The comparison of p - d $A_y(\theta)$ data and n - d calculations between $E_N = 30$ MeV and 65 MeV suggests that the $A_y(\theta)$ discrepancy is already very small at 30 MeV and non-existent anymore at $E_N = 50$ MeV and 65 MeV [Glö96]. Of course, here we have assumed that Coulomb effects are small at these relatively high energies. This assumption is supported by the existing n - d data, although the experimental uncertainties are larger than those for p - d scattering [Glö96]. If the analyzing power puzzle is indeed caused by incorrect ^3P_j NN interactions used in the calculations, then the question arises whether the ^3P_j interactions are correct above about $E_N = 30$ MeV and incorrect only below this energy. In Ref. [Glö90] 3N calculations are presented for $A_y(\theta)$ at $E_n = 35$ MeV and 50 MeV. The results are compared to calculations where the ^3P_j interactions were turned off. It was found that the shape of the $A_y(\theta)$ angular distribution obtained in the full calculation resembles to some extent the shape obtained without ^3P_j interactions included. This finding could imply that $A_y(\theta)$ is not very sensitive anymore to the ^3P_j interactions at these high energies, i.e., the ^3P_j NN interactions could be wrong at higher energies, too. In fact, this was assumed in the work of Ref. [Wit91], where modified ^3P_j phase shifts were proposed in the entire energy range investigated (5 to 50 MeV).

In the present work we investigated the sensitivity of $A_y(\theta)$ to modifications of the ^3P_j NN interactions using the AV18 NN potential in rigorous 3N calculations. Our results for n - d scattering are shown in Figure 2.3-4 where the relative difference ΔA_y (in percent) between the original AV18 calculation and the modified ($^3P_j \times 1.10$) results at the positive maximum of $A_y(\theta)$ is given as a function of energy. Clearly, the $^3P_0$ and $^3P_2$ NN interactions remain fairly sensitive even at energies above 35 MeV. Surprisingly, the sensitivity at 35 MeV is only a factor of two lower than observed at 3 MeV. A 1% change in $^3P_0$ or $^3P_2$ results in a 1% change in $A_y(\theta)$ at the backward angle maximum. Therefore, considering the fact that there is close agreement between n - d (and p - d) data and n - d calculations at energies above 30 MeV, we conclude that the N - d analyzing power puzzle is a low-energy phenomenon, i.e., the ^3P_j NN interactions obtained from phase-shift analyses of NN data

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Figure 2.3-4: Sensitivity (measured in percent) of the calculated n - d $A_y(\theta)$ to 10% changes of the AV18 NN interactions (a) ${}^3P_0$, (b) ${}^3P_1$, and (c) ${}^3P_2$ as a function of neutron energy.

and used in NN potential models are correct above 30 MeV.

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2.3.4 Measurement of the Neutron-Deuteron Analyzing Power at $E_n = 2.0$ MeV

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According to rigorous three-nucleon calculations [Tor97], the relative difference between the magnitude of the neutron-deuteron (n - d) and proton-deuteron (p - d) analyzing power $A_y(\theta)$ in the angular region of the $A_y(\theta)$ maximum near $\theta_{c.m.} = 100^\circ$ increases dramatically with decreasing incident nucleon energy below $E_N = 3.0$ MeV. This behavior is due to the Coulomb interaction in the case of p - d scattering. Unfortunately, accurate n - d data do not exist below $E_n = 3.0$ MeV to check on this theoretical observation. In addition, data for the low-energy n - d $A_y(\theta)$ and their comparison to the existing high-accuracy p - d $A_y(\theta)$ data [Shi95] at the same energy provide a sensitive probe for studying possible charge-symmetry breaking (CSB) effects in the ^3P_j nucleon-nucleon (NN) interaction.

In order to study the issues mentioned above at very low energies, a n - d $A_y(\theta)$ measurement at $E_n = 2.0$ MeV is currently underway at TUNL. For this purpose we create a beam of transversely-polarized neutrons via the $^3\text{H}(\vec{p}, \vec{n})^3\text{He}$ reaction. The high-intensity atomic-beam polarized ion source (APBIS) provides a beam of polarized protons. After acceleration through the tandem accelerator (~ 3.01 MeV) the proton beam is then directed down the 38° beam leg onto a tritiated titanium target with a molybdenum beam stop. The beam current on target is in the order of $2 \mu\text{A}$. The resulting neutron beam is collimated by a polyethylene shield/collimator so that only the deuterated target and the neutron polarimeter's helium gas cell are directly illuminated by the neutron beam. The target or center detector (CD) consists of a glass vessel filled with NE-232 deuterated liquid scintillator with a cylindrical active volume 1.91 cm in diameter and 2.54 cm in height, mounted via a lucite light pipe onto a photo-multiplier tube. Neutron detector pairs are presently deployed to measure $A_y(\theta)$ at $\theta = 90^\circ, 72^\circ$ and 54° (lab). In addition, a neutron polarimeter monitors the neutron beam polarization at the same time the $A_y(\theta)$ data is acquired (see Figure 2.3-5.) The energy of the scattered neutrons is measured by time-of-flight (TOF.) The TOF start signals are provided by a coincidence between the CD and neutron detectors, and the stop signals are provided by the neutron detectors. Events due to n - d scattering produce a prominent peak in the TOF spectra for each neutron detector. Events falling in these n - d TOF peaks are gated and their associated CD pulse-height (CDPH) spectra due to recoil deuterons in the CD are generated for later analysis and extraction of $A_y(\theta)$. It is our goal to obtain a statistical accuracy of $\pm 3\%$ or better for $A_y(\theta)$ in the angular range of the $A_y(\theta)$ maximum.

Figure 2.3-5: Experimental setup for neutron-deuteron $A_y(\theta)$ measurement.

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2.3.5 Status of Neutron-Induced Deuteron Breakup Cross-Section Measurements at 16.0 MeV

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This ongoing experiment seeks to measure the absolute cross section of neutron-deuteron (n - d) breakup at 16.0 MeV for various orientations of the star plane³. The star configurations refer to the kinematic situations where the ejected nucleons have equal momenta in the center-of-mass system. It is our objective to achieve a statistical accuracy of $\pm 5\%$ or better in 0.5 MeV bins along the S curve at each star configuration. For our setup with an incident deuteron beam current of 2 μ A, the estimated aggregate trigger rate is 17 events/hour. Thus, approximately ten days of beam time are required for each orientation to reach our statistical precision goal.

Currently we have completed 390 hours of net data accumulation for the space-star configuration. This amount of data would be more than enough to reach our statistical goal; however, only a fraction of the data might be useable due to problems caused by the way we operate the charge-integrating ADCs. We have been aware for some time of a periodic "structure" in our time-of-flight (TOF) spectra gated by pulse-shape discrimination (PSD). A sample spectrum for one detector is shown in Figure 2.3-6. After running many tests offline with sources, we determined that the LeCroy 2249SG ADC has a time-dependent pedestal which in our circuit is proportional to the time difference between the ADC Start signal and the arrival of the Gate signal for a particular channel (approximately 1 count for every 50 ns of difference). This pedestal had the effect of "mixing" gamma and neutron events at low pulse heights. Because the ADC Start and Gate mimic the center and side detector timing respectively, trying to put a cut between the gamma and neutron events produces the nearly 50 ns periodic structure seen in our TOF spectra (see Figure 2.3-6).

We have more confidence in the data at neutron-detector threshold settings at and above $1 \times \text{Cs}$ (one times the electron recoil edge for γ rays from ^{137}Cs), because here the neutron and gamma events are very clearly separated in PSD. Attempts are being made to correct the pulse-height data for the time-dependent pedestal by using the TOF spectra, but little success has been made at this time. The problem has been resolved for future runs by replacing the LeCroy ADCs with the 7167 model from Phillips Scientific. We have tested this module with sources and confirmed that it can be operated in our circuit without producing a time-dependent pedestal.

A preliminary cross section from the analysis of our data is not available at this time, but we show a total energy spectrum ($E_{n1} + E_{n2} + E_p$) in Figure 2.3-7 for a portion of

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³For experimental setup and other aspects, refer to TUNL Progress Report XXXVI 1996-97, pp.42-44.

Figure 2.3-6: A time-of-flight spectrum for one detector gated by pulse-shape discrimination, showing an approximately 500 channel (50 ns) periodic “structure”.

Figure 2.3-7: Total energy spectra (foreground and background) for the space-star configuration at a $1 \times Cs$ software threshold setting. Note that this represents only about 80 hours of the total accumulated data.

the data accumulated with a threshold setting of $1 \times \text{Cs}$ on the neutron detectors. This spectrum is the sum of the energies of the two detected neutrons as determined from TOF and the energy of the recoil proton found from the center detector light-response function. The enhancement at about 13.8 MeV indicates our “true” breakup events (this energy is the difference between the 16.0 MeV incident neutron energy and the deuteron Q value of 2.225 MeV). After accidental subtraction a gate around the peak will be implemented and the net yield will be used to determine the breakup cross section. Our plan is to finish data accumulation for the space star in August 1998, with preparations for measuring the coplanar star to commence soon afterwards.

2.3.6 Scaling Properties of the Longitudinal and Transverse $\vec{n}\text{-}\vec{d}$ Total Cross-Section Differences

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Contrary to the low-energy three-nucleon (3N) continuum where rigorous 3N calculations using modern nucleon-nucleon (NN) interactions describe the available experimental 3N data very well [Glö96] (except for the notorious 3N analyzing power puzzle), the same NN interactions fail to reproduce correctly important 3N bound-state properties. For example, the binding energy of ^3H is underpredicted by about 500-800 keV, thus clearly indicating the need for a more complicated dynamics, i.e., three-nucleon forces (3NFs). At higher energies ($E_N > 60$ MeV) evidence is emerging that 3NFs are also needed to correctly describe 3N scattering data. The nucleon-deuteron differential cross-section [Wit98] and analyzing power data are better reproduced by 3N calculations when the Tucson-Melbourne (TM) 3NF [Coo79, Coo81] is added to the NN interactions.

It has been known for quite some time that certain 3N bound-state properties “scale” with the 3N binding energy, i.e., the theoretical predictions obtained using various NN interactions can be rather different, but they coincide, if a properly adjusted 3NF is added. Here, the cutoff parameter of the 3NF must be chosen such that the combination of NN and 3NF yields the experimental ^3H binding energy. Such a “scaling” phenomenon has not been observed yet in the low-energy continuum.

In our search for “scaling” at low energies, we have investigated the polarized neutron-polarized deuteron ($\vec{n}\text{-}\vec{d}$) total cross-section differences $\Delta\sigma_L = \sigma(\vec{\uparrow}\vec{\uparrow}) - \sigma(\vec{\uparrow}\vec{\downarrow})$ and $\Delta\sigma_T = \sigma(\vec{\uparrow}\vec{\downarrow}) - \sigma(\vec{\uparrow}\vec{\uparrow})$ for longitudinal ($\Delta\sigma_L$) and transverse ($\Delta\sigma_T$) geometry, respectively. We calculated $\Delta\sigma_L$ and $\Delta\sigma_T$ for neutron energies between 1 and 65 MeV by solving the 3N Faddeev equations using four modern NN interactions: AV18 [Wir95], CD Bonn [Mac96], Nijm I [Sto94], and Nijm II [Sto94]. All partial-wave states with total angular momentum $j_{max}=3$ in the two-nucleon subsystem were included. In addition, the TM 3NF with properly ad-

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Figure 2.3-8: Results obtained for $\Delta\sigma_L$. The symbols are explained in the text. Figure 2.3-9: The same as in Figure 2.3-8 but for $\Delta\sigma_T$.

justed cutoff parameter was used. It was found that the individual results obtained for $\Delta\sigma_L$ and $\Delta\sigma_T$ with only the NN interaction turned on differed by about 5 to 10% (depending on energy). However, including the 3NF reduced the scatter in the results dramatically to about 1 to 2% at incident neutron energies below 20 MeV (40 MeV for $\Delta\sigma_L$). In Figures 2.3-8 and 2.3-9 the individual symbols represent the ratio of $\Delta\sigma_L$ and $\Delta\sigma_T$, respectively, calculated without a 3NF and the average value of $\Delta\sigma_L$ and $\Delta\sigma_T$, respectively, obtained from four NN potentials plus the TM 3NF. This ratio deviates considerably from 1.0, especially in the zero-crossing energy region of $\Delta\sigma_L$ around 12 MeV, where the sensitivity to 3NFs becomes very large, thus making this observable an ideal probe for determining the importance of 3NF in the 3N continuum at low energies. Calculations based on NN interactions only predict a zero-crossing energy of about 11.8 MeV while the associated calculations using in addition the TM 3NF predict a zero-crossing energy of 12.2 MeV. The symbols joined by lines give the ratio of the $\Delta\sigma_L$ and $\Delta\sigma_T$ results, respectively, obtained for individual NN + TM 3NF force models and the average value based on all four NN + TM 3NF models studied in the present work. These ratios are close to 1.0, clearly showing "scaling" of the two observables in the low-energy continuum.

Measurements of $\Delta\sigma_L$ for $\vec{n}-\vec{d}$ are presently underway at TUNL to study these theoretical predictions.

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3 Dynamics of Very Light Nuclei

3.1 Four and Five-Nucleon Reactions

3.1.1 Polarization Transfer in the ${}^3\text{H}(\vec{p}, \vec{n}){}^3\text{He}$ Reaction and the 0^- Level in ${}^4\text{He}$

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We present results from measurements of the longitudinal and transverse polarization-transfer coefficients, $K_z^{z'}(0^\circ)$ and $K_y^{y'}(0^\circ)$ in the ${}^3\text{H}(\vec{p}, \vec{n}){}^3\text{He}$ reaction from 1.3 – 2.8 MeV. Previous data extended no lower than 4 MeV and 3 MeV proton energies, respectively [Jar74, Don71]. The new measurements were carried out in an energy range which corresponds to excitation of the 21.0 MeV 0^- second excited state of ${}^4\text{He}$ [Til92]. This narrow 0^- level lies close to the broad subthreshold 20.2 MeV 0^+ first excited state, and R -matrix calculations predict a very clear signature for the presence of these levels: values of $K_z^{z'}(0^\circ)$ approaching 1.0 at the peak of the 0^- resonance, with values of $K_y^{y'}(0^\circ)$ essentially zero.

The measurements were made possible by the development of a dynamically polarized proton target which could be used as a high-efficiency neutron spin analyzer [See95]. Using the polarized target required an order of magnitude less time per energy than conventional double-scattering measurements, and allowed us to map out the energy dependence over the whole energy range in a short amount of time. See [Wal98] for experimental details.

The value of $K_y^{y'}(0^\circ)$ at $E_p = 1.62$ MeV was found to be 0.086 ± 0.111 , where the neutron polarization was determined by double scattering. Results of the $K_z^{z'}(0^\circ)$ measurements are plotted in Figure 3.1-1. Error bars include both statistical and systematic uncertainties. The absolute calibration of the polarization times thickness for the proton target was determined from a separate double scattering experiment (at $E_p = 1.62$ MeV).

The most notable features of the data are the sharp resonance-like behavior of $K_z^{z'}(0^\circ)$ around $E_p = 1.52$ MeV, and the fact that $K_y^{y'}(0^\circ)$ is essentially zero at this same energy. Following the M -matrix formalism of La France and Winternitz [Fra80], the polarization-transfer coefficients are given by

$$\sigma_0 K_z^{z'}(0^\circ) = 2|M_{11}^{11}|^2 + 2\text{Re}\{M_{00}^{11*} M_{00}^{00}\}, \quad (3.1)$$

and

$$\sigma_0 K_y^{y'}(0^\circ) = 2\text{Re}\{M_{11}^{11*} (M_{00}^{11} + M_{00}^{00})\}, \quad (3.2)$$

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Figure 3.1-1: Comparison of TUNL experimental data for $K_z^{z'}(0^\circ)$ with previous data of Jarmer *et al.* [Jar74], and with an R -matrix calculation based on the phase-shift parameters of Hale [Hal97]. The error bars are the sum in quadrature of the statistical and systematic uncertainties.

with the unpolarized differential cross section

$$\sigma_0 = 2|M_{11}^{11}|^2 + |M_{00}^{11}|^2 + |M_{00}^{00}|^2. \quad (3.3)$$

Here $M_{\nu'\nu}^{s's}$ is the M -matrix element for channel spin $s(s')$, channel spin projection $\nu(\nu')$ for the incoming (outgoing) channels. The solid curve in Figure 3.1-1 is a calculation of $K_z^{z'}(0^\circ)$ based on phase-shift parameters derived from a full R -matrix analysis of the $A = 4$ system by Hale [Hal97]. The agreement with the resonance structure at 1.7 MeV is excellent and fully confirms the 0^- assignment to the second excited state of ${}^4\text{He}$ at 21.0 MeV. The value of $K_y^{y'}(0^\circ)$ is also predicted to be small, again agreeing well with the measurement.

The results imply that the reaction at low energies is dominated by just two interfering amplitudes, the 21.0 MeV 0^- level and the broad subthreshold 20.2 MeV 0^+ level. Only M_{00}^{00} is non-zero for a 0^+ resonance and only M_{00}^{11} is non-zero for a 0^- resonance. As a result,

$$K_z^{z'}(0^\circ) \approx \frac{2\Re(M_{00}^{11*} M_{00}^{00})}{|M_{00}^{11}|^2 + |M_{00}^{00}|^2} \quad \text{and} \quad K_y^{y'}(0^\circ) \approx 0. \quad (3.4)$$

If the relative 0^+ and 0^- strengths are equal, $K_z^{z'}(0^\circ)$ approaches unity as $K_y^{y'}(0^\circ)$ remains small. This is effectively what is seen in the polarization-transfer data.

In conclusion, the measurements confirm the R -matrix analysis of [Hal97] and provide perhaps the most direct evidence yet for the presence of the 0^- level in ${}^4\text{He}$. The ${}^3\text{H}(\vec{p}, \vec{n}){}^3\text{He}$ reaction is an excellent source of longitudinally polarized neutrons at ~ 700 keV.

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3.1.2 The ${}^4\text{He}(\gamma, dd)$ Reaction at $E_\gamma = 150\text{--}250$ MeV

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Cross-section data for the ${}^4\text{He}(\gamma, dd)$ reaction with $E_\gamma = 150\text{--}250$ MeV are reported. The experiments were performed at the LEGS facility (BNL) and the Saskatchewan Accelerator Laboratory (SAL). The data were divided into two bins with $E_\gamma = 150\text{--}190$ MeV and $E_\gamma = 190\text{--}250$ MeV. The mid-energy bin data represent the first measurement of the cross section in this energy range. The angular distribution for this bin is shown in Figure 3.1-2. The angular distribution is peaked at 90° in the center-of-mass frame. The total cross section for this bin was extracted using a Legendre polynomial fit including P_0 , P_2 , and P_4 , and was found to be $6.85 \pm 0.25 \pm 0.49$ nb. The first error is purely statistical while the second represents a 7.1% systematic uncertainty.

The high-energy bin data are shown in Figure 3.1-3. Also shown are the world data obtained at energies near $E_\gamma = 220$ MeV. The results for the high-energy bin are in very good agreement with the Silverman data [Sil84] and are generally above the Arends data [Are76]. The angular distribution is peaked at 90° in the center-of-mass, in agreement with the results of both Arends and Silverman, but in disagreement with O'Rielly [O'R97]. The total cross section for this bin was extracted using a Legendre polynomial fit including P_0 , P_2 , and P_4 , and was found to be $3.68 \pm 0.19 \pm 0.52$ nb. The first error is purely statistical while the second represents a 13% systematic uncertainty. The total cross-section data from both energy bins are presented in Figure 3.1-4 along with a selection of world data for E_γ above 30 MeV.

We have also measured the analyzing power $A(\theta)$ using linearly polarized γ rays of energy $E_\gamma = 185\text{--}237$ MeV. These are the first polarization observable data for this reaction at these energies. The large statistical error, coupled with an unknown but likely sizable contamination from the *npd* channel, makes conclusions about the angular distribution

Figure 3.1-2: SAL differential cross section for $E_\gamma = 150$ to 190 MeV. Exploiting the symmetry of the system, measured data (circles) have been reflected about $\theta_{c.m.} = 90^\circ$ and plotted (squares). The uncertainties shown are purely statistical and do not include a 7.1% systematic uncertainty.

Figure 3.1-3: SAL differential cross section for $E_\gamma = 190$ to 250 MeV. Exploiting the symmetry of the system, measured data (hollow circles) have been reflected about $\theta_{c.m.} = 90^\circ$ and plotted (hollow squares). The uncertainties for the present work are purely statistical and do not include a 13% systematic uncertainty. World data for this cross section near $E_\gamma = 220$ MeV are also shown in the plot.

Figure 3.1-4: World data compared with the results of the present measurements. Uncertainties quoted for the present work are purely statistical and do not include systematic uncertainty (7.1% for the mid-energy bin and 13% for the high-energy bin).

difficult. The only firm conclusion that can be drawn is that the analyzing power is negative at all angles.

A transition matrix element analysis of the data (both cross section and analyzing power) including E1, M1, E2, and M2 multipole transitions was performed. This analysis found that between 60% and 100% of the cross section arises from capture to the D state of ^4He . The dominant contribution to this comes from *s*-wave capture to the D state. Furthermore, it was found that the maximum in the cross-section angular distribution at 90° is a consequence of E2-E2, E1-M2, and E2-M2 constructive interference.

Some conclusions which can be drawn from the present work: First, the absolute total cross section for $^4\text{He}(\gamma, dd)$ for E_γ near 220 MeV favors the lower values of those published during the last 35 years.

Second, the angular distribution was found in this work to be maximum at 90° , in agreement with the Arends [Are76] and Silverman [Sil84] measurements. The first observation of this sparked debate because such an angular distribution is normally associated with E1 radiation [Sil84], whereas E2 transitions are expected to dominate this reaction. E2 angular distributions typically exhibit a $\sin^2 2\theta$ shape which is minimum at 90° and maximum near 45° and 135° .

This inconsistency caused Silverman [Sil84] to suggest that the shape of the angular distribution arose from E1 radiation coming from meson-exchange currents. The isoscalar nature of both the deuteron and ^4He , however, makes such exchange currents unlikely. In this work we have shown that it is, in fact, possible to create an angular distribution that is

peaked at 90° using E2 s -wave capture to the D state interfering constructively with d -wave E2 capture to the D state or with M2 radiation. M1-E2 constructive interference can also contribute to this shape. It is not necessary to resort to meson-exchange currents to explain the observed angular distribution.

These observations indicate the vital importance of the tensor force in the present system. The possibility that it plays a dominant role at such high energies is quite intriguing. We hope that this result will motivate four-body theorists to investigate this reaction at these energies in the near future.

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3.1.3 Measurements of the $^3\text{He}(d,p)^4\text{He}$ Reaction at Low Energies

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The $^3\text{He}(d,p)^4\text{He}$ reaction proceeds primarily through a broad $\frac{3}{2}^+$ s -wave resonance at a deuteron energy of 430 keV. For a $\frac{3}{2}^+$ s -wave reaction amplitude the cross section is isotropic, while the analyzing powers follow certain relationships [Sei74], namely the tensor analyzing powers $A_{yy} = \frac{1}{2}$, $A_{zz} = (1 - 3\cos^2\theta)/2$, and $A_{xz} = -\frac{3}{2}\cos\theta\sin\theta$, and the vector analyzing power A_y is zero. Measurements of these analyzing powers around the resonance will enable us to better understand the reaction mechanism and determine if higher partial waves, which can contribute through a direct process, are important in the low-energy regime. The measurements were also used in an R -matrix parameterization of the ^5Li system resulting in a new level structure assignment. From the R -matrix analysis a determination of the bare nuclear cross section was calculated at very low energies and used in electron screening calculations.

We have completed our measurements of the differential cross section and the analyzing powers for the $^3\text{He}(d,p)^4\text{He}$ reaction. We have measured full angular distributions of σ , A_y , A_{yy} , A_{xz} , and A_{zz} at $E_d = 60, 99, 199, 424$ and 641 keV. These are the first analyzing power measurements made below 300 keV for this reaction. These measurements were performed by accelerating a polarized deuteron beam through the low-energy beam facility [Bla93] and into an ion-implanted ^3He target [Gei96]. The reaction products were measured in pairs of silicon detectors placed symmetrically on rotating plates inside the high-voltage chamber [Lud97]. An excitation function of the relative cross section from 245 to 685 keV and an absolute determination of the cross section was also measured. These

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measurements were also made in the low-energy beam facility and used a ^3He beam and a deuterated carbon target. For the absolute cross-section determination, the target thickness was measured with the $^2\text{H}(d,p)^3\text{H}$ reaction where the cross section is known [Bro90] to better than 3%. The absolute cross section was measured to be 777 ± 33 mb close to the resonance ($E_d = 426$ keV).

The data were included in a global R -matrix analysis of the ^5Li system. This analysis includes data from all available reaction channels up to about 18 MeV of excitation in ^5Li . As seen in Figure 3.1-5, the R -matrix parameterization describes the data well. Inclusion of the present data in the parameterization has helped to better define the $J^\pi = \frac{3}{2}^+$ level now determined to be located at $E_x = 16.86$ MeV in ^5Li . One surprising result of the R -matrix analysis is that the solution contained a $\frac{1}{2}^+$ level slightly below the $^3\text{He} + d$ threshold. This level is not reported in the most recent level compilation of ^5Li [Til98]. We are currently investigating this level more closely.

Figure 3.1-5: The angular distributions of analyzing powers for the $^3\text{He}(d,p)^4\text{He}$ reaction at $E_d = 430$ keV. The solid curves are obtained from an R -matrix parameterization of the ^5Li system and the dashed curves are the relations assuming the reaction proceeds only through a $\frac{3}{2}^+$ s -wave resonance.

Electron screening calculations using the bare nuclear cross section obtained from the new R -matrix analysis and the experimental data of Engstler *et al.* [Eng88] yielded a screening potential, U_e , of 177 ± 29 eV as shown in Figure 3.1-6. This value is in disagreement with the currently accepted maximum theoretical screening potential value [Bra90] of 120 eV and the most recent previously determined value [Lan96] of 130 ± 8 eV. Although, if the previously determined value of [Lan96] is recalculated in a procedure consistent with the present determination, a value of 170 ± 28 eV is obtained.

Figure 3.1-6: Electron screening calculations using the R -matrix calculations for the bare nuclear cross section (dashed curve) and the data from Engstler *et al.* (solid circles). The data were fit allowing both a scale factor and the screening potential to vary, resulting in $U_e = 177 \pm 29$ eV. The solid curve is the calculated enhancement for a screening potential of $U_e = 177$ eV while the dotted curves show the error in U_e .

This work has resulted in very accurate measurements of the ${}^3\text{He}(d,p){}^4\text{He}$ reaction below 1 MeV. These measurements contributed greatly to an R -matrix analysis of the ${}^5\text{Li}$ system. Also, calculations are currently being undertaken to evaluate the role of direct contributions to this reaction.

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3.2 Measurements of D States of Very Light Nuclei Using Transfer Reactions

3.2.1 Analyzing Powers of (${}^6\bar{\text{Li}}, d$) Reactions and the D State of ${}^6\text{Li}$

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Studies of the D-state components of the wave functions of light nuclei provide sensitive tests of the tensor force in the NN interaction. The parameter usually used to quantify the D state in the wave function is η , the ratio of the D- and S-state asymptotic normalization constants. Current estimates of the D-state amplitude in the ${}^6\text{Li}$ wave function for the $d + \alpha$ relative motion are so widely varying that even the sign of η is unknown [Leh90]. Calculations of the tensor analyzing powers for (${}^6\bar{\text{Li}}, d$) reactions are sensitive to the magnitude and sign of η . This effect can be seen in Figure 3.2-1.

Figure 3.2-1: Finite-Range DWBA calculations of the ${}^{58}\text{Ni}({}^6\bar{\text{Li}}, d){}^{62}\text{Zn}$ reaction leading to the 0^+ gs and the 2^+ first excited state showing the sensitivity of the TAP A_{xz} to the magnitude and sign of η . The solid curve corresponds to a calculation with $\eta = 0$. The long-dashed (dotted) curves correspond to calculations with $\eta = +0.015$ (-0.015) while the dot-dashed (short-dashed) curves correspond to calculations with $\eta = +0.0075$ (-0.0075). Our data are shown for comparison.

Last year [Vea97], we reported measurements of the analyzing powers A_y , A_{zz} , and A_{xz} for the ${}^{58}\text{Ni}({}^6\bar{\text{Li}}, d){}^{62}\text{Zn}$ and ${}^{40}\text{Ca}({}^6\bar{\text{Li}}, d){}^{44}\text{Ti}$ reactions at $E({}^6\text{Li}) = 34$ MeV leading to the

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0^+ ground state and the 2^+ first excited state for each reaction. The experimental details were presented at that time as well.

We have analyzed the reactions within the framework of the DWBA, assuming a direct α -particle transfer process. The optical-model parameters used to generate the distorted waves came from global parameterizations of ${}^6\text{Li}$ and deuteron elastic scattering. To describe the $\langle d\alpha | {}^6\text{Li} \rangle$ bound-state overlap, we have used a Woods-Saxon effective potential, with $R = 1.90$ fm and $a = 0.65$ fm [Kub72] where the depth was chosen to reproduce the separation energy between the α and the deuteron. The α -target bound state was described similarly, with $R = 1.25A_T^{1/3}$ fm and $a = 0.65$ fm.

We have obtained good agreement between the DWBA calculations of the cross section and VAP and the data for the four transitions considered here. Treating η as the only remaining adjustable parameter in the calculations, we have determined via χ^2 minimization the best-fit value of η for each of the eight TAP angular distributions. The statistical uncertainty in each determination was taken to be the difference between the value of η at χ_{min}^2 and the value of η at $\chi_{min}^2 + 1$. However, since the chi-square per degree of freedom χ_ν^2 for six of the eight determinations was > 1 , we chose to multiply those statistical uncertainties by $\sqrt{\chi_\nu^2}$. The eight best-fit values for η along with their respective statistical uncertainties (smaller error bars) are shown in Figure 3.2-2.

Figure 3.2-2: Determinations of η from the eight tensor analyzing power measurements. The smaller error bars represent the statistical uncertainty whereas the larger error bars represent the total uncertainty, as described in the text. The solid line represents the average of the individual values weighted by the total uncertainty for each value. The dashed lines represent the limits of the error in the average.

The calculated TAPs (and therefore η) were very sensitive to the potential binding the α particle to the target nucleus. Since these potential parameters have varied somewhat in previous (${}^6\text{Li}, d$) reaction studies, we treated them as uncertain by $\pm 15\%$. The uncertainty in η due to the α -target bound state was taken to be the difference between the best-fit

value of η for the parameters given above and the best value of η calculated when each parameter was changed by $\pm 15\%$. These were then added in quadrature and reported as $\Delta\eta_{BS}$.

To verify that the extracted value of η could not be influenced by the presence of tensor potentials, we separately included deuteron-nucleus and ${}^6\text{Li}$ -nucleus tensor potentials into the DWBA calculations. The potential had a radial form suggested by Raynal [Ray63] where the parameters came from 30-MeV deuteron scattering off neighboring nuclei [Per77] and 30-MeV ${}^6\text{Li}$ scattering off ${}^{12}\text{C}$ [Ker95]. Including the tensor potentials made almost no change in the calculated TAPs and therefore they have very little effect on the extracted value of η . However, an estimate of this small effect was included in the overall uncertainty determination.

The uncertainty in each of the eight determinations was determined by adding in quadrature the statistical uncertainty, and the uncertainties due to the α +target bound state and the tensor potentials. The final value for η was found by taking the average of all eight determinations, weighted by the overall uncertainty in each determination, with the result being $\eta = +0.0003 \pm 0.0009$.

A short paper describing this work has been published in the Physical Review Letters.

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3.3 Radiative-Capture Reactions and Few-Nucleon Systems

3.3.1 The Study of the ${}^2\text{H}(\vec{p},\gamma){}^3\text{He}$ and ${}^1\text{H}(\vec{d},\gamma){}^3\text{He}$ Reactions below 80 keV

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Additional measurements of the ${}^2\text{H}(\vec{p},\gamma){}^3\text{He}$ and ${}^1\text{H}(\vec{d},\gamma){}^3\text{He}$ reactions at $E_d = 80$ keV have added significantly to the physics we have been able to extract from this work. For example, the addition of our $iT_{11}(\theta)$ data allowed us to determine the values of both the doublet and the quartet M1 cross sections at 80 keV. These were found to be in remarkably good agreement with ab-initio 3-body theory when meson-exchange current effects are included. The abstract of our recent paper on this subject is given below.

Data obtained from studies of the ${}^2\text{H}(\vec{p},\gamma){}^3\text{He}$ and the ${}^1\text{H}(\vec{d},\gamma){}^3\text{He}$ reactions have been used to extract the transition amplitudes corresponding to $S = 1/2$ (doublet) and $S = 3/2$ (quartet) M1 radiative capture. Protons (deuterons) of 40 keV (80 keV) were stopped in D_2O (H_2O) ice targets. Angular distributions of σ , A_y , T_{20} , P_γ and iT_{11} were measured and fit simultaneously in terms of the four possible E1 p -wave capture amplitudes and the two ($S = 1/2$ and $3/2$) possible M1 s -wave capture amplitudes. The results obtained at $E_{c.m.} = 23.3$ keV indicate that the $S = 1/2$ M1 capture cross section is 13.77 ± 0.66 nb, while the $S = 3/2$ M1 capture cross section is 6.74 ± 0.44 nb. These results agree with the predictions of a recent three-body theoretical calculation which includes two-body currents (*e.g.* meson-exchange currents (MEC's)). They also agree with the previous experimental determination of the doublet and quartet fusion rates obtained using the Wolfenstein-Gerstein effect to vary the relative population of $S = 1/2$ and $3/2$ nuclear spins in the μ - p - d molecule prior to fusion.

Our full data set, including all spherical tensor analyzing powers and γ -ray polarizations, is now adequate to enable us to extract accurate amplitudes and phases of the contributing matrix elements. A comparison of the predictions of 3-body theoretical calculations indicates that the theoretical values of the $S = 3/2$ E1 strength is a factor of 5-to-6 times too small. Changing the M1 phases relative to the E1 phases can resolve the " A_y Puzzle" in this reaction: *i.e.* the 30% discrepancy between the measured and calculated values of A_y (see Ref. [Ric97]). Of course, the physical origin of this phase discrepancy remains to be determined. A more detailed description of this data set and our analysis is given below.

The current data along with the TME fit to the data is shown in Figure 3.3-1. Using this enlarged data set we have been able to determine the TMEs for this reaction to a high degree of accuracy. We have compared these experimental values with those predicted by

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theoretical calculations of these reactions [Viv96]. The TME fit is quite good for all of the observables except T_{21} and P_γ . We have not been able to determine the problem with the T_{21} data, but it seems to be at odds with the other observables. A new measurement of this observable is planned for early fall. The discrepancy in P_γ is probably caused by a miscalibration in the sensitivity of the Compton polarimeter used to measure the polarization. New measurements of the sensitivity using Compton backscattered γ rays from the Duke FEL and a Monte-Carlo simulation of the polarimeter is underway to clear up this problem.

Figure 3.3-1: The current measured data for the 9 observables and their associated TME fits.

Summary of Present Results for the $^2\text{H}(\vec{p}, \gamma)^3\text{He}$ Reaction below 80 keV

1. The slope of the S factor for the $^2\text{H}(\vec{p}, \gamma)^3\text{He}$ reaction has been experimentally determined below 80 keV. It was confirmed to be linear with $S_1 = 0.0071 \pm 0.0004$ eV b keV $^{-1}$.
2. The experimentally determined value of the S factor at $E = 0$ was found to be 35% lower than previously assumed: $S(0) = 0.165 \pm 0.014$ eV b.
3. The asymptotic D-to-S state ratio for ^3He was determined from the T_{20} data at $E_d = 80$ keV, $\eta = -0.0399 \pm 0.0091$, in good agreement with theory and other experiments.

4. The quartet-to-doublet M1 cross-section ratio at $E_{c.m.} = 23$ keV was determined to be 0.49 ± 0.04 , in good agreement with 3-body theory when MEC currents are included. The absolute cross sections for the doublet (13.77 ± 0.66 nb) and the quartet (6.74 ± 0.44 nb) are in good agreement with theory.
5. We have established the “ A_y problem” for the capture channel.
6. Significant discrepancies remain between experiment and 3-body theory with 2-body currents included. What new physics is needed to resolve these is an open question.

[Ric97] B. J. Rice *et al.*, Phys. Rev. **C56**, 2917 (1997).

[Viv96] M. Viviani *et al.*, Phys. Rev. **C54**, 534 (1996).

3.3.2 ${}^2\text{H}(\vec{d}, \gamma){}^4\text{He}$ Reaction at $E_d = 100$ keV

S.J. Gaff, S.O. Nelson, R.M. Prior¹, M. Spraker¹, and H.R. Weller

Measurements at TUNL at an energy of 80 keV of the tensor analyzing power, A_{yy} , of ${}^2\text{H}(\vec{d}, \gamma){}^4\text{He}$ clearly showed the presence of strong p -wave capture in contrast to the assumption that the low-energy data should be dominated by s -wave capture [Kra93]. These measurements used a deuterated titanium target and a polarized deuteron beam from the TUNL atomic beam polarized ion source (ABPIS) along with large anti-coincidence-shielded NaI(Tl) detectors. The yields were at the limit of detectability of the 24-MeV gamma rays, meaning that only a few data points could be collected in many weeks of data acquisition.

We are beginning a new series of measurements in which the yields should be significantly improved. We will use a deuterated ice target, building on our experience with ice targets for the ${}^2\text{H}(\vec{p}, \gamma){}^3\text{He}$ and ${}^1\text{H}(\vec{d}, \gamma){}^3\text{He}$ reactions. The target will be biased negatively to increase the beam energy above the 80 keV provided by ABPIS. Calculations indicate that increasing the beam energy to 100 keV and using an ice target will increase the yield by a factor of five. With increased yields it will be possible to measure all the tensor analyzing powers. A complete data set will allow a much better extraction of transition matrix elements, providing a better basis for interpretation of the reaction mechanism and for comparison with exact four-body calculations which are now imminent.

A new facility for low-energy capture reactions is being built. The facility will include a platform to support the large anti-coincidence-shielded NaI(Tl) detectors so that they may be placed closer to the target and easily moved to different angles about the target. The new ice target structure will be much smaller than the present target, also allowing

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the detectors to be closer to the target. The target will be attached to a new high-voltage chamber setup that can be biased up to 60 kV. This biased target setup will also be used in other future experiments with other targets.

Data taking is expected to begin in the Fall of 1998.

[Kra93] L. Kramer *et al.*, Phys. Lett. **B304**, 208 (1993).

3.3.3 A Study of ${}^3\text{H}(\vec{p}, \gamma){}^4\text{He}$ for E_p below 80 keV

R.S. Canon, J.H. Kelley, R.M. Prior¹, E.C. Schreiber, M. Spraker¹, D.R. Tilley, H.R. Weller, and E.A. Wulf

Theorists are on the verge of completing exact calculations of four-body systems in nuclear physics [Fon98, Kie98]. Foreseeing a need for precision data to test against calculations we have begun measurements on the ${}^3\text{H}(\vec{p}, \gamma){}^4\text{He}$ reaction at energies below 80 keV using the atomic beam polarized ion source. The reaction at our energies also holds promise as a convenient and portable source of 20 MeV γ rays for practical applications and development. An accurate set of measurements of the cross sections at low energies is critical for some of these applications.

A previous study conducted by the radiative capture group of polarized p - d capture at energies below 80 keV revealed the major role played by meson-exchange current effects and provided a clean testing ground for state-of-the-art 3-body theory [Sch96, Sch97]. Four-body theory is on the threshold of being able to make similar ab-initio predictions. The p - t capture reaction is expected to exhibit strong MEC effects at very low energies for reasons similar to those in p - d capture. These effects are associated with M1 radiation, which should manifest itself as non-zero analyzing powers at 90° in the $\vec{p}$ - t capture reaction. Preliminary results from our measurements indicate finite values of $A_y(90^\circ)$ in the 50-80 keV region.

Measurements of the angular distribution of the cross section and analyzing power have been carried out in two separate runs. Preliminary analysis indicates the presence of some M1 strength in the reaction at these energies. At 80 keV, $A_y(90^\circ)$ was found to be 0.03 ± 0.004 . Since the 90° analyzing power requires interference of radiation of opposite parity, A_y is expected to be of the form $b_1 P_1^1(\theta)$. An associated Legendre polynomial fit (see Figure 3.3-2) was performed to determine b_1 and it was found to be $-0.05 \pm \pm 0.007$.

A tritiated titanium target was used in these experiments. It consists of a copper disk which has a thin layer of titanium evaporated on to it. This titanium layer is then tritiated and is effectively loaded with a ratio of 1.6 tritium atoms to each titanium atom. The titanium layer is thick enough that an 80 keV beam is stopped within this layer. Two forms of target cooling have been used. In one instance, a liquid nitrogen bath was kept in

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Figure 3.3-2: Analyzing power for ${}^3\text{H}(\vec{p}, \gamma){}^4\text{He}$.

thermal contact with the target. In the other case, chilled water was circulated around a copper block that was in thermal contact with the target rod.

In both runs a 10" $\times$ 10" sodium iodide (NaI) detector with a plastic scintillating anti-coincidence shield surrounding the detector was used. The shield allows cosmic-ray events to be rejected. In the second run, an unshielded NaI detector was also used. A spectrum for the anti-coincidence shielded detector is shown in Figure 3.3-3.

Figure 3.3-3: Raw spectrum in ${}^3\text{H}(\vec{p}, \gamma){}^4\text{He}$.

In the future, we hope to extend these measurements. A study of the tritium target properties will be performed, so that an accurate determination of the cross section can be obtained. Also, we intend to extend the measurement to lower energies. By biasing the target we plan to extract a measurement of the slope of the astrophysical S factor between

50-130 keV. This will also allow us to determine the cross sections, angular distributions, and analyzing powers at these energies. Finally, a detector platform is currently being constructed that will support two shielded NaI detectors. This platform will include carts that can rotate around an axis in line with the center of the target. This will enable us to quickly and precisely change the detector angles. Construction should be completed by the end of the summer of 1998.

[Fon98] A. Fonseca, private communication, 1998.

[Kie98] A. Kievsky, private communication, 1998.

[Sch96] G. Schmid *et al.*, Phys. Rev. Lett. **76**, 3088 (1996).

[Sch97] G. Schmid *et al.*, Phys. Rev. **C56**, 2565 (1997).

3.3.4 Angular Distribution Coefficients for γ -Ray Polarizations Produced in Polarized Capture Reactions

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Previous publications in this area have dealt with the angular momentum formalism of both linear and circularly polarized photons in (γ, x) reactions on both polarized and unpolarized targets. In the present case, we are dealing with the polarization of the γ rays which are produced in the inverse (capture) reactions, including the possibility of having incident polarized spin $\frac{1}{2}$ projectiles. These capture reactions are denoted by $a(\vec{x}, \vec{L})c$, where $\vec{x}$ is the incident polarized spin $\frac{1}{2}$ projectile and $\vec{L}$ represents the outgoing polarized γ ray. Expressions for the γ -ray polarization (P_γ) in terms of the contributing (complex) transition matrix elements (TMEs) can be written for the case of spin-up ($P_\gamma^\uparrow$) and spin-down ($P_\gamma^\downarrow$) incident beams. The new observable $A_\gamma = P_\gamma^\uparrow - P_\gamma^\downarrow$ provides another independent relationship between the TMEs.

The present work utilizes the general formalism of Welton [Wel63]. In a paper which we are preparing, we will present the formalism, in a convenient form, display a sample table of coefficients, and illustrate its use by means of several examples. A FORTRAN code will be made available for generating similar coefficients for other reactions. A manuscript for submission to "Atomic Data and Nuclear Data Tables" is being finalized.

[Wel63] T. A. Welton, In J. B. Marion and J. L. Fowler, editors, *Fast Neutron Physics*, volume II, p. 1317. Interscience, New York, 1963.

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4 Nuclear Astrophysics

4.1 Radiative-Capture Reactions

4.1.1 Cross-Section Studies of the ${}^7\text{Li}(p,\gamma){}^8\text{Be}$ Reaction at Low Energies

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Over the last few years, we have been studying the ${}^7\text{Li}(p,\gamma){}^8\text{Be}$ reaction at energies $E_p = 80\text{--}0$ keV. Due to the proton's very low incident energy, the beam is stopped within the target and the cross sections previously measured have been for the full energy range from 80 to 0 keV. Evidence for p -wave effects in this energy range ([Cha94], [God96] for example) has led us to pursue measurement of the cross section as a function of energy in order to determine the slope of the S factor.

We performed the present measurements using three $10'' \times 10''$ NaI detectors. Although the energy resolution is relatively poor ($\sim 3\%$), the efficiency for 17 MeV gamma rays is about 25 times higher than that of the available Ge detectors. Two 20 kV power supplies of opposite polarity were connected to the target chamber. The supplies were computer controlled and provide voltages from 0 to ± 20 kV with an accuracy of better than 1 kV. Data have been taken using proton beams with both 80 keV and 60 keV incident energy. The incident proton beam was then accelerated by the target bias to energies 20 keV above and below the incident energy. Data was taken from 40 to 80 keV in 10 keV steps and from 60 to 100 keV in 5 keV steps. The times spent at each energy were set so that nearly equal statistical accuracies were obtained in each energy bin. Furthermore, the cycle time over the full voltage range was less than 1 hour for both measurements, allowing the data at different energies to be taken under similar experimental conditions.

The data have been analyzed and show a *negative* S-factor slope for capture to both the ground state and the first excited state of ${}^8\text{Be}$, as well as a large non-zero analyzing power down to 40 keV. In an attempt to explain this data, calculations which include the effects of the "negative energy" resonance at 16.6 MeV have been performed. From these calculations, it is clear that E1 and M1 direct capture alone yield a zero slope and no analyzing power at these low energies. When the two M1 higher energy resonances (at 441 keV and 1.03 MeV) are included, a non-zero analyzing power is seen, but the S-factor slope is slightly positive. With the inclusion of the subthreshold 2^+ state at 16.6 MeV, the negative slope of the capture to the ground state can be reproduced if the capture to this state occurs at 40–50 fm. This state is of particular interest because its $T = 1$ component is the isobaric

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analog of the ground state of ^8B , which is the residual nucleus of the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction, which is of central importance to the solar neutrino problem.

We are presently involved with a new effort to obtain a definitive measurement of the absolute cross section for this reaction at energies at and below 100 keV. Further calculations are underway in an attempt to account for all of the experimental results.

[Cha94] R. M. Chasteler *et al.*, Phys. Rev. Lett. **72**, 3949 (1994).

[God96] M. A. Godwin *et al.*, Phys. Rev. **C53**, R1 (1996).

4.1.2 The Spin-Parity of the 7.478 MeV State of ^{10}B from the $^9\text{Be}(\vec{p},\gamma)^{10}\text{B}$ Reaction at 280 keV

R.S. Canon, S.J. Gaff, J.H. Kelley, S.O. Nelson, K. Sabourov, E.C. Schreiber, D.R. Tilley, H.R. Weller, and E.A. Wulf

A previous experiment at TUNL measured analyzing powers for the reaction $^9\text{Be}(\vec{p},\gamma)^{10}\text{B}$ with 100 keV protons [Wul98]. The results showed a large analyzing power at 90° . Contrary to the claims of [Zah95], these measurements suggest that the spin-parity of the 7.478 MeV state of ^{10}B must be 2^+ rather than 2^- . The statistical errors for the analyzing power data are fairly large (17%). To improve on these statistics, the current measurement was made using a 280 keV beam. At this energy the cross section is about 300 times higher. Also measurements were made at more angles, in order to map out the angular dependence of the analyzing power.

The measurement was carried out in the TUNL High-Voltage Chamber, using two 60% HPGe detectors. Because of space constraints they were oriented vertically and gamma rays impinged on the sides of the detectors. The polarized proton beam stopped in the ^9Be target. About 90% of the gamma yield comes from protons with energies above 200 keV, so a beam energy of 240 keV was used in the calculations.

Figure 4.1-1 shows the preliminary results for the analyzing power at six angles for the ground-state transition. Typical uncertainties of the data are about 7%.

Calculations were done using the program HIKARI [Wel80], which adds single-particle resonance amplitudes to the direct capture amplitudes. The parameters were adjusted to fit the cross-section data as in [Wul98] and A_y was calculated without further adjustment. The tails from two states in ^{10}B contribute to the capture process leading to the ground state (3^+) with $E_x=6.838$ MeV. The two relevant states have excitation energies of 7.478 and 7.75 MeV. These states are listed in the compilation [AS88] as having spin-parities of 2^+ and 2^- , respectively. The solid curve in Figure 4.1-1 shows the results of the calculations for these assignments of spin-parity. A recent paper by Zahnow *et al.* [Zah95] argues that the spin-parity of the 7.478 MeV state in ^{10}B should be 2^- on the basis of the quality of

Figure 4.1-1: Analyzing power for the ${}^9\text{Be}(\vec{p}, \gamma){}^{10}\text{B}$ reaction leading to the ground state. The solid curve represents the HIKARI calculation where the 7.478 MeV state in ${}^{10}\text{B}$ has a spin-parity of 2^+ . The dashed curve is the calculation using a spin-parity of 2^- for that state.

their fits to the cross-section data alone. For this case the result is shown as the dashed curve. Since the 90° analyzing power arises from E1-M1 interference, the 2^+ assignment, which produces M1 strength, is needed to obtain the large A_y observed in the experiment.

Clearly, the analyzing power measured in the present experiment yields the spin-parity assignment 2^+ for the 7.478 MeV state of ${}^{10}\text{B}$. This work is presently being prepared for publication.

[AS88] F. Ajzenberg-Selove, Nucl. Phys. **A490**, 152 (1988).

[Wel80] H. R. Weller and N. R. Roberson, Rev. Mod. Phys. **52**, 699 (1980).

[Wul98] E. A. Wulf *et al.*, Phys. Rev. **C58**, 517 (1998).

[Zah95] D. Zahnow *et al.*, Nucl. Phys. **A589**, 95 (1995).

4.1.3 The $^{11}\text{B}(\vec{p},\gamma)^{12}\text{C}$ Reaction below 115 keV

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As a continuation of our study of low-energy reaction dynamics, the radiative-capture group is engaged in a measurement of the S-factor slope and analyzing powers for the $^{11}\text{B}(p,\gamma)$ reaction at very low energies. Measurements of the reaction cross sections and vector analyzing powers, as a function of energy and angle, have been carried out at proton energies of 80 to 115 keV in order to determine the influence of near-resonance states on the capture cross section.

Asymmetric cross sections and non-zero vector analyzing powers observed in polarized proton ($\vec{p}$) capture on ^7Li [God96] and ^9Be [Wul98] targets indicate s -wave and p -wave interference and contradict the general assumption of pure s -wave capture amplitudes at low energies (see for example [Cec92]). It is our intention to investigate low-energy $\vec{p}$ capture reactions on light nuclei with the aim of improving the methodology for extracting astrophysical reaction rates. For example, the analyzing power at 90° is especially sensitive to the interference of different multipolarities and can be used to determine the amplitudes and phases of the interfering terms. In addition, a determination of the slope of the S factor, obtained from measurements of the energy dependence of the cross section, is not sensitive to the detailed problems involved in absolute cross-section measurements and can be combined with the angular distributions and analyzing powers to provide constraints for theoretical models.

We measure the γ rays emitted when a beam of 30-50 μA of polarized protons is stopped in a thick enriched ^{11}B target. To obtain the S-factor slope, we bias the target with a negative HV power supply which accelerates the beam by up to 35 keV above the nominal beam energy of 80 keV. The energy-dependent cross sections (related to the S-factor slope) are obtained from the difference in γ -ray fluxes as a function of beam energy. We measure α particles that are produced in the $^{11}\text{B}(p,\alpha)$ reaction as a monitor of beam intensity and target stability. In order to avoid potential problems with unstable beam on the target, a series of short runs are taken, with energy steps of 5 or 10 keV between runs. At the completion of a series of runs the process is repeated.

A number of different detector arrangements have been used to obtain the accumulated set of data. With the exception of a 128% HPGe detector used in one setup, large 10 inch diameter by 10 inch long NaI detectors were used to detect the γ rays. The low cross sections made it necessary to use plastic anti-coincidence shields to minimize the background. We have used a large 4 inch thick plastic annulus that surrounds the NaI and provides over 98% cosmic ray rejection. Also we have used a thin paddle that is placed above the detector and provides over 20% rejection.

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The angular distribution of γ rays obtained when 100 keV protons impinge on the ^{11}B target have the best statistics. These data are shown in Figure 4.1-2, with the results of a Transition Matrix Element (TME) analysis and with a prediction from the radiative-capture code (HIKARI) which includes the effects of resonant and direct capture. Capture to both the ground state and first excited state are observed to have s - and p -wave mixing. In the case of capture to the ground state (γ_0) the asymmetric angular distribution indicates the interference, while the large analyzing power found in γ_1 shows the interference. The TME analysis indicates that at 100 keV there are 40% p -wave contributions in the case of $^{11}\text{B}(p,\gamma_0)$ and 45% p -wave contributions in the case of $^{11}\text{B}(p,\gamma_1)$.

Figure 4.1-2: Preliminary results for angular distributions and analyzing powers (A_y) for the $^{11}\text{B}(p,\gamma)$ reaction at 100 keV. The solid curve is from a TME analysis fit to the data, and the dashed curve is from a direct plus resonance capture prediction.

Thus far, most analysis has been focused on the $^{11}\text{B}(p,\gamma_1)$ reaction because the rate is much higher. We have used the high-energy data of Segel *et al.* [Seg65] (400 keV and above), the spectroscopic factors from Cohen and Kurath [Coh67], and the $^{12}\text{C}^*$ (16.1 MeV) state parameters from Ajzenberg-Selove [Ajz90] to determine resonant state strength parameters and relative signs of the interference terms in our direct-plus-resonant capture calculation, see Figure 4.1-3. The calculation includes $^{12}\text{C}^*$ states at 16.10, 16.57 and 17.23 MeV.

In the case of $^{11}\text{B}(p,\gamma_1)$ the value of $S(0)$ that we obtained is significantly larger (≥ 2 times) than that obtained by Cecil *et al.* [Cec92]. The extrapolation that they used simply added a resonance to a linear S factor without any interference effects, which appear to be important. The two calculations shown in Figure 4.1-3 are meant to indicate the sensitivity of the reaction to the details of the interference effects. Changing the relative signs of the resonance amplitudes leads to different values of the $S(0)$ (see Figure 4.1-3a). Fortunately, the analyzing powers can be used to select the physical solution (see Figure 4.1-3).

Figure 4.1-3: The $^{11}\text{B}(p,\gamma)$ reaction is sensitive to interference effects. A) shows the S factors predicted by HIKARI, and B) shows the analyzing power measured at 90° shown in comparison with predicted values from HIKARI.

These calculations can give insight into the low-energy reaction dynamics and the importance of interference effects, and give improved predictions for $S(0)$ values when compared to simple extrapolations.

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 [Seg65] R. E. Segel *et al.*, Phys. Rev. **139**, 818 (1965).
 [Wul98] E. A. Wulf *et al.*, Phys. Rev. **C58**, 517 (1998).

4.1.4 Measurement of the Mean Lifetime for the Astrophysically Important $E_x = 6.79$ MeV Subthreshold State in ^{15}O Using the Doppler Shift Attenuation Method

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Radiative proton capture on ^{14}N is the slowest reaction in the stellar CN-cycle. Therefore, in a massive main sequence star whose energy is generated mainly through this cycle, the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction has the role of setting the energy generation rate for the star and consequently the time scale for its evolution [Rol88]. In addition, the rate for this reaction

is a significant variable in determining the width of the distribution of mean globular cluster ages derived from computer models of stellar evolution. The one-sided 95% confidence limit lower bound for this distribution is thought to be a lower limit on the age of the universe [Cha96]. The extrapolation of existing S-factor data for the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction to stellar energies is complicated by interference effects from the $E_x = 6.79$ MeV subthreshold level in ^{15}O [Wal97]. The situation could be improved by a direct determination of the mean lifetime for this state.

We have attempted such a measurement using the Doppler-Shift Attenuation method. With the DSA method one observes the Doppler shift in energy of γ rays emitted from a recoiling compound nucleus. A measure of the difference in energy shift between two angles (with respect to the incident beam direction) and knowledge of the slowing down process the recoiling compound nucleus undergoes in the target, allows for determination of the mean lifetime for the intermediate state. We utilized a beam of (unpolarized) protons from the TUNL Atomic Beam Polarized Ion Source, accelerated to 300 keV by the mini-tandem, to populate the $E_x = 7.56$ MeV level in ^{15}O ($\Gamma_{c.m.} = 0.99$ keV) via the proton-capture resonance at $E_p = 278$ keV. This state has a 23% branch to the state of interest, which in turn has a 100% branch to the ground state. We observed the γ rays from this ground-state transition using three 60% HPGe detectors: one at 0° , another at 144° to maximize the Doppler-shift difference, and a third at 90° to observe the unshifted line shape. The target, which had a nominal thickness of $30 \mu\text{g}/\text{cm}^2$, was made by implanting 120 keV $^{14}\text{N}^+$ ions into a tantalum backing [Seu87] using the ion implantor located in the UNC-Chapel Hill Department of Physics and Astronomy Microelectronics Laboratory.

Preliminary analysis suggests that we observed the full Doppler shift, indicating the mean lifetime of this state is so short that recoiling compound nuclei emit γ rays as the slowing down process begins. In this situation only an upper limit for the mean lifetime can be deduced. Given that the DSA method is not sensitive enough to measure lifetimes shorter than 1-2 femtoseconds, this result is consistent with previous work and the known lifetime of the analog state in ^{15}N [Sch87, AS91]. Further analysis will yield a new, more stringent, upper limit for the mean lifetime of the $E_x = 6.79$ MeV bound state in ^{15}O . We will also determine what effect the new upper limit has on the uncertainty in the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ S factor at astrophysically important energies.

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4.1.5 Sub-Coulomb α Transfers on ^{12}C

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The $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction is a very important helium-burning process in massive stars, as the rate greatly affects the resulting ratio of ^{12}C to ^{16}O , the subsequent nucleosynthesis of heavier elements, and the final fate of the star (i.e., black hole or neutron star). The extrapolation of the measured cross sections ($E_{c.m.} \geq 1$ MeV) to lower energies is complicated by two states located 45 keV ($J^\pi = 1^-$) and 245 keV ($J^\pi = 2^+$) below the $^{12}\text{C} + \alpha$ threshold. The cross section at astrophysical energies arises largely from the high-energy tails of these states, but the properties of these states are only weakly constrained by cross-section measurements at higher energies. The γ -ray widths of these levels are known, but there is considerable uncertainty in the reduced α widths which parameterize the strength of $\alpha + ^{12}\text{C}$ clustering at the nuclear surface. The reduced α width of the 1^- state has been inferred in [Azu94] by fitting a large body of data including the β -delayed α spectrum of ^{16}N . Very little information exists for the 2^+ state.

The reduced α widths can in principle be determined from α -transfer reactions, by comparing data to theoretical calculations using the Distorted Wave Born Approximation (DWBA). Historically the interpretation of measurements of this type has been hampered by uncertainties in the potential parameters and the presence of compound-nuclear processes. Our new approach is to utilize the α -transfer reactions $^{12}\text{C}(^6\text{Li}, d)^{16}\text{O}$ and $^{12}\text{C}(^7\text{Li}, t)^{16}\text{O}$ at sub-Coulomb energies; previous measurements of this type were performed at beam energies between 10 and 100 MeV.

The Li-induced α -transfer reactions at very low energies offer several attractive features. The slightly negative Q -values for the reactions to the subthreshold states (-1.23 and -2.22 MeV for the $(^6\text{Li}, d)$ and $(^7\text{Li}, t)$ reactions to the bound 2^+ state) mean that the outgoing deuterons or tritons will also have energies below the Coulomb barrier. Under these conditions, the DWBA calculations are determined mainly by Coulomb potentials, with very little dependence on nuclear potential parameters. The calculated cross sections are thus essentially model independent, except for the absolute normalization, which depends in turn on the reduced α widths of the ^{16}O state and the Li nucleus which contributed the α particle. The weak binding of the α particles in these final states serves to enhance the direct cross section for sub-Coulomb reactions. In addition, the compound-nuclear cross section at low energies is predicted to be small compared to the direct cross section, and decreases *faster* than the direct reaction cross section as the beam energy is lowered.

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Figure 4.1-4: Sample γ -ray spectra obtained at 31° .

Experimentally, we have first approached this problem by bombarding carbon targets with Li beams, and detecting γ decays from the ^{16}O states of interest. The measurements were conducted by bombarding targets with $^6,^7\text{Li}$ beams supplied by the Caltech 3-MV Pelletron accelerator. The targets consisted of $20 \mu\text{g}/\text{cm}^2$ of ^{12}C evaporated onto Cu substrates, and were oriented at 45° with respect to the incident beam. The Li beams lose between 45 and 65 keV in the target. Gamma rays resulting from the bound $J^\pi = 3^-, 2^+$, and 1^- states of ^{16}O were detected with high-purity Ge detectors located at 31° and 110° where the $P_4(\cos\theta)$ Legendre polynomial vanishes. Note that the branching ratios of these states to the ground state of ^{16}O are essentially 100%. The total cross section for populating states with $J \leq \frac{7}{2}$ can be determined, with no ambiguity from angular-distribution effects, by applying Gaussian quadrature to the measured yields. Detailed angular distribution measurements were also performed for a few energies with a single detector in good geometry ($Q_2 = 0.98$, $Q_4 = 0.94$). Sample γ -ray spectra are shown in Figure 4.1-4. The $^{12}\text{C}(^7\text{Li},\alpha)^{15}\text{N}$ reaction populates several bound states between 7 and 10 MeV excitation in ^{15}N , producing considerable background in the region of interest. These states are not populated with the ^6Li beam, giving rise to significantly cleaner spectra. We do not positively identify the 7.12-MeV γ ray from the $^{12}\text{C}(^7\text{Li},t)^{16}\text{O}$ reaction.

The cross-section measurements are summarized in Table 4.1-1. The $^{13}\text{C}(^6\text{Li},t)^{16}\text{O}$ reaction was measured since it involves the same compound nucleus (^{19}F) as the $^{12}\text{C}(^7\text{Li},t)^{16}\text{O}$

Table 4.1-1: Center-of-mass energy ranges in MeV where the cross section for populating bound states of ^{16}O were determined for various beam and target combinations.

reaction	final state		
	3^-	2^+	1^-
$^{12}\text{C}(^6\text{Li},d)^{16}\text{O}$	1.8-4.7	1.8-4.7	2.0-4.7
$^{12}\text{C}(^7\text{Li},t)^{16}\text{O}$	2.6-4.4	3.0-4.4	-
$^{13}\text{C}(^6\text{Li},t)^{16}\text{O}$	1.9-4.1	1.9-4.1	-

Figure 4.1-5: Total cross sections measured for $^{12}\text{C}(^6\text{Li},d)^{16}\text{O}$ for the bound 2^+ ($\square$) and 1^- ($\circ$) states of ^{16}O . The solid curves are DWBA calculations normalized to the data with $E_{c.m.} \leq 3.0$ MeV.

reaction, and may hence provide diagnostic information on the magnitude of compound-nuclear processes. The measured energy dependences and γ -ray angular distributions for the $^{12}\text{C}(^6\text{Li},d)^{16}\text{O}$ reaction to the bound 2^+ and 1^- states and the $^{12}\text{C}(^7\text{Li},t)^{16}\text{O}$ to the bound 2^+ state are in good agreement with DWBA predictions. The results for $^{12}\text{C}(^6\text{Li},d)^{16}\text{O}$ are shown in Figure 4.1-5. Further analysis is in progress.

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4.1.6 The $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$ Reaction at Stellar Energies

B. Pierce, A. Ram, M. Sorrenti, and W. Tornow

The understanding of the $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ reaction is very important to nuclear astrophysics. Both the elemental abundance predicted from nucleosynthesis and the final evolutionary

state of a massive star (neutron star versus black hole) depend critically on the rate of the reaction $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ [Red87, Oue92]. Unfortunately, at stellar energies, the cross section is too small to be measured, and extrapolations from higher energy data are associated with rather large uncertainties in the value of the astrophysical S factor at stellar helium burning energies ($E_{c.m.} = 0.3$ MeV). Although the reaction $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ has been studied extensively for the past 20 years, $E_{c.m.} = 1.0$ MeV is the lowest energy where data exist.

In order to extend the energy range closer to the energy of interest, we are planning to perform the inverse reaction: $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ using the monoenergetic gamma-ray beams available at the Duke Free-Electron Laser Laboratory. Intense beams will be sent through a long container filled with oxygen gas and lined with CR-39 plastic track detectors. The low-energy (~ 1 MeV and below) α particles generated from the $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ reaction shall hit the CR-39, which will later be etched and examined.

We have tested various samples of CR-39 using α , β , and γ sources. After irradiation we etched the samples in 6.25 N NaOH. The trail region caused by the incident α particles reacts faster with the NaOH than the undamaged material, thus creating tracks which can be viewed under a microscope or with automatic and computerized scanning. The CR-39 track detector "TASTRAK" obtained from TASL¹ gave so far the best results for α particles. The efficiency of TASTRAK to α particles was found to be 100% for angles of incidence up to about 65° and α energies down to about 0.3 MeV. At the same time β particles and γ rays did not produce any visible tracks or damage in the CR-39 samples investigated.

We plan to test and calibrate our method at the $E_{c.m.} = 2.39$ MeV resonance of the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction which corresponds to a γ -ray energy of $E_\gamma = 9.5$ MeV for the $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$. If successful, we will try to extend these measurements to lower γ -ray energies.

[Oue92] J. M. L. Ouellet *et al.*, Phys. Rev. Lett. **69**, 1896 (1992).

[Red87] A. Redder *et al.*, Nucl. Phys. **A462**, 385 (1987).

4.1.7 Investigation of $^{22}\text{Ne}(p, \gamma)^{23}\text{Na}$ and $^{23}\text{Na}(p, \gamma)^{24}\text{Mg}$ Using ($^3\text{He}, d$) Spectroscopy

J.C. Blackmon, A.E. Champagne, S.E. Hale, V.Y. Hansper, C. Iliadis, and D.C. Powell

The reactions that produce and destroy sodium in globular cluster red giants are determined primarily by the contributions of low-lying (p, γ) resonances. These reactions are responsible for the observed sodium-oxygen abundance anticorrelations [Lan93]. One explanation for this effect is deep, non-convective mixing between the envelope of the star

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and the upper levels of the hydrogen burning shell [Swe79]. Because the temperature gradient is steep across this region, nuclear reaction rates can vary greatly. Thus, the final abundances are a sensitive function of mixing depth. There are resonances in two of the reactions that affect the sodium abundances, $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ and $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$, which currently have sizable uncertainties in their strengths. At the stellar energies involved in the appropriate temperature region, $T_9=0.03-0.08$, the individual resonance reactions are dominated by the proton partial width, Γ_p , which is immeasurably small. The proton partial width can be calculated using C^2S , where C is an isospin Clebsch-Gordon coefficient and S is a spectroscopic factor, and a single-particle partial width, Γ_{sp} :

$$\Gamma_p = C^2S \times \Gamma_{sp}.$$

We have measured the proton-stripping reactions $^{22}\text{Ne}(^3\text{He},d)^{23}\text{Na}$ and $^{23}\text{Na}(^3\text{He},d)^{24}\text{Mg}$ using the Enge Split-Pole Spectrometer. The cross sections will be compared with Distorted Wave Born Approximation (DWBA) calculations to determine C^2S .

The $^{22}\text{Ne}(^3\text{He},d)^{23}\text{Na}$ reaction was measured in September, 1997, while the reactions $^{23}\text{Na}(^3\text{He},d)^{24}\text{Mg}$ and $^{27}\text{Al}(^3\text{He},d)^{28}\text{Si}$ were measured in February, 1998. The latter was measured in order to investigate the behavior of the focal-plane detector. All were measured at a beam energy of 20 MeV. Angular distributions were collected for each reaction between 3° and 35° . Implanted ^{22}Ne targets, evaporated ^{23}Na and $^{23}\text{NaBr}$ targets and self-supporting ^{27}Al targets were used. A charged-particle telescope was placed in the target chamber to monitor the targets during bombardment.

Analysis of the $^{22}\text{Ne}(^3\text{He},d)^{23}\text{Na}$ data is ongoing. The angular distributions for 9 states have been analyzed using the DWBA code DWUCK4 [Kun83]. Two of these are shown in Figure 4.1-6 for the states 8.828 and 9.701 MeV. These correspond to resonances at 34 and 907 keV (c.m.), respectively. The parameter of interest, C^2S , is obtained by comparing the experimental cross section with that predicted by DWUCK4. The two cross sections are related via

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = N \frac{(2J_f + 1)}{(2J_t + 1)(2j + 1)} C^2S \left(\frac{d\sigma}{d\Omega}\right)_{DWBA}$$

in which N is the overlap integral of the ^3He in the entrance channel and the deuteron in the exit channel, J_f is the spin of the final state, J_t is the spin of the target, j is the spin of the transferred particle.

The deuteron spectra from the $^{23}\text{Na}(^3\text{He},d)^{24}\text{Mg}$ and $^{27}\text{Al}(^3\text{He},d)^{28}\text{Si}$ reactions have been re-sorted offline and calibrated for further analysis. A section of the 17.5° spectra from the NaBr target is shown in Figure 4.1-7. The spectrum has been calibrated as a function of deuteron energy, with peaks from contaminants in the target being labelled by the final state formed.

Analysis of the data is expected to be completed before the end of the year, resulting in improved reaction rates for the reactions which produce and destroy sodium. Preliminary

[illegible]

Figure 4.1-7: Deuteron spectrum from $^{23}\text{Na}(^3\text{He},d)^{24}\text{Mg}$ at $E_{^3\text{He}} = 20$ MeV and $\theta = 17.5^\circ$. Peaks are labeled by excitation energy in ^{24}Mg or as background final states.

results indicate that the reaction rates are at the current lower limit, requiring the mixing to go deeper into the star than is currently believed to occur. Network calculations will be run to determine the effects of the new rates on the sodium abundances.

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[Lan93] G. E. Langer, R. Hoffman, and C. Sneden, *Pub. Astron. Soc. Pac.* **105**, 301 (1993).

[Swe79] A. V. Sweigart and J. G. Mengel, *Ap. J.* **229**, 624 (1979).

4.1.8 Thermonuclear Reaction Rate of $^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$

P.M. Endt¹, M. Fantini², H. Herndl³, C. Iliadis, and H. Oberhummer³

Explosive stellar burning of hydrogen in the mass $A > 20$ range is characterized by a large number of proton-capture reactions and β decays. At low stellar temperatures $T_9 < 0.1$ the isotope ^{23}Mg is synthesized in the NeNa-cycle. Under such conditions the β decay of ^{23}Mg and the subsequent $^{23}\text{Na}(p,\alpha)$ reaction convert material back into ^{20}Ne , giving rise to cycling of material in the NeNa mass range. If the stellar temperature is sufficiently high the proton-capture reaction on ^{23}Mg becomes faster than the competing β decay. In this case the reaction flow breaks out of the NeNa mass region and a whole range of heavier nuclei could be synthesized, depending on the temperature-density conditions and the duration of the astrophysical event. This scenario, for example, might be responsible for the synthesis of elements such as Si, S and Ar, which have been found to be overabundant in the ejecta of ONeMg novae [Pol95]. Therefore, a quantitative estimate of the stellar reaction rate for $^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$ is important in order to model the nucleosynthesis in the mass $A > 20$ range.

We have reanalyzed the $^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$ reaction rate for several reasons. First, in previous work [Kub95] it was pointed out that the analog assignments of the two lowest-lying proton threshold states in ^{24}Al are still uncertain, resulting in large errors of the derived stellar reaction rates. Second, the proton and γ -ray partial widths of the resonances in question have never been measured. These quantities were crudely estimated in previous work by adopting ‘typical’ single-particle spectroscopic factors and ‘average’ γ -ray transition strengths.

In the present work we use ^{24}Al excitation energies recommended by Ref. [End98] which are based on previously published experimental results. We present additional support for the analog assignments of the proton-threshold levels in ^{24}Al . Furthermore, we calculate

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the proton and γ -ray partial widths of astrophysically important levels by using the nuclear shell model. Our results show that the direct capture process determines the stellar rates at low temperatures of $T_9 < 0.2$. The $E_R=478$ keV resonance dominates the reaction rates in the range $T_9=0.2-1.0$. The $E_R=663$ keV resonance is of importance at high temperatures above $T_9=1$ only. The resonances at $E_R=939$ and 1029 keV are negligible over the whole temperature range. Our results are compared in Figure 4.1-8 with previous work. At stellar temperatures above $T_9=1$ the reaction rates of the present work are smaller than previous results by about 70%. In the temperature range $T_9=0.2-0.5$ important for hydrogen burning in novae the present reaction rates deviate up to a factor of 3 from the values given in Kubono *et al.*, and up to a factor of 2 from the results of Wiescher *et al.* The reaction rates for $^{23}\text{Mg}+p$ are therefore now based on more consistent experimental and theoretical input parameters.

Figure 4.1-8: Ratio of the present reaction rate to previous results of Wiescher *et al.* [Wie86] and Kubono *et al.* [Kub95]. The reaction rates are based on measured ^{24}Al excitation energies.

Figure 4.1-9 presents temperature and density conditions for which the proton capture reaction on ^{23}Mg and the ^{23}Mg β decay are of equal strength. Recent results of hydrodynamic studies of ONeMg novae [Pol95] are also shown. The full circles represent temperature and density conditions at the peak of the thermonuclear runaway for accretion onto white dwarfs of different initial masses ($1.00M_{\odot}$, $1.25M_{\odot}$ and $1.35M_{\odot}$). Our results indicate that for white dwarfs of masses $\leq 1.25M_{\odot}$ the proton-capture reaction on ^{23}Mg is slower than the competing β decay and, therefore, is of minor importance for the resulting nucleosynthesis.

Figure 4.1-9: Temperature-density boundary at which the proton-capture reaction on ^{23}Mg and the ^{23}Mg β decay are of equal strength. Peak temperature and density conditions achieved in the nova models of Ref. [Pol95] are indicated by full circles.

However, for accretion onto very massive white dwarfs ($1.35M_{\odot}$ model of Ref. [Pol95]) the $^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$ reaction dominates over the ^{23}Mg β decay and will influence the nucleosynthesis in the mass $A > 20$ range. Details regarding our work can be found in Ref. [Ili].

[End98] P. M. Endt, Nucl. Phys. **A633**, 1 (1998).

[Ili] C. Iliadis *et al.*, in print (1998).

[Kub95] Kubono *et al.*, Nucl. Phys. **A588**, 521 (1995).

[Pol95] M. Politano *et al.*, Astrophys. J. **448**, 807 (1995).

[Wie86] M. Wiescher *et al.*, Astron. Astrophys. **160**, 56 (1986).

4.1.9 Determination of the $^{24}\text{Mg}(p,\gamma)^{25}\text{Al}$ Reaction Rate at Low Stellar Temperatures

A.E. Champagne, C.A. Grossmann, S.E. Hale, V.Y. Hansper, C. Iliadis, L.K. McLean, E.F. Moore, and D.C. Powell

Isotopic anomalies (C, O, N, Na, Al, and Mg) observed on the surface of globular cluster red giant branch stars are thought to be the result of mixing of material from the envelope into regions of hydrogen burning [Swe79]. Recent observations made by Shetrone show an anticorrelation between the isotopic abundances of Al and ^{24}Mg on the surfaces of M13 red giant stars [She97]. The rates of production of Al and destruction of ^{24}Mg depend on the $^{24}\text{Mg}(p,\gamma)^{25}\text{Al}$ reaction rate at stellar temperatures $T_9 \approx 0.04 - 0.07$ [Cav98], which is influenced by the total width Γ of the $E_p = 223$ keV ($E_x = 2485$ keV) resonance [Zai97].

The total width of this resonance can be determined experimentally using two methods. The first method requires measuring the strength $\omega\gamma$ and the branching ratio Γ_γ/Γ of the $E_p = 223$ keV resonance. The total width Γ can be calculated from these two measurements. The preliminary value for the ratio is $\Gamma_\gamma/\Gamma = 0.907 \pm 0.031$. The experiment is described in more detail in [Pow97]. For $\omega\gamma$ we measured a value of 12.45 ± 0.92 meV (Sect. 4.1.10).

Another method for determining the total width Γ is measuring the mean lifetime τ_m of the corresponding compound nuclear state at $E_x = 2485$ keV state using the Doppler-Shift Attenuation Method (DSAM). The width of the state is determined through the relation $\Gamma = \hbar/\tau_m$. The observed shift in a γ -ray energy is described by

$$\Delta E = E_{\gamma_0} F(\tau_m) \frac{v_o}{c} \cos(\theta) \quad \text{where,} \quad (4.1)$$

$$F(\tau_m) = \frac{1}{v_o c} \int_0^\infty v e^{-t/\tau_m} \overline{\cos(\phi)} dt \quad (4.2)$$

and E_{γ_0} is the γ -ray energy with no Doppler shift, $F(\tau_m)$ is the ratio of the average Doppler shift relative to the full Doppler shift, τ_m is the mean lifetime of the state, θ is the angle of the detector relative to the incident particle direction, v is the velocity of the recoiling nucleus (v_o is the initial recoil velocity), c is the speed of light, t is time, e^{-t/τ_m} describes the radioactive decay of the recoiling nucleus, and ϕ is the angle of divergence of the recoiling nucleus from the original recoil direction due to interactions with the target nuclei.

The DSAM measurement took place at the High Resolution Laboratory at TUNL. Protons were incident onto a thick ^{24}Mg implanted target. Collimators allowed for a 3 mm diameter beam spot and ≈ 7 μA of beam current on target. A cold trap placed just before the target helped to reduce carbon buildup on the target. Water cooling was applied to the target to prevent target deterioration. The protons were incident with $E_p = 1616$ keV in order to populate the $E_x = 3823$ keV excited state in ^{25}Al . Three 60% Ge detectors were placed at 0° , 90° , and 140° with respect to the incident proton beam direction. The

distances of the detectors were approximately 10 cm from the target location and lead shielding was used to reduce background contributions.

The $E_x = 3823$ keV state was found to decay to the state of interest ($E_x = 2485$ keV) with a branching ratio of 7%, which subsequently decays to the first excited state ($E_\gamma = 2034$ keV) with an 82% branching ratio, to the second excited state ($E_\gamma = 1541$ keV) with a 15% branching ratio, and to the ground state with a 3% branching ratio. A sample spectrum showing the 2034 keV γ -ray line at the three different detector angles is shown in Figure 4.1-10.

To obtain the mean lifetime from the observed $F(\tau_m)$ value one must understand the slowing down process of the recoiling nuclei. A program written by E.F. Moore (FITFTAU) was modified in order to take low recoil velocities properly into account. Given a target of known stoichiometry and density, the stopping powers are calculated using TRIM and incorporated into the FITFTAU program. The program numerically integrates Eq. 4.2 and generates for a given lifetime the value for $F(\tau_m)$. Data analysis and testing of the program are underway.

Figure 4.1-10: The Doppler Shifted γ rays used to determine the value for $F(\tau)$ from which the mean lifetime τ is determined.

[Cav98] R. M. Cavallo *et al.*, Ap. J. **492**, 492 (1998).

[Pow97] D. C. Powell *et al.*, TUNL Progress Report, **XXXVI**, 73 (1997).

- [She97] M. D. Shetrone, *Astron. J.* **112**, 2639 (1997).
 [Swe79] A. V. Sweigart and J. G. Mengel, *Ap. J.* **229**, 624 (1979).
 [Zai97] C. S. Zaidins and G. E. Langer, *Pub. Astron. Soc. Pac.* **109**, 252 (1997).

4.1.10 Low-Energy Resonance Strengths for Proton Capture on Mg and Al Nuclei

A.E. Champagne, S.E. Hale, V.Y. Hansper, C. Iliadis, D.C. Powell, R.A. Surman, and K.D. Veal

The knowledge of absolute resonance strengths is crucial in several subfields of nuclear physics. For example, measurements of resonance strengths yield information on partial widths for transitions involved in a nuclear reaction and can be used to test quantitative predictions of various nuclear models. In the field of nuclear astrophysics absolute resonance strengths also play an essential role in the determination of reaction rates for stellar sites where nuclear reactions proceed through isolated and narrow resonances. Because of large discrepancies for resonance strengths in the literature we present a new standard set of absolute (p, γ) resonance strengths for proton captures on the nuclei ^{24}Mg , ^{25}Mg , ^{26}Mg and ^{27}Al .

The experiments took place at TUNL. Protons extracted from the ABPIS source and accelerated through the minitandem were incident on transmission targets located inside a scattering chamber. A charged-particle detector was placed at a distance of 7.6 cm from the target and an angle of 155° with respect to the incident protons. The charged-particle detector observed the elastically scattered protons from the target. A 128% Ge detector was placed at a distance of 7 cm and an angle of 125° . The Ge detector observed the γ rays emitted from the de-excitation of the compound nuclei. Targets were fabricated by evaporating Mg and Al metal onto $20 \mu\text{g}/\text{cm}^2$ C foils. The targets were about 5 keV thick at $E_p \approx 400$ keV.

As a result of the low incident bombarding energy, the proton scattering can be described by Rutherford scattering. If the resonant γ -ray yield is measured simultaneously with the scattered protons and the target thickness is large compared to the width of the resonance, the resonance strength can be written

$$\omega\gamma = \frac{2}{\lambda^2} \frac{1}{B_\gamma W_\gamma(\theta)} \frac{\Omega_{cm}}{\epsilon_\gamma} \int_0^\infty \frac{N_\gamma(E)}{N'_p(E)} \sigma_{Ruth}(E) dE, \quad (4.3)$$

where λ is the de Broglie wavelength of the incident particle, Ω_{cm} is the solid angle subtended by the charged-particle detector in the center-of-mass system, B_γ is the branching ratio of the γ ray observed, ϵ_γ is the photopeak efficiency of the Ge detector, W_γ is the angular

Table 4.1-2: Preliminary Resonance Strength Values

Reaction	E_p (keV)	$\omega\gamma$ (meV) Present
$^{24}\text{Mg}(p,\gamma)^{25}\text{Al}$	223	12.45 0.92
$^{24}\text{Mg}(p,\gamma)^{25}\text{Al}$	419	42.8 2.9
$^{25}\text{Mg}(p,\gamma)^{26}\text{Al}$	435	93.9 5.6
$^{26}\text{Mg}(p,\gamma)^{27}\text{Al}$	338	325 14
$^{26}\text{Mg}(p,\gamma)^{27}\text{Al}$	454	729 44
$^{27}\text{Al}(p,\gamma)^{28}\text{Si}$	406	8.79 0.57

distribution of the γ rays, $N_\gamma(E)$ is the observed γ -ray yield, $N'_p(E)$ is the number of observed scattered protons and $\sigma_{Ruth}(E)$ is the calculated Rutherford scattered cross section at the incident proton energy E .

One of the largest contributions to uncertainties in the final value of the resonance strength derives from the efficiencies of the charged-particle detector and the Ge detector. The relative photopeak efficiency of the Ge detector was determined at low energies from a ^{56}Co source and at higher energies from well-known $^{27}\text{Al}(p,\gamma)^{28}\text{Si}$ resonances at $E_p = 992$ and 1317 keV. The ratio $\Omega_{cm}/\epsilon_\gamma$ of the charged-particle and Ge detection efficiencies was determined from the $^{19}\text{F}(p,\alpha_2\gamma)^{16}\text{O}$ reaction at $E_p = 340$ keV. The reaction produces 1.7 MeV α_2 particles and 6129 keV γ rays in equal numbers.

Another source of uncertainty are γ -ray branching ratios. The $^{24}\text{Mg}(p,\gamma)$ branching ratios for the $E_p = 223$ and 419 keV resonances and for the $E_p = 406$ keV resonance in $^{27}\text{Al}(p,\gamma)$ were measured in the present experiment. Branchings for the other states were taken from the literature [Maa78, End88]. Preliminary resonance strengths are listed in Table 4.1-2.

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[Maa78] J. W. Maas *et al.*, Nucl. Phys. **A310**, 237 (1978).

4.1.11 Explosive Hydrogen Burning of ^{27}Si , ^{31}S , ^{35}Ar and ^{39}Ca in Novae and X-ray Bursts

P.M. Endt¹, C. Iliadis, N. Prantzos², and W.J. Thompson³

The proton captures on the radioactive target nuclei ^{23}Mg , ^{27}Si , ^{31}S , ^{35}Ar and ^{39}Ca have been identified in the literature [Rem97] as the key reactions for an understanding of explosive hydrogen burning nucleosynthesis in the mass region above $A = 20$. Recently, we have reevaluated the stellar rates for $^{27}\text{Si}+p$, $^{31}\text{S}+p$, $^{35}\text{Ar}+p$ and $^{39}\text{Ca}+p$. Our new reaction rates are based on the most recent experimental nuclear structure information. In the current literature, realistic uncertainties are usually not assigned to stellar reaction rates and, consequently, little information is available regarding the reliability of the published results. Therefore, we have compared nuclear structure properties (i.e., excitation energies, spectroscopic factors, proton partial widths and γ -ray partial widths) of states belonging to the same isospin multiplet, in order to estimate the uncertainties involved. Based on these results, we have deduced for the first time reliable uncertainties of our reaction rates. Subsequently, we have incorporated our results into reaction network calculations and investigated astrophysical consequences of varying the reaction rates within their uncertainties. We specifically address the question if additional experimental work (e.g., direct cross-section measurements with radioactive ion beams) is needed in order to improve the nuclear physics input information entering hydrodynamic simulations of specific astrophysical events. Some of our nuclear physics methods and results have been described previously [Ili97]. Here, we outline the results of our reaction network calculations. For more specific information, see Ref. [Ili98].

For the nuclear burning in ONeMg novae we find that reaction rate uncertainties of proton captures on ^{27}Si , ^{31}S , ^{35}Ar and ^{39}Ca change the calculated final abundances and the total nuclear energy generation by negligible amounts only. Even arbitrary variations in reaction rates by factors of 10 change the final abundances by less than 50%. This variation is smaller than uncertainties of observed elemental nova abundances (typically a factor of two) and cannot be regarded as substantial. For the nuclear burning in type I X-ray bursts (Figure 4.1-11) we have shown that uncertainties in the $^{27}\text{Si}+p$, $^{31}\text{S}+p$, $^{35}\text{Ar}+p$ and $^{39}\text{Ca}+p$ reaction rates have a negligible effect on the total nuclear energy generation and on the residual hydrogen or helium abundance. Final abundances of other isotopes change by less than 55%. Arbitrary reaction rate variations by factors of 10 cause slightly larger abundance changes. However, these reaction rate uncertainties influence only abundances of nuclei in the mass $A = 40-48$ range with very small overproduction factors. Therefore, we expect only negligible astrophysical consequences, even if a fraction of the processed

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Figure 4.1-11: Major nuclear abundance flows for an X-ray burst model. The thickest solid arrows show dominant nuclear flows. Arrows of intermediate (smallest) thickness correspond to flows which are at least one (two) order(s) of magnitude weaker compared to the maximum flow. Stable isotopes are represented by shaded squares.

material escapes the large gravitational potential well of the neutron star. In conclusion, the present study provides stellar rates for the $^{27}\text{Si}+p$, $^{31}\text{S}+p$, $^{35}\text{Ar}+p$ and $^{39}\text{Ca}+p$ reactions that are of sufficient accuracy for quantitative predictions of nuclear burning processes in novae and type I X-ray bursts. Contrary to the suggestion of Ref. [Rem97], we find in the present study no compelling evidence for measuring these reactions at radioactive ion beam facilities.

[Ili97] C. Iliadis *et al.*, TUNL Progress Report, **XXXVI**, 78 (1997).

[Ili98] C. Iliadis *et al.*, submitted for publication, 1998.

[Rem97] F. Rembges *et al.*, *Astrophys. J.* **484**, 412 (1997).

4.1.12 Study of the $^{40}\text{Ca}(^3\text{He},t)^{40}\text{Sc}$ Reaction

A.E. Champagne, S.E. Hale, V.Y. Hansper, C. Iliadis, and D.C. Powell

Proton-rich nuclei are produced in explosive hydrogen burning and possible sites for this process include accreting white dwarf stars in close binary systems (novae), and accreting neutron stars (Type I X-ray bursts.) The isotopes ^{23}Mg , ^{27}Si , ^{31}S , ^{35}Ar and ^{39}Ca have been predicted to be waiting points in the reaction flow [Wie89] and therefore are candidates for direct (p,γ) cross-section measurements [Rem97]. These beams are costly to develop and therefore the importance of these reactions needs to be verified. Iliadis *et al.* [Ili98] have calculated the effect of these reactions on nucleosynthesis energy generation and using existing nuclear data they found that the significance of these reactions was not as great as first assumed. To complement this study, an experimental program to check the nuclear parameters used in the calculations by Iliadis *et al.* was started. The first of these measurements was designed to examine the relevant energy levels in ^{40}Sc .

For $A = 40$, the flow of nucleosynthesis proceeds via the proton capture sequence $^{39}\text{Ca}(p,\gamma)^{40}\text{Sc}(p,\gamma)^{41}\text{Ti}$. Since the Q -value for $^{39}\text{Ca}(p,\gamma)^{40}\text{Sc}$ is low, ($Q = 0.5391$ MeV), its reaction rate is determined by three resonances corresponding to the 2nd, 3rd and 4th excited states of ^{40}Sc . It has also been surmised that the 4th excited state could be a triplet state [Shu71]. These states were populated via the $^{40}\text{Ca}(^3\text{He},t)^{40}\text{Sc}$ reaction at 26.0 MeV. Outgoing tritons were detected at the focal plane of the Enge split-pole spectrometer. Data were collected at $\theta_{\text{lab}} = 5^\circ$, 10° and 15° . Analysis of this data is partially completed, and at this stage, it appears that there is no multiplet state at the 4th excited state of ^{40}Sc .

Some data for a similar measurement with a ^{28}Si target were taken at the end of the most recent run in April of 1998. Analysis of these data is currently in progress, however more data are required to complete the analysis.

Figure 4.1-12: Calibrated $^{40}\text{Ca}(^3\text{He},t)^{40}\text{Sc}$ spectrum taken at $\theta_{lab}=10^\circ$. Peaks from ^{40}Sc are labelled according to the energy of the residual excited state in keV. Errors on these assignments are presently ± 20 keV. Contaminant peaks from ^{16}O are labelled as ^{16}O . Note that the peaks at 1807 and 2390 are contaminated by lines from ^{16}O .

- [Ili98] C. Iliadis *et al.*, submitted for publication, 1998.
- [Rem97] F. Rembges *et al.*, *Astrophys. J.* **484**, 412 (1997).
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- [Wie89] M. Wiescher and J. Görres, *Astrophys. J.* **346**, 1041 (1989).

4.2 Nucleon Induced Reactions

4.2.1 The ${}^9\text{Be}(\vec{p},d){}^8\text{Be}$ and ${}^9\text{Be}(\vec{p},\alpha){}^6\text{Li}$ Reactions at Low Energies

C.R. Brune, W.H. Geist, H.J. Karwowski, E.J. Ludwig, and K.D. Veal

The Be abundance in low-metallicity stars is an important probe of cosmic-ray and Big-Bang nucleosynthesis, as well as stellar evolution models. In particular, significant Be depletion is observed in some stars. This depletion presumably results from the mixing of material from the stellar surface with material from the interior where the temperature is sufficient for the ${}^9\text{Be}(p,d){}^8\text{Be}$ and ${}^9\text{Be}(p,\alpha){}^6\text{Li}$ reactions to be effective. A previous measurement [Sie73] indicated that a subthreshold state at $E = 6.57$ MeV in ${}^{10}\text{B}$ may significantly enhance the cross section for ${}^9\text{Be}(p,d){}^8\text{Be}$ at very low energies. The rate of stellar Be depletion may thus be significantly higher than usually assumed.

We have measured angular distributions of cross section and analyzing power for seven energies with $77 \leq E_p \leq 321$ keV. We confirm the finding of [Sie73] that the ${}^9\text{Be}(p,d){}^8\text{Be}$ differential cross section is highly anisotropic about $\theta_{c.m.} = 90^\circ$. The large anisotropy at very low energies is unusual – in fact it was this finding which led previous workers to assume that the tail of the subthreshold state was making a substantial p -wave contribution to the cross section. However, we find the analyzing power at low energies to be very small, which is inconsistent with the properties of the the 6.57-MeV state assumed in [Sie73]. Our analysis indicates that the anisotropy can be easily explained by assuming a direct reaction mechanism, and that the presence of the subthreshold level does *not* lead to an enhancement of the cross section at very low energies.

These data and conclusions are now published [Bru98]. A detailed study of the sensitivity of Be depletion to the destruction reaction rates in various stellar environments has also recently been performed [Bro98]. The large enhancements in the ${}^9\text{Be}+p$ reaction rates considered in this paper are ruled out by our work. Subsequent to the completion of our study, improved low-energy unpolarized cross-section data have been reported by the Bochum group [Zah97]. Significant enhancements of the low-energy S factors are seen, which the authors attribute to electron screening. Their conclusions concerning the direct reaction mechanism and the thermonuclear reaction rate are very similar to our own, although the screening correction implied by their analysis is 3–4 times that predicted by atomic physics models.

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[Bru98] C. R. Brune *et al.*, *Phys. Rev.* **C57**, 3437 (1998).

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[Zah97] D. Zahnow *et al.*, Z. Phys. **A359**, 211 (1997).

4.2.2 Search for the $E_R=351$ keV Resonance in $^{35}\text{Cl}(p,\alpha)^{32}\text{S}$

A.E. Champagne, S.E. Hale, V.Y. Hansper, C. Iliadis, B. Kehler, B. Kirkwood, D.C. Powell, J.G. Ross¹, and C. White²

The two competing reactions $^{35}\text{Cl}(p,\gamma)^{36}\text{Ar}$ and $^{35}\text{Cl}(p,\alpha)^{32}\text{S}$ influence the synthesis of elements Si, S and Ar, which have been found to be overabundant in the ejecta of ONeMg novae [Pol95]. While the stellar rates for the (p,γ) reaction are well known in the important stellar temperature range $T_9=0.2-0.4$, the rates of the (p,α) reaction are uncertain by large factors. Furthermore, in a recent β -delayed α -particle decay study of ^{36}K [Ili96], a new α -particle emitting state in ^{36}Ar has been found which might dominate the (p,α) stellar reaction rates.

We have described previously [Ili97] a first attempt to search for the corresponding resonance at $E_R=351$ keV in $^{35}\text{Cl}(p,\alpha)$. In the present work we have improved the experimental setup. A new scattering chamber has been constructed which allows the simultaneous detection of α particles and γ rays in close geometry. The NaCl transmission targets used in our early study were found to be unstable under proton bombardment. Instead, we used directly water-cooled BaCl_2 beam-stop targets which were stable over the course of our measurements. Thick ($2.2\text{ }\mu\text{m}$) Havar foils were placed in front of the charged-particle detector in order to minimize the large number of elastically scattered protons incident on the detector. The energy calibration of the detector (with foil) was obtained by measuring α particles from the (p,α) reactions on ^{19}F and ^{23}Na . We find no indication of an α -particle group at the expected peak position. The data are currently being analyzed in order to determine an experimental upper limit on the strength of this expected (p,α) resonance.

[Ili96] C. Iliadis *et al.*, Nucl. Phys. **A609**, 237 (1996).

[Ili97] C. Iliadis *et al.*, TUNL Progress Report, **XXXVI**, 78 (1997).

[Pol95] M. Politano *et al.*, Astrophys. J. **448**, 807 (1995).

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4.3 Radioactive Beams

4.3.1 Nuclear Astrophysics with Radioactive Beams

A.E. Champagne for the RIBENS collaboration¹

Reactions involving radioactive nuclei are an important component of nucleosynthesis in stellar explosions such as novae, X-ray bursts and supernovae. In the case of novae and X-ray bursts, they (along with reactions on stable nuclei) are also the primary energy source. Our understanding of these events comes from a comparison between observations and detailed numerical simulations. Important ingredients in the latter are detailed thermonuclear reaction rates and nuclear systematics. The work of the RIBENS collaboration at the Holifield Radioactive Ion Beam Facility (HRIBF) is centered on direct measurements of astrophysically-interesting reactions. We have proposed 5 experiments using beams of ^{17}F , ^{18}F and ^{56}Ni and all were approved by the Oak Ridge PAC. Our first priority is a measurement of $^{17}\text{F}(p,p)^{17}\text{F}$ which will be used to locate an important resonance in the $^{17}\text{F}(p,\gamma)$ reaction. We hope to begin taking data during the summer of 1998.

During the past year, our work has focused on commissioning the Daresbury Recoil Separator (DRS) and on simulating RIB experiments using stable beams. The DRS will be used to separate capture recoils from the beam and its critical operating parameters are the beam-rejection factor and transport efficiency. Ideally, we would like to see no beam at the focal plane and to have the transport efficiency determined solely by the charge-state fraction of the recoils. In reality, some beam particles will always find their way to the focal plane and therefore it is important that the focal-plane detector be able to distinguish these from the recoils of interest. Although the DRS optics have been modified and a new time-of-flight leg has been added, we have retained the original focal-plane detectors because they have proven to work very well for our purposes.

After initial test runs with the DRS, we measured the $^1\text{H}(^{12}\text{C},^{13}\text{N})\gamma$ reaction at $E_{12} = 8.65$ MeV ($E_{c.m.} = 670$ keV) using a polypropylene target. A particle-identification spectrum is shown in Figure 4.3-1. The continuous band in the spectrum is produced by the 500 ^{12}C 's that made it to the focal plane by scattering, charge-changing collisions, etc. during 9.2 hrs of bombardment. However, this corresponds to 1.7×10^{-11} of the incident beam. This beam-rejection factor can be improved, but it is already adequate for our experiments. The ^{13}N group can be cleanly identified, but the yield is only 14% of what was expected from the known cross section. We believe that the problem stems from both the beam tune and the DRS tune and we are presently working to resolve it.

Our $^{17}\text{F}(p,p)^{17}\text{F}$ study does not use the DRS at all and so we have been able to develop this experiment in parallel with DRS-related activities. To simulate this measurement, we

¹Involving TUNL, Oak Ridge National Laboratory, Yale Univ., Tennessee Tech. Univ., Univ. of Edinburgh, Ruhr-Universität Bochum, Univ. of Bombay, C.I.A.E., and Univ. of Liverpool.

Figure 4.3-1: A ΔE - E spectrum of recoils from the $^1\text{H}(^{12}\text{C},^{13}\text{N})\gamma$ reaction.

Figure 4.3-2: Excitation function for the $^1\text{H}(^{17}\text{O},^{17}\text{O})^1\text{H}$ reaction. The solid curve is a 2-level Breit-Wigner fit.

populated known resonances in the $^{17}\text{O}(p,p)^{17}\text{O}$ reaction at $E_{c.m.} = 556$ and 676 keV. These energies are near to the expected location of the resonance of interest in ^{18}Ne and so the kinematics for the two reactions are quite similar. Scattered protons were detected in a partial annulus of single-sided Si strip detectors based on the LEDA design. The target was a thin plastic foil and the beam current was limited to $10^5 - 10^6/\text{s}$ in order to mimic the expected operating conditions with a ^{17}F beam. Past measurements of elastic scattering with radioactive beams (see e.g. [Cos94]) have used thick targets. The advantage of this approach is that a wide range of energies can be sampled simultaneously, but it does require a careful deconvolution of the measured line shape to extract a cross section. With a thin target, we avoided the deconvolution at the expense of having to change the beam energy for each step in the excitation function. Since the energy could be changed rather quickly and since the target remained stable during the run, this appears to be a viable technique.

The resulting excitation function is shown in Figure 4.3-2. The data were fit with a simple, 2-level Breit-Wigner expression. The widths and spins that we extract from the fits are in agreement with the tabulated values, but the resonance energies of 553 and 667 keV are lower than the accepted values of 556 and 676 keV. Some of the discrepancy may result from the simple 2-level fit, but it is also possible that the energy calibration of the tandem accelerator is off.

We have also successfully developed a second measurement, involving the $^1\text{H}(^{17}\text{F},\alpha)^{14}\text{O}$ reaction. Assuming that a beam current of $10^5/\text{s}$ can be achieved, then we expect that both experiments can be run during the upcoming year.

[Cos94] R. Coszach *et al.*, Phys. Rev. **C50**, 1695 (1994).

5 Rare Nuclear Processes

5.1 Double-Beta Decay

5.1.1 Measurement of the $\beta\beta$ Decay Rate of ^{100}Mo to the First Excited 0^+ State in ^{100}Ru

L. DeBraekeleer, H.K. Gerberich, C.R. Gould, M.J. Hornish, and W. Tornow

Two groups have attempted the observation of the double-beta ($\beta\beta$) decay of ^{100}Mo to the first excited 0^+ state of ^{100}Ru by looking for the single γ rays characteristic of the de-excitation of this level. Assuming similar matrix elements to those governing the transition to the ground state, one expects a partial half-time of 4×10^{20} years. At present the two groups report conflicting results: $(6.1^{+1.8}_{-1.1}) \times 10^{20}$ years [Bar95] and a null result at the level of 1.2×10^{21} years [Blu92]. Very low background-detection systems have been developed for these experiments. The detectors were built using low-radioactivity materials and they were operated in an underground laboratory which offers efficient shielding against the cosmic-ray background.

In the present work, the background problem was approached differently: we detected *in coincidence* the two γ rays following the $\beta\beta$ decay of ^{100}Mo to the first excited 0^+ state of ^{100}Ru . We believe that the detection of the two gamma rays, $E_{\gamma 1} = 539.6$ keV and $E_{\gamma 2} = 590.8$ keV, in coincidence, is a necessary and sufficient condition to prove the existence of the $\beta\beta$ -decay transition to the first excited state in ^{100}Ru . Indeed, the $\beta\beta$ decay to this state necessarily implies the emission of two photons since the transition to the ground state is forbidden ($0^+ \rightarrow 0^+$). Both transitions have very low internal transition probabilities and the lifetime of the intermediate state is very short compared to the resolution time of the electronics. To argue that it is also a sufficient condition, one must show that no other mechanism can generate these two photons in coincidence. Because the energy of a γ ray is highly characteristic of the nucleus from which it has been emitted, the detection, with good energy resolution, of two γ rays in coincidence can be unambiguously ascribed to a unique nucleus. Therefore, the only plausible mechanisms of background would be the neutron excitation of ^{100}Ru located close to the setup or the $^{100}\text{Ru}(n,p)^{100}\text{Tc}$ reaction which subsequently β^- decays to the first excited 0^+_1 state in ^{100}Ru with a small branching ratio. Both processes would also occur for the ^{102}Ru isotope which is more abundant than the ^{100}Ru isotope, 31.6% vs. 12.6%. The coincidence between the photons emitted by the ^{102}Ru isotope, $E_{\gamma 1} = 475.1$ keV and $E_{\gamma 2} = 468.6$ keV, is experimentally not observed. We conclude that these mechanisms do not generate a measurable background for the present experiment which we now describe.

A disk of natural Molybdenum (9.6% ^{100}Mo) is sandwiched between the front faces of two large high-purity Germanium detectors. The optimum thickness of the sample results from a compromise between the total number of atoms and the escape probability of the two photons. The detectors, 85 mm diameter by 50 mm length, were custom made by EG&G Ortec. The probability to detect the full energy of both photons has been determined by measurement with radioactive sources and by Monte-Carlo simulation [Poo]. This determination includes the effects of the extended geometry, the attenuation of the photons in the sample, the full energy peak efficiency of the detectors and the strongly anisotropic angular correlation between the γ rays. We find $\epsilon = 1.0\%$. The setup is surrounded by an active veto counter (NaI annulus) and inserted in a passive shielding made of lead bricks. The background at the expected location of the signal is about 1 count per keV^2 per year when the coincidence between the two Germanium detectors is required and 0.1 count per keV^2 per year when the active veto is used in addition. In a counting period of 5 months, we have detected 3 coincidences between a 540 keV and a 590 keV photon which implies a lifetime in the order of 10^{21} years. There is no evidence for a transition to the second excited 0^+ state and the 2^+ state in ^{100}Ru , which implies a lower limit of 10^{22} years for these transitions.

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[Blu92] D. Blum *et al.*, Phys. Lett. **B274**, 408 (1992).

[Poo] A. Poon and L. DeBraekeleer, to be submitted to Nucl. Instrum. Methods.

5.1.2 Production of a ^{102}Rh Source

L. DeBraekeleer, H.K. Gerberich, C.R. Gould, M.J. Hornish, and W. Tornow

The determination of the efficiency of a double-beta decay apparatus where a coincidence between two photons is required is a rather difficult problem. We have addressed this question by a Monte-Carlo simulation [Poo]. This calculation includes the effects of the extended geometry, the attenuation of the photons in the sample, the full-energy peak efficiency of the Germanium detectors and the strongly anisotropic angular correlation between the γ rays. However, we would like to check the accuracy of the Monte-Carlo simulation itself. For this purpose we have produced a radioactive source that not only emits two photons at almost the same energy as the ones emitted in the $\beta\beta$ decay of ^{100}Mo but also has the same angular correlation. We decided that ^{102}Rh is very convenient because its lifetime is very long, 200 days, and it decays to the first excited 0^+ state of the daughter nucleus via electron capture only; this implies no radiation from annihilation or bremsstrahlung and makes the measurement of the efficiency very simple. The source was produced via a (p,n) reaction by bombarding a natural Ruthenium (Ru) target with a 5 MeV proton beam. The

efficiency of our apparatus can now be measured as a function of the distance from the center of the detector. Moreover, the attenuation of the photons in the Molybdenum sample can be studied by surrounding the source with two disks of molybdenum or a material of similar atomic number.

[Poo] A. Poon and L. DeBraekeleer, to be submitted to Nucl. Instrum. Methods.

5.1.3 Search for the Neutrinoless $\beta\beta$ Decay Rate of ^{76}Ge to the First Excited State in ^{76}Se

L. DeBraekeleer, H.K. Gerberich, C.R. Gould, M.J. Hornish, and W. Tornow

The discovery of the neutrinoless double- β decay would provide definite evidence for physics beyond the Standard Model. From an experimental point of view, the study of such a transition to an excited 0^+ state is very interesting because one can set up a three-fold coincidence between monoenergetic signals: the energy sum of the two electrons, the energy of the first photon ($0^+ \rightarrow 2^+$) and the energy of the second photon ($2^+ \rightarrow 0^+$).

Of course, there is a small suppression due to kinematics. If the matrix element governing the transition to the excited state is similar to the one describing the transition to the ground state, one expects a reduction by a factor of four in sensitivity to neutrino mass [Sin88]. The complete absence of background should however easily make up for this small suppression.

Although we do not have an apparatus to measure such a triple coincidence, we have looked for a double coincidence between one photon and the 2 electrons in one Germanium detector and the second photon in the other Germanium detector. We have analyzed about 6 months worth of double-coincidence data. It is quite puzzling that we have recorded two events that fit this decay scheme. We still have to perform a Monte-Carlo simulation to determine the efficiency of our apparatus for such a decay in order to deduce a lifetime for this transition.

In collaboration with F. Avignone and A. Barabash, we are currently studying the feasibility of acquiring a few kilograms of ^{76}Ge for the construction of a segmented ^{76}Ge detector to study this transition in a triple coincidence.

[Sin88] J. Sinatkas, L. D. Skouras, and J. D. Vergados, Phys. Rev. **C37**, 1229 (1988).

5.1.4 Possible Nonconservation of Electric Charge and Search for a $\Delta Q = 2$ Interaction

L. DeBraekeleer, H.K. Gerberich, C.R. Gould, M.J. Hornish, and W. Tornow

Several authors have speculated on the possibility that the conservation of the electronic charge may break down [Oku89]. In particular, Mohapatra [Moh87] has suggested the existence of a current that changes an electron into a positron, hence violating charge conservation by two units ($\Delta Q = 2$). Such an interaction should lead to electronless double-beta ($\beta\beta$) decay¹ just like the coupling between a neutrino and an antineutrino leads to neutrinoless double-beta decay.

At first, it seems that electronless double-beta decay can not be observed experimentally and indeed, to our knowledge, it has never been searched for. Let us now explain how it can nevertheless be measured. Experimentally, the signature of an electronless $\beta\beta$ decay is the fact that the sum of the electron energies is zero. Now, suppose that an apparatus made of two Germanium detectors and operating in coincidence is used. If a ^{76}Ge nucleus double-beta decays to the first excited 0^+ state in ^{76}Se , there will be an emission of two photons as the excited state decays to the ground state ($0^+ \rightarrow 2^+ \rightarrow 0^+$). Now, there is a probability that one photon will be absorbed in the detector in which the double-beta decay occurred and the second photon will be detected in the second detector. Finally, if the two detectors record the correct energy for these two photons, it implies that no additional energy was deposited in the two detectors and therefore that no electrons were emitted in this double-beta decay.

We are currently performing such an experiment and have already obtained a lower limit of 10^{22} years on the partial decay time for this transition. It remains to be seen what ultimate limit can be derived on the $\Delta Q = 2$ current from this experiment and if such a limit will be competitive with existing limits derived directly from the stability of atoms.

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[Oku89] L. Okun, Soviet Physics, Uspekhi, **32**, 543 (1989).

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¹We would like to thank Professor R. Mohapatra for a private communication about this new process.

5.2 Exponential Decay Law

5.2.1 Measurement of Lifetime of ^{209}Bi and Test of the Exponential Decay Law

L. DeBraekeleer, H.K. Gerberich, C.R. Gould, M.J. Hornish, N. Stoute, and W. Tornow

It is well known that an exponential decay law contradicts the causality principle at time $t = 0$. Recently, this issue has been raised in connection with the nucleon-decay problem. Indeed, if the universe is only 10 billion years old while the nucleon lifetime is at least 10^{30} years, it is clear that a non-exponential decay during the first part in 10^{20} would have drastic consequences. The obvious way to test the behavior of a quantum system at such a short time relative to the decay time is to produce a radioactive nucleus with a lifetime of the order of 10^{20} years and compare it to the lifetime of an "old, normal" nucleus. The problem is to find a suitable nucleus. Perhaps, ^{209}Bi is an interesting candidate. Although it is currently considered as a stable element, it is in fact an alpha-emitter isotope. Hanna [Hin58] estimated that its half-life should be around 10^{18} years. The current limit on the lifetime of this element should not be considered as an accurate determination because that work assumed an incorrect Q value for the transition.

We have started to investigate the alpha decay of bismuth (natural Bi is monoisotopic ^{209}Bi). Our apparatus is made of a BGO scintillator located inside a NaI annulus operated in anticoincidence to reject the radioactivity background as well as the cosmic-ray background. We have actually detected a signal at the expected energy of 3.14 MeV. However, the peak is broader than expected and we must study this signal more carefully. Perhaps we are seeing the transition to the ground state as well as the transition to the first excited state.

If it turns out that in fact Bi does decay by alpha emission with a lifetime of the order of 10^{18} years, a test of the non-exponential decay rate might be feasible. Indeed, one could produce "fresh" Bi nuclei by activation of lead (neutron + ^{208}Pb) which produces ^{209}Pb which in turn decays rapidly to ^{209}Bi . Therefore, a "fresh" sample of Bi can actually be made.

[Hin58] E. P. Hincks and C. H. Millar, Can. J. Phys. **36**, 231 (1958).

6 Sub-Nucleonic Degrees of Freedom

6.1 Electromagnetic Form Factors of Nucleons

6.1.1 Measurements of Electromagnetic Form Factors of the Nucleons by Recoil Polarization: JLAB E93-027, E93-038 and E89-033

S. Churchwell, C.R. Howell, R. Macri, R.L. Walter, and the Hall-A and E93-038 Collaborations

The elastic electromagnetic (*em*) form factors of the nucleon are fundamental quantities that in the nonrelativistic limit describe the distributions of charge and current within the proton and neutron. Since nucleon form factors enter into calculations of most reactions involving electromagnetic probes on nucleons or nuclei, it is vital to have precise values for these fundamental quantities over a broad range in momentum transfer Q^2 . Many models have been developed to predict nucleon form factors and/or to fit data, but the large dispersion in the predictions make them too uncertain for use in realistic calculations. Instead, these models are most useful in providing insight about subnucleonic dynamics, quarks and gluons at short distances (high Q^2) and mesons at long ranges. The transitional region between the quark-gluonic and mesonic dominated dynamics is poorly understood and theoretically challenging. Accurate form-factor data are needed to develop realistic models that give a coherent description of nucleons over distances relevant to strongly interacting nuclear matter. A rich body of electron-scattering experiments to determine nucleon elastic form factors dates back more than three decades. One feature common to most measurements was the use of the Rosenbluth formula to separate the electric and magnetic form factors, $G_E(Q^2)$ and $G_M(Q^2)$, from a series of cross-section measurements at each value of Q^2 . Though clever, the Rosenbluth-separation technique has practical limitations on the achievable statistical precision.

A promising alternative to the Rosenbluth-separation technique is based on the sensitivity of polarization-transfer coefficients in electron-nucleon elastic scattering to the nucleon *em* form factors [Arn81]. Since the Q^2 dependence of the polarization observables differ from that of the cross section, they provide complementary information which can be used to improve the accuracy of the form factors in regions where more cross-section measurements will have little impact. In the case of the neutron where the form factors are determined from *en* quasi-free scattering on a deuteron or ^3He target, polarization measurements have an advantage over cross sections in that the extraction of the form factors is less model dependent [Arn81].

Our group is participating in three experiments at the Jefferson Laboratory E89-033,

E93-027 and E93-038 to measure the *em* form factors of the proton and neutron. All measure the ratio of the electron-nucleon longitudinal-transverse and longitudinal-longitudinal polarization-transfer coefficients to determine the ratio of the form factors, $g = G_E/G_M$. By taking the ratio of transfer coefficients, the value of g is independent of the electron beam polarization and the analyzing power of the analyzer in the nucleon polarimeter.

In E89-033 the polarization transfer coefficients were measured for quasi-free scattering of electrons from protons in the *s* and *p* shells in ^{16}O . The first part of the experiment was run during the summer 1997. The completion of data acquisition for E89-033 should be in spring 1999. The primary motivation for these measurements is to investigate medium modifications to the proton form factors. The protons are detected in coincidence with the scattered electrons in the two high-resolution magnetic spectrometers in Hall A, and the polarization of the proton is measured with a focal-plane polarimeter (FPP) in the hadron-detector package. The proton polarization is analyzed by elastically scattering them from a carbon block and measuring the azimuthal angular dependence of the scattering rate in a nearly 2π detector. The measurements are done with a water-fall target, and *ep* scattering provides a mechanism for monitoring the systematics. The proton electric form factor was measured at $Q^2 = 0.80(\text{GeV}/c)^2$ to a statistical accuracy of better than $\pm 3\%$.

Our main effort in Hall A is on E93-027, the determination of G_E^p via polarization recoil measurements. Our group has had a continuous presence during the first phase of beam time (May - June) and will continue at the same rate of participation during the final stage of data accumulation in August. We measure g and use it to determine G_E^p from existing G_M^p data. The power of our technique is illustrated in Figure 6.1-1 where the data from E93-027 are plotted as solid circles and compared with existing data [Lit70, Ber71, Bar73, Wal89, And94, Mil98] from cross-section measurements for G_E^p/G_D , where G_D is the dipole form. Because data analysis is still in a very preliminary state, our data are plotted assuming the dipole form with a value of 1.0. The errors on the present data are statistical only and include the 1 to 2% uncertainty in G_M^p . To utilize the higher beam energies that are becoming available at Jefferson Laboratory and to exploit the investment in developing the FPP and the experimental techniques, we are preparing a proposal in collaboration with the spokespersons of E93-027 to make measurements between Q^2 values of 3.5 and 5.5 $(\text{GeV}/c)^2$. The predicted uncertainties are shown in Figure 6.1-1 with the error bars on the solid diamond data points. Methods are being investigated to reduce the uncertainties on the data at the proposed Q^2 points.

The measurement of the neutron *em* form factors via recoil neutron polarization measurements, E93-038, has been scheduled to run in Hall C during the spring 2000. As in E93-027, the nucleon polarization measurement determines g , the ratio of the electric and magnetic form factors. However, in the case of the neutron, G_M^n is poorly known. To obtain accurate values of G_E^n , our collaboration will measure G_M^n at the same Q^2 points as g by measuring the scaled cross section. The TUNL group is responsible for the G_M^n measurements. The goal is to measure G_M^n to an experimental uncertainty (statistical and

Figure 6.1-1: Plot of G_E^p/G_D as a function of Q^2 . The references for the existing data are given in the figure. The error bars on the solid circles indicate the uncertainty obtained in E93-027, and those on the solid diamonds represent the estimated uncertainties that can be achieved at higher Q^2 values. The E93-027 data are plotted with the values of 1.0, since the analysis is not completed. The solid diamond data points are plotted with a value of 1.0 to avoid suggesting preference for a particular parameterization or model of G_E^p .

systematic) less than $\pm 5\%$ at each value of Q^2 . The main source of uncertainty is the uncertainty in the neutron detection efficiency. The associated-particle technique will be used to determine the efficiency of the neutron detector. We plan to use the $\gamma^* + p \rightarrow \pi^+ + n$ reaction and to detect the π^+ (in the magnetic spectrometer) and the n in coincidence. Simulations indicate that the efficiency can be determined with this technique to an absolute accuracy of about $\pm 3\%$. The readiness report will be submitted in January 1999, and installation of the neutron detector shielding will commence in the winter 2000.

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7 The Many-Nucleon Problem

7.1 Phenomenology of Preequilibrium Nuclear Reactions

The exciton model of preequilibrium nuclear reactions provides a simple way to describe the continuum energy and angular distributions of particles emitted during energy equilibration in light particle induced reactions at incident energies of around 14 to 200 MeV. Because of its simplicity, its physical transparency, its utility, and its adaptability, the exciton model continues to be used in spite of the development of more microscopic and quantum-mechanical models.

The TUNL code system, PRECO, has been used around the world (either alone or as modules in Hauser-Feshbach codes) in applied projects, in support of Radioactive Ion Beam studies, and in other basic physics research. Model and code development uses relatively simple physical concepts and appeals to available data to direct choices between alternative formulations and to provide values for key model parameters that cannot be obtained from independent sources.

Current work involves refining and benchmarking both the code and its global input set against a broad range of experimental energy spectra from the literature to allow the reliable calculation of unmeasured or unmeasurable reaction spectra without the use of adjustable parameters. The present focus is on nucleon-nucleon reactions. Earlier work emphasized the preequilibrium calculations while current work relates mostly to the equilibrium part. All of the work described has been written up and submitted for publication.

7.1.1 Equilibrium Shell Corrections

C. Kalbach Walker

Over the years, shell corrections to the total state densities used in equilibrium calculations have involved either a modified level-density parameter, a , or a shell-related energy shift or both. So far in PRECO equilibrium shell effects have included only an energy shift even though the preequilibrium state densities use both types of correction. The need to include shell corrections in the level-density parameter, a , became apparent [Kal98] when the neutron evaporation components in the lead region were found to be systematically steeper than the experimental ones.

The shell correction to the level-density parameter was obtained from the shell-shifted equi-spacing model (S^2 -ESM) single-particle states used in the preequilibrium calculations. A simple staircase weighting function averages the single-particle states, with the center of the averaging interval placed in the middle of the shell gap. This value is used for closed

shell configurations. For nearby nuclei, a is a weighted average of the closed-shell value and the original ESM result, with the ESM part weighted progressively higher in moving away from the magic number. The width of the averaging interval was adjusted for the three spectra closest to the ^{208}Pb double-shell closure. For other mass regions the width of the averaging interval is assumed to scale as the temperature from the constant temperature part of the equilibrium state density. Thus the only new parameter is the averaging width normalization.

Next the shell-related equilibrium energy shift was reexamined in an effort to minimize a general overestimation of the proton evaporation components [Kal98], particularly for $A \geq 90$. Various options were studied using sample experimental (n, xp) and (p, xp) spectra in the Zr-Mo region. The best option found was to retain the previous value for a closed shell configuration and to assume that the energy-shift decreases in moving away from the shell closure in the same way as the preequilibrium shell corrections and the shell effect in a .

Finally, the range and rapidity of the washout of shell structure was revised. Based largely on the proton primary evaporation components, it was found that the previously assumed range of $D/2d$ (D is the width of the shell gap and d is the ESM single particle spacing) needed to be roughly doubled. Compared to the previously assumed linear falloff, the data require a more rapid decrease in shell effects very close to the shell closure and a more gradual one further away. This leads to $F_{\nu\text{-shell}}$, the fraction of the shell effects remaining for a given N , of

$$F_{\nu\text{-shell}}(N) = 1 - \left(\frac{|N - N_{\text{mag}}|}{D_{\nu}/d_{\nu}} \right)^{1/2}.$$

The set of shell-corrected a -values obtained using this washout assumption is shown in Figure 7.1-1 which displays the same general structure as other sets in the literature. The effect of this change on the $^{209}\text{Bi}(n, xn)$ spectrum at 14.1 MeV is also shown in the figure.

With all of these changes, the neutron evaporation spectra in a large set of literature data are well reproduced, even in the lead region where they were previously deficient. The balance in intensity between the (n, p) and (p, p') evaporation spectra in the zirconium region is improved, but their intensity is still overestimated.

[Kal98] C. Kalbach, J. Phys. G, **24**, 847 (1998).

[Tak92] A. Takahashi *et al.*, *Double and Single Differential Neutron Emission Cross Sections at 14.1 MeV: Vol. 2*, Technical Report OKTAVIAN A-92-01, Osaka University, 1992.

Figure 7.1-1: The left portion of the figure shows the shell-corrected level-density parameter as a function of A . The right portion shows the effect of the shell-corrected level-density parameter on the $^{209}\text{Bi}(n,xn)$ reaction. The data are from [Tak92].

7.1.2 Proton Total Reaction Cross Sections

C. Kalbach Walker

Accurate calculation of charged-particle evaporation spectra requires a delicate balance between the residual state density and the exit channel total reaction cross section since they are both changing rapidly with emission energy but in opposite directions. Since work on the state densities failed to resolve the regular overestimation of the proton evaporation components, attention is here turned to the proton total reaction cross sections below the Coulomb barrier. These are calculated from a parameterization [Cha81] of the values obtained from the Becchetti-Greenlees optical-model potential. That potential was arrived at by studying reactions at 10 to 40 MeV; energies generally above the Coulomb barrier.

The cross sections from [Cha81] go to zero too rapidly below the Coulomb barrier, causing the calculated reaction spectra to cut off sooner than the data. The experimental cutoffs in the nickel region were used to guide an adjustment in one of the numerical constants in the parameterization. This corrected the cutoff problem but accentuated the intensity problem and caused the reaction cross sections for targets $A \geq 100$ to exhibit a minimum at low energies rather than going to zero.

These issues were all dealt with by applying a global renormalization function below the Coulomb barrier. The needed function was determined for the primary evaporation components of five experimental energy spectra from the literature and the results were found to follow a common trend when plotted against $\epsilon - B_C$. Here ϵ is the energy of the proton and B_C is the Coulomb barrier height. This trend was fit with a barrier penetrability formula (see Figure 7.1-2) which goes to unity at higher energies. The resulting global

Figure 7.1-2: Determination of the global correction factor to the proton total reaction cross sections. The curve is the fit to the empirical points.

correction function works well when tested on a broad range of spectra from the literature.

[Cha81] A. Chatterjee, K. H. N. Murthy, and S. K. Gupta, *Pramana*, **16**, 391 (1981).

7.1.3 Compensating for γ -Ray Competition with Secondary Protons

C. Kalbach Walker

Calculations of secondary proton evaporation [Kal98] were sometimes dramatically too high at the one or two lowest emission energies considered. This problem was attributed to the neglect of γ -ray emission which could compete when the neutron channel is closed and the proton channel is severely hindered by the Coulomb barrier. The problem persists even after the sub-barrier proton total reaction cross sections are adjusted. The explicit inclusion of γ competition in PRECO-E would significantly complicate a part of the calculations which is largely peripheral to its main purpose. Instead, the energy requirement in the primary residual nucleus for secondary particle emission to be calculated was modified to compensate for its neglect. The previous requirement was $U \geq \epsilon_{\min} + \min(B_n, B_p)$ where $\epsilon_{\min}$ is the lowest emission energy in the discrete grid used in the calculations and where B_n and B_p are the neutron and proton binding energies in the primary residual nucleus. The new requirement is $U \geq \min(\epsilon_{\min} + B_n, \epsilon_{p-\min} + B_p)$. Here $\epsilon_{p-\min}$ is the lowest emission energy in the grid for which $\sigma_{p-rxn}(\epsilon)/\sigma_{n-rxn}(\epsilon) \geq R_\gamma$ and R_γ is much smaller than unity.

The value of R_γ was investigated using 19 test spectra from the literature. A value of

$R_\gamma = 0.005^{+0.001}_{-0.0005}$ was selected which adequately accounted for 16 of the test spectra. The remaining three represent extremely weak reaction channels.

[Kal98] C. Kalbach, J. Phys. G, **24**, 847 (1998).

7.2 Neutron Scattering

7.2.1 Sensitivity Tests on Parameters of the Nucleon-Nucleus Dispersive Optical Model

G.J. Weisel and R.L. Walter

TUNL has applied the dispersive optical model (DOM) to a number of neutron-nucleus scattering systems and has written software that optimizes the quality of fit of the DOM predictions to the data, as measured by chi-squared [Wei96]. In the course of this work, two questions have arisen concerning the DOM formalism. The first concerns the constraint, found in all DOM analyses using Woods-Saxon form factors, that the real- and imaginary-volume potentials share the same geometrical parameters. The second concerns the functional form of the energy dependence of the surface imaginary potential $W_s(E)$.

We used an $n + {}^{208}\text{Pb}$ DOM for the two sensitivity tests, since we had experience with this scattering system from work on a unified DOM analysis of $n + {}^{208}\text{Pb}$ and $n + {}^{209}\text{Bi}$ from -20 to +80 MeV [Wei96]. In the final stages of that study, we found it easy to compromise between the two scattering systems for the parameters of the volume-imaginary potential, but difficult for those of the surface-imaginary potential. As [Wei96] points out, this was due to differences in the high-energy regime between the total cross-section data for ${}^{208}\text{Pb}$ [Sch88] and ${}^{209}\text{Bi}$ [Fin93]. As a result, the "partially constrained" ${}^{208}\text{Pb}$ and ${}^{209}\text{Bi}$ DOMs of [Wei96] had considerably different slope factors for $W_s(E)$, of $C_s = 0.0128$ and $C_s = 0.0197$, respectively. Since newer $n + {}^{208}\text{Pb}$ total cross-section data are available from Finlay *et al.* [Fin93], we tried using it in the present work. We found that the $W_s(E)$ parameters of the ${}^{208}\text{Pb}$ DOM now favored values within 5% of those for ${}^{209}\text{Bi}$, thus eliminating the need for two separate partially constrained DOMs. The parameters of our new unified ${}^{208}\text{Pb}$ - ${}^{209}\text{Bi}$ DOM are the same as those appearing in the "w/ W_{so} " column of [Wei96], except for the following differences: $A_v = 5.87$, $B_v = 29.32$, $A_s = 9.95$, $B_s = 4.91$, and $C_s = 0.0200$. Note that the model uses a significantly larger C_s value than the partially constrained ${}^{208}\text{Pb}$ DOM of [Wei96]. In preparation for the sensitivity studies, we started with the new unified DOM and optimized the quality of fit to the ${}^{208}\text{Pb}$ data alone by fine-tuning the DOM parameters, except for the spin-orbit parameters and the slope B_{HF} of the Hartree-Fock (HF) field. (We found that $B_{HF} = 0.350$ was best for the prediction of bound-state quantities.) We refer to this standard model as DOM I.

In conventional optical-model analyses, optimization of the fit to data usually requires that the radius of the volume imaginary potential be made four to six percent greater than the radius of the real potential. In contrast to this, all published DOMs have constrained the HF potential and volume imaginary potential to share the same geometrical parameters. This assumption is convenient since it allows one to determine the total volume real potential simply by adding the strengths of the HF potential and the volume dispersive correction,

and multiplying the sum by a common geometrical form factor. In the first set of sensitivity tests, we relaxed this constraint by using a total volume real potential of the form:

$$V_v(r, E) = V_{HF}(E)f_{WS}(r, R_{HF}, a_{HF}) + \Delta V_v(E)f_{WS}(r, R_v, a_v). \quad (7.1)$$

The $f_{WS}(r, R_v, a_v)$ is a Woods-Saxon form factor, where the nuclear radius R_v is written in terms of the parameter r_v and the total mass number as $R_v = r_v A^{1/3}$. We refer to a model incorporating Eq. 7.1 as a DOM II. In our tests, we held the radius r_{HF} of the HF field constant while increasing the radius r_v of the volume imaginary potential in 0.01 fm steps. We also maintained a constant difference between r_{HF} and r_v , and stepped their values in unison. For each pairing, the other DOM parameters, (except for the spin-orbit parameters and B_{HF}), were reoptimized for the chi-squared quality of fit to the data. None of the DOM IIs demonstrated better fits to the data. However, this modification did alter the trade off between the W_v and W_s strengths, such that $W_s(E)$ could be made smaller-valued at high energies. While DOM I gave a W_s strength as high as 3.0 MeV at $E = 80$ MeV, DOM II (using $r_{HF}/r_v = 1.23/1.28$) gave a W_s strength of 1.9 MeV, as can be seen in Figure 7.2-1. Although DOM II introduces a satisfying change to the W_s energy dependence, it does not improve fits to the data and introduces two new parameters, r_{HF} and a_{HF} . Attempting to set $r_v = r_s$ and $a_v = a_s$ resulted in a significantly worse fit to the data. Allowing the radius of the volume-imaginary potential to be greater than that of the volume-real potential is not a favorable modification for a DOM of the $n + {}^{208}\text{Pb}$ system.

Figure 7.2-1: Bands of $W_s(E)$ corresponding to a chi-squared tolerance of 2% for DOM I, DOM II, and DOM III.

The second test deals with the energy dependence of $W_s(E)$ at high energies. Consider the following form for $W_s(E)$, which is parameterized about the Fermi energy E_F and

contains an undetermined power j . For $E > E_p$, where E_p is the average energy of the single-particle bound states,

$$W_s(E) = \frac{A_s(E - E_p)^2}{(E - E_p)^2 + B_s^2} \exp[-C_s(E - E_p)^j] \quad (7.2)$$

and for $E_F \leq E \leq E_p$, $W_s(E) = 0$. The $W_s(E)$ is an even function with respect to E_F . In all of TUNL's past DOM analyses, we set $j = 1$ and found that fits to the data favored values for C_s as low as 0.0108 MeV^{-1} (which made $W_s(E)$ relatively large at high energies) [Wei96, Nag98]. Within a chi-squared tolerance of 2%, DOM I (featuring the new total cross-section data) favors C_s values in the range 0.0190 ± 0.0050 . Higher C_s values are possible with DOM II, which favors values in the range 0.0270 ± 0.0060 . To determine how low the magnitude of $W_s(E)$ at 80 MeV could be forced, our second set of sensitivity tests adopted Eq. 7.2 with $j = 2$. We refer to such a model as a DOM III. Within a chi-squared tolerance of 2%, the resulting parameter sets favored values of C_s in the range $(0.0320 \pm 0.0130) \times 10^{-2} \text{ MeV}^{-2}$. DOM III did not improve the fits to the data. Figure 7.2-1 shows $W_s(E)$ using the favored ranges of C_s values for DOM I (dotted curves), DOM II (dashed), and DOM III (solid).

In attempting to determine which of these energy dependencies is preferable, we found it impossible to make use of a qualitative or quantitative judgement of the quality of fits to the data; all of the models under consideration gave fits that were nearly identical from visual inspection and had chi-squared values within 4% of one another. Two scattering observables which are sensitive to the high-energy behavior of $W_s(E)$ are differential cross section and analyzing power at high incident neutron energies ($E > 40 \text{ MeV}$) and large angles ($\theta > 60^\circ$). To demonstrate this sensitivity, we compared two versions of DOM III using the lowest and highest favored values for C_s . In the 60° - 90° region, the two models yield differential cross-section predictions in the 1-10 mb/sr range that differ by 30%. At this time, none of the available $^{208}\text{Pb}(n,n)$ differential cross-section data above 40 MeV has been taken at large angles. As new data in the high-energy, large-angle regime becomes available, it will be possible to place stronger constraints on the energy dependence of $W_s(E)$ in the 30-80 MeV range.

[Fin93] R. W. Finlay *et al.*, Phys. Rev. **C47**, 237 (1993).

[Nag98] M. M. Nagadi *et al.*, to be published, 1998.

[Sch88] R. L. Schutt *et al.*, Phys. Lett. **B203**, 22 (1988).

[Wei96] G. J. Weisel *et al.*, Phys. Rev. **C54**, 2410 (1996).

7.2.2 Analyzing Power Measurements for $^{12}\text{C}(n,n)^{12}\text{C}$ from 2.2 to 8.5 MeV

R.T. Braun, Q. Chen, Z. Chen, A.S. Crowell, D.E. González Trotter, C.R. Howell, C.D. Roper, F. Salinas, H.R. Setze, W. Tornow, and R.L. Walter

Measurements of the $A_y(\theta)$ for neutrons elastically scattered from ^{12}C have been performed using the Neutron Time-of-Flight Facility at TUNL [Rop97]. A total of 311 measurements of the $n\text{-}^{12}\text{C}$ $A_y(\theta)$ were made for 38 neutron energies from $E_n = 2.2$ to 8.5 MeV at lab angles from 25° to 145° with an average statistical uncertainty of $\pm 3\%$. These measurements fill a gap in previous measurements in the region from 4 to 7 MeV, and also overlap with the previous measurements above and below this energy region. The results of the measurements will be combined with previous cross-section and analyzing power data for input into a phase-shift analysis. The results of this phase-shift analysis will be used to generate a new $n\text{-}^{12}\text{C}$ $A_y(\theta)$ library. This library is needed in order to calculate corrections for the polarization dependence of the neutron detector efficiency for detectors used in the high accuracy $n\text{-}p$ and $n\text{-}d$ analyzing power measurements performed at TUNL. In addition to the phase-shift analysis, there is also interest in including these data in an R -matrix analysis for the ^{13}C system. The final values of the neutron polarization (which will be used to calculate the $n\text{-}^{12}\text{C}$ $A_y(\theta)$ values) have been extracted from the polarimetry measurements. The phase-shift analysis for $n\text{-}^{12}\text{C}$ $A_y(\theta)$ will be completed as soon as the measured $A_y(\theta)$ values have been corrected for the effects of the finite geometry of the detector setup and for various multiple scattering processes.

For the first step in the final analysis of the $n\text{-}^{12}\text{C}$ $A_y(\theta)$ measurements, the event data were replayed with several improvements over the online data-sorting process. For $E_n \geq 4$ MeV, the pulse-height threshold was increased by a factor of 1.5 (from 0.33 to 0.5 times the Compton edge in the pulse-height spectrum of ^{137}Cs). All of the pulse-shape discrimination (PSD) gates used for sorting were carefully checked and set in a more consistent way than the online gates. Once the time-of-flight (TOF) spectra gated by PSD were generated, the asymmetry was extracted using an automated system for subtracting backgrounds and setting the windows around the elastic peak in the background subtracted TOF spectrum. This system was much more consistent than the online analysis process in which the TOF gates were set by hand in the raw TOF spectra.

The final analysis of the neutron polarimetry measurements has been completed. These measurements were made concurrently with the $n\text{-}^{12}\text{C}$ $A_y(\theta)$ measurements using a high pressure ^4He gas scintillator as the active target for $^4\text{He}(n,n)^4\text{He}$ scattering. As in the case of the $n\text{-}^{12}\text{C}$ $A_y(\theta)$ event data, the neutron polarimetry event data were also replayed with an improved data-sorting code. The PSD gates and the TOF gates used for the sorting process were carefully set in order to insure the quality of the four center detector pulse-height (CDPH) spectra. The asymmetry was calculated from the yields in the CDPH spectrum for each detector and spin state (Left-Up, Left-Down, Right-Up, and Right-Down). From

the measured asymmetry, the neutron polarization was calculated using an $A_y(\theta)$ that had been corrected for the effects of finite geometry and multiple scattering. The corrected $A_y(\theta)$ was produced by performing a Monte-Carlo simulation of the neutron polarimetry measurements.

In order to make n - ^{12}C $A_y(\theta)$ measurements at 25° and 35° , the neutron polarimeter (located at 0°) had to be removed due to spatial conflicts with the large shielding of the main neutron detectors. As a result, the only source of polarization information during these measurements was the spin-filter polarimeter (SFP) measurements of the deuteron polarization at the ion source. The expression relating the deuteron polarization measured by the SFP to the polarization of the neutrons emitted at 0° by the $^2\text{H}(d,n)^3\text{He}$ source reaction is shown in Eq. (7.3).

$$p_{y'}(\text{neutron}) = \frac{\frac{3}{2}p_Z K_y^{y'}}{1 - \frac{1}{4}p_{ZZ}A_{zz}}. \quad (7.3)$$

The variable $K_y^{y'}$ is the polarization-transfer coefficient at 0° for the $^2\text{H}(d,n)^3\text{He}$ reaction. Using values for the polarization-transfer coefficient $K_y^{y'}$ and the tensor analyzing power A_{zz} in Eq. (7.3), the neutron polarization can be determined from the values of p_Z and p_{ZZ} measured using the spin-filter polarimeter (SFP).

Figure 7.2-2: $K_y^{y'}$ values for the $^2\text{H}(d,n)^3\text{He}$ reaction at 0° plotted as a function of mean neutron energy. The solid curve is a cubic polynomial fit of the combined data set with a 95% confidence limit defined by the dotted curves.

Presently, the most complete measurement of $K_y^{y'}$ in the energy range of interest was performed by Lisowski *et al.* at TUNL [Lis75]. However, the value of $K_y^{y'}$ can also be

extracted from the present measurements using the SFP measurements of the vector and tensor deuteron polarization, the neutron polarimeter measurements, and the published values of A_{zz} . The $K_y^{y'}$ values extracted from the present measurements along with the Lisowski values are plotted as a function of neutron energy in Figure 7.2-2. The cubic polynomial fit of the combined $K_y^{y'}$ values is given by Eq. (7.4).

$$K_y^{y'} = -1.108281 + 0.631263E_n - 0.075732E_n^2 + 0.003053E_n^3. \quad (7.4)$$

The dotted curves in Figure 7.2-2 define a 95% confidence interval for the cubic polynomial function. The RMS error (weighted standard error) of the fit is 0.831410 with 34 degrees of freedom, indicating that the average deviation of the data from the fit is statistically consistent with the error bars shown.

[Lis75] P. W. Lisowski *et al.*, Nucl. Phys. **A242**, 298 (1975).

[Rop97] C. D. Roper, TUNL Progress Report, **XXXVI**, 105 (1997).

7.3 Nuclear Data Evaluation for $A = 3-20$

7.3.1 Data-Evaluation Activities

C.M. Cheves, J.H. Kelley, D.R. Tilley, and H.R. Weller

The Nuclear Data-Evaluation Group at TUNL is a part of the United States Nuclear Data Network and the International Nuclear Structure and Decay Data network, and is responsible for evaluations in the mass range $A = 3-20$. The TUNL group published reviews for $A = 3$ and $A = 4$ in 1987 and 1992, respectively, and was assigned the additional responsibility of continuing evaluation activities for $A = 5-20$ following the retirement of F. Ajzenberg-Selove (Univ. of Pennsylvania) in 1990. Since that time, TUNL has published reviews for $A = 16-17$ in 1993, and $A = 18-19$ in 1995. An evaluation of $A = 20$ done in collaboration with S. Raman of Oak Ridge National Laboratory was submitted to the publisher in October 1997 and has now been published in *Nuclear Physics A* 636 (1998) 247-364. A review of the $A = 5-7$ nuclides in collaboration with G.M. Hale of Los Alamos National Laboratory and H.M. Hofmann of the Universität Erlangen-Nürnberg was begun in the summer of 1996. The preliminary version for $A = 5$ was issued in February 1998. The review of $A = 6$ is underway, and a preliminary version should be ready for mailing in late summer 1998.

7.3.2 ENSDF

ENSDF files for $A = 18-19$ were prepared at TUNL by R.M. Chasteler and submitted to NNDC in mid-1995. ENSDF files for $A = 20$ incorporating the adopted levels and gammas, decay data and reaction data contained in the 1998 $A = 20$ TUNL review were completed by J.H. Kelley and submitted to NNDC in June 1998. J.H. Kelley has developed computer routines which facilitate conversion of data from the $\text{\LaTeX}$ files (which the TUNL group prepares for the "Energy Levels of Light Nuclei" publications in *Nuclear Physics A*) into ENSDF format. The availability of these procedures is enabling the TUNL group to accelerate the preparation of more extensive ENSDF files for $A = 3-20$. For example, they are being used to produce files for $A = 5$ (now in preliminary version) and $A = 6$. In addition, the group is now working to provide complete ENSDF files for the nuclides which had been reviewed earlier by TUNL but for which existing ENSDF files did not reflect the TUNL evaluations. J.H. Kelley has now completed updates of ENSDF files for $A = 3$ and $A = 4$, and has begun to incorporate fully the contents of the 1993 TUNL review of $A = 16-17$.

7.3.3 World-Wide Web Services

TUNL continues to develop new WWW services for the nuclear science and applications communities. During the past year, C.M. Cheves, who developed the TUNL Data-Evaluation Project web site from its inception, implemented a completely new design which emphasizes individual nuclides as well as categories of information, thereby providing several methods of convenient access to this information. Currently, the following items are available:

- Energy-Level Diagrams in the style of Fay Ajzenberg-Selove for $A = 4-20$.
- Abridged versions of TUNL's published evaluations for $A = 3, 16, 17, 18, 19, 20$, and $A = 5$ (preliminary).
- An abridged version of Fay Ajzenberg-Selove's $A = 5-10$ compilation. (We have received permission from *Nuclear Physics A* to put her old compilations on the Web, altered to use NNDC key numbers where possible. We hope to have the most recent evaluation of each mass chain online by the end of 1998.)
- Postscript ENSDAT output of the $A = 3-20$ ENSDF files.
- A short version ($A = 1-20$) of the *Table of Isotopes*, provided by the Berkeley Isotopes Project.
- Information about the status of the project and our publications.
- Updated list of references for $A = 6$ nuclides (see below).

A new item on our web site is a set of lists of the most important papers published since the most recent evaluation of the $A = 6$ mass chain. The references are divided into categories of level information, reaction information, decay information, and other properties, with experimental and theoretical subdivisions for each. This item represents the beginning of a new initiative by the TUNL group to provide to the nuclear community a continuously updated guide to important new work that has appeared in the literature since the most recent published review for each nuclide. In addition to the efforts of all members of the TUNL Nuclear Data-Evaluation Group, we have the assistance of J. Purcell of Georgia State University for this priority task.

8 Nuclear Instruments and Methods

8.1 Tandem Accelerator Operation

8.1.1 Tandem Operation

E.P. Carter, R.M. O'Quinn, and C.R. Westerfeldt

The TUNL FN tandem accelerator was operated for 5278 hours at terminal potentials ranging from 0.627 MV to 8.73 MV during the period 8/1/1997 to 6/22/1998. Beams accelerated during this period include polarized and unpolarized protons and deuterons, and also ^3He . The terminal operating potential during the reporting period is shown graphically in Figure 8.1-1.

Figure 8.1-1: Terminal operating potential as a function of time.

There were two accelerator maintenance periods this reporting period. The tandem was opened for maintenance in February 1998 after 29,680 hours of post upgrade operation, and again in May at 30,692 hours. In February, after the machine exhibited unstable operation and entry was made, the high-energy suppressor lead was found to be arcing to the high energy compression fitting. No other damage was found and after this was repaired, normal stable operation was resumed. The corona needles were also replaced during this opening to improve performance for an upcoming low-energy run. In May, two charge pickoff pulleys

were replaced due to failed bearings. During a check of the column resistors, eight were found to be out of tolerance near the entrance to tube 2 and were replaced. A histogram showing the fraction of experimental time spent at various terminal potentials is given in Figure 8.1-2.

Figure 8.1-2: Time spent at various terminal potentials.

8.2 KN Accelerator Operation

8.2.1 KN Accelerator

W.C. Beal, E.G. Bilpuch, E.P. Carter, C.A. Grossmann, L.K. McClean, R.M. O'Quinn, G.E. Mitchell, J.D. Shriner¹, J.F. Shriner, Jr.¹, and C.R. Westerfeldt

The TUNL KN high energy-resolution accelerator was operated 120 days, for a total of 2457 hours during the period August 1, 1997 through June 22, 1998 at terminal potentials ranging from 0.952 MV to 2.40 MV. Six machine openings were made during this period for reasons including: replacement of the rf oscillator tubes, replacement of failed control rods, and several minor electrical problems. A plot of the operating potential of the accelerator for the reporting period is shown below in Figure 8.2-1.

Figure 8.2-1: Terminal operating potential as a function of time.

The accelerator was opened 4 times during this period for maintenance and repairs. Maintenance openings were required on two occasions to install new ion source bottles and to adjust the charging and collector screens. Repairs included: replacement of failed ion source oscillator tubes on two occasions.

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In Figure 8.2-2 we present a histogram depicting the number of days of operation as a function of terminal potential.

Figure 8.2-2: Time spent at various terminal potentials.

8.2.2 Laboratory Improvements and Modifications

W.C. Beal, E.G. Bilpuch, E.P. Carter, C.A. Grossmann, L.K. McClean, R.M. O'Quinn, G.E. Mitchell, J.D. Shriner¹, J.F. Shriner, Jr.¹, and C.R. Westerfeldt

There were no modifications made to laboratory equipment or systems during the past year. Additional hardware was purchased to complete the new energy-control system. This system will replace the present PC/Labview system with a newer Pentium Processor, the current version of LabView and Group 3 ControlNet hardware. This latter system is comprised of fiber optically interconnected intelligent controllers with specialized I/O ports for monitoring and controlling distributed hardware without ground loops of EMI problems. The software is being configured this summer with the goal of having the basic loops operational by August 1998.

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8.3 Nuclear Astrophysics Facility

8.3.1 Construction of the LENA Laboratory

A.E. Champagne and C.R. Westerfeldt

As discussed in last year's progress report, we are currently constructing a new laboratory for low-energy nuclear astrophysics (LENA) studies. It consists of a low-energy, high-intensity accelerator (0-200 keV, 0-5 mA) coupled to a 1-MV Van de Graaff. A switching magnet directs beams from both accelerators to a common target location (see Figure 8.3-1). The advantage of this design is that normalizations or systematic checks can be performed using the Van de Graaff without changing the operating conditions for long production runs with the low-energy machine. Thus, the facility can be both simple and flexible.

Figure 8.3-1: Layout of the LENA laboratory.

Unfortunately, renovations of the laboratory space took longer than anticipated and this has forced us to slide our timeline by about a year. At this point, the Van de Graaff has been disassembled and cleaned, and is awaiting reassembly. The 200-kV table and high-current ion source have been constructed and both accelerator tubes have been refurbished. The optical design has been finalized with one modification to the design that was described last year. The original design called for 2 quadrupole doublets for each accelerator. However, by using 3 identical doublets, it is possible to eliminate the fourth. In the current design, a

doublet is placed at the exit of each accelerator and a single doublet is used on the target beamline. With this configuration, it is still possible to run telescopic optics for the low-energy machine and traditional optics (i.e. horizontal waists at the image and object slits of the switching magnet) for the Van de Graaff. We have recently acquired these quadrupoles from the University of Pennsylvania.

Our efforts for the rest of 1998 will be focused on reconstruction of the Van de Graaff and layout of the beamlines in order to run test beams in early 1999. At this point, we hope to replace the antiquated control system with some form of computer control. The plan would then be to extend the control system to accommodate both machines, if resources permit.

8.4 Polarized Ion Source

8.4.1 Atomic Beam Polarized Ion Source

T.B. Clegg, J.D. Dunham, and S. Lemaitre

TUNL's polarized ion source continues to be used heavily. During the period 7/1/97-6/30/98, it provided polarized (unpolarized) beams for experiments for 38% (16%) of the calendar days, with an additional 12% of the calendar days scheduled for routine maintenance. The high use of beams in the low-energy experimental area also continued, with 34% (20%) of the calendar days taken by beams for experiments below (above) 680 keV. There was also reduced use of deuterium beams: 104 (35) days were devoted to polarized $H^\pm$ ($D^\pm$) operation, 55 (0) days to unpolarized $H^\pm$ ($D^\pm$) operation, and 2 days for use with ^3He .

We experienced an unusually large number of system failures during operation this year which required 24 days total of unscheduled maintenance and approximately three weeks of operation with reduced beam intensity while repairs were being implemented. The most problematic, and costly, was failure of the highly regulated, high-voltage supply for the polarized source frame potential. A new supply had to be ordered. While awaiting delivery, we operated several weeks at lower extracted beam energies with resulting lower beam intensity.

Typical polarized beam currents measured after the first analyzing magnet are 4 (40) μA for negative (positive) beams with beam polarizations usually ranging between 75 and 80% of the theoretical maximum. The Lamb-shift polarimeter installed on the source in fall 1995 is now used routinely by all experimenters. It is most beneficial for setting up and optimizing the rf transitions needed at the beginning of an experiment, and for monitoring the beam polarization thereafter. It provides convenient and reliable relative polarization measurements, but has been shown to provide absolute polarization values which often are 3 to 5% higher than those measured on target with traditional nuclear polarimeters. The cause of this discrepancy is described below.

8.4.2 Lamb-Shift Polarimeter

T.B. Clegg

We now understand why there is persistent lack of full agreement between beam polarizations measured by the Lamb-shift spin-filter polarimeter and beam polarizations measured by nuclear scattering. This new idea has not yet been fully tested experimentally, but is capable of explaining all general experimental features. The explanation goes as follows (for both H and D; but see explanation for experimental differences between H and D below):

Polarized ions are produced in our source when ionization of polarized H atoms occurs inside the ECR ionizer plasma. We then extract polarized H^+ ions, accelerate them to the cesium oven, which is Lens 4 at potential V_4 and where they have a kinetic energy of (eV_4) . There, two consecutive collisions with cesium first produce a polarized H atom, and then a polarized H^- ion. This polarized negative ion is then accelerated further.

At the same time, we extract H_2^+ ions from the ECR ionizer plasma. These are produced when background water vapor or hydrocarbons are ionized, or when polarized H atoms collide with surfaces inside the ionizer, recombine to form H_2 and depolarize, and then are reionized. All these H_2^+ molecular ions are unpolarized, and all are accelerated with the beam of polarized H^+ ions. When the H_2^+ ion collides with a cesium atom, both an H atom and an H^+ ion are formed. Both of these are unpolarized, and both have an energy of $1/2(eV_4)$.

These unpolarized species are distinguishable from the desired, polarized H and H^+ ONLY by having $1/2$ the kinetic energy. If as is typical, $V_4 \approx 500$ to $700V$, then this beam energy difference is only 250 to 350 eV. This small energy difference will persist throughout further charge exchange to make H^- ions, subsequent beam acceleration, and transport. Only if the spin precession system, beam focusing, or beam transport systems have sufficient energy resolution will these polarized and unpolarized H^- beam components ever become physically separated. If the energy resolution is only marginally sufficient, then the fraction of unpolarized H^- beam in the primary polarized H^- beam may be tune dependent. Whatever occurs, any target polarization measurement will measure the full beam's polarization, including any diluting contribution of the arriving unpolarized background beam component.

Now consider the process of measuring the beam polarization with the spin-filter polarimeter. This is accomplished by having the arriving polarized H^+ ions collide inside the cesium oven with a cesium atom to produce an excited, metastable $H(2S)$ atom. The spin-filter then measures the magnetic substate populations of these atoms to infer the polarization of the arriving H^+ ions. Simply attaching the electron to the H^+ to form $H(2S)$ does nothing to destroy the original nuclear polarization when this attachment occurs in a strong B-field.

Consider, however, what occurs when an unpolarized H_2^+ ion arrives at the cesium oven. When it collides with cesium, it dissociates into an H and an H^+ . There is very low probability that in one collision it can produce a metastable $H(2S)$ atom. Thus, the spin-filter polarimeter, which requires $H(2S)$, is very insensitive to the unpolarized part of the beam, and will provide a polarization measurement only of the polarized component of the beam. When negative ion beams are being accelerated, this spin-filter polarization measurement can therefore never be lower than the polarization measured after beam acceleration by nuclear scattering.

We have observed experimentally that the polarization difference, as measured by the spin-filter polarimeter and by nuclear scattering, is often much greater for hydrogen than

for deuterium. This can be explained by the fact that the ECR ionizer will have far greater backgrounds from H_2O vapor than from D_2O vapor. Such differences are largest immediately after a source pumpdown, and become smaller over a period of several days as the source base vacuum improves. Not only does the overall beam polarization improve as the vacuum improves, but the measured difference should decrease too.

There should NOT be any measured polarization difference for accelerated polarized H^+ ions, because the unpolarized background H_2^+ beam is always separated from the desired polarized H^+ beam in the bending magnet.

The above explanation suggests a test when accelerating negative ions by comparing the polarizations measured with the spin-filter and with a nuclear polarimeter as a function of the power injected into the ECR plasma. If the explanation is correct, the increased power should produce a hotter plasma, leading to an increase in H_2^+ dissociation BEFORE positive beam extraction and acceleration. This would mean that any unpolarized background would now be present in the H^+ instead of the H_2^+ beam, and should dilute the polarization as measured by the spin-filter.

8.4.3 New Plasma Ionizer

T.B. Clegg, J.D. Dunham, and S. Lemaitre

New approaches are being tested to improve the ionization system for polarized atoms from an atomic beam source. They are based on use of a storage cell to increase the polarized atom target thickness [Cle96].

The major problem in using low energy H^+ or D^+ ion beams arises from their space charge [Cle97]. No beam transport for mA-beams through the storage cell is possible for energies as low as 1 eV where the charge-exchange cross section is very high ($> 10^{-15} \text{ cm}^2$, resonant charge exchange).

We are now investigating the idea that a deuterium (hydrogen) plasma beam confined in a 1 kG magnetic field may be used to ionize polarized hydrogen (deuterium) atoms stored in a cell through which the plasma beam passes (see Figure 8.4-1).

High ion beam densities are in principle possible in this case since space charge compensation is provided by the accompanying electrons. Usage of an ECR plasma to generate a high density plasma at limited gas pressure seemed to be most promising ([Tay93]).

At our testbench 2.45 MHz microwaves of up to 1 kW power are fed into the plasma chamber through an AlO_2 -window. A calibrated flow of H_2 is fed into the plasma chamber (mass flow controller) and the pressure inside this chamber is monitored.

Four watercooled coils enclosed by soft iron provide a uniform magnetic field well above 1 kG covering the plasma chamber and a short drift region for the plasma beam. An iron collar around the plasma chamber allows for the magnetic field to match the ECR condition (875 G) within the chamber volume.

Figure 8.4-1: Sketch of new polarized ion beam setup.

A pumping station was built providing a TPH 2200 Turbo (2200 l/s N_2) in series with a TMP 150 (150 l/s N_2). The large pumping speed allows for the pressure in the plasma chamber to be $1 \cdot 10^{-3}$ mbar while the pressure is still around $1 \cdot 10^{-5}$ mbar for the drifting plasma beam. A control for the pumping station was designed and built which allows for local and remote control of the pumps.

For the diagnostics of the plasma beam a monitor was developed which consists of a compression tube with a Penning gauge (see Figure 8.4-2). With stepping motors the monitor can be moved in x, y, z along the drift region of the beam. A LabVIEW interface was developed to control the positioning of the monitor and for automated scanning of the beam profile.

Figure 8.4-2: Plasma Beam Intensity Monitor to scan plasma beam emerging from ECR discharge.

Using the above described monitor the plasma beam profile was scanned. During the measurements the microwave power dissipated in the ECR chamber was about 300 W and $0.2 \text{ cm}^3/\text{minute}$ at STP of H_2 gas was constantly fed into the ECR discharge. The plasma beam emerged from a 5 mm diameter hole in the ECR chamber. The entrance hole of the compression tube was 2 mm.

The first results show that after drifting a distance of about 10 cm the plasma beam is

well confined within the diameter of a storage cell. The integrated beam intensity was 1.5 mA. After positioning the monitor at the location of the peak beam intensity the microwave power into the ECR discharge was increased to 1 kW resulting in 6 times higher peak beam intensity. This would suggest a total beam intensity of about 10 mA is possible.

After very promising results so far we will study the parameters of the plasma source in detail.

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8.4.4 Proposed Studies of Light Nuclei with Increased Polarized Beam Intensities

C.R. Brune, B.J. Crowe III, H.J. Karwowski, and E.J. Ludwig

- LEBF Experiments

At TUNL we are well-instrumented to carry out low-energy gamma-ray and charged-particle experiments (including two large volume high-purity Ge detectors and a 105 cm scattering chamber). The beam intensity available is a major limiting factor – most experiments can easily take a factor of ten increase in intensity without any modification of the existing equipment. Several of these experiments are described below.

- The analyzing powers of the $d + p \rightarrow {}^3\text{He} + \gamma$ capture reaction allow one to sort out the various capture amplitudes involved. Particularly interesting are the M1 capture amplitude (sensitive to meson-exchange contributions) and capture into the ${}^3\text{He}$ D state. This reaction has been the focus of two theses at TUNL (Schmid and Ma), but with increased polarized beam we could learn much more. Higher beam intensity would provide the statistical precision needed to test theoretical predictions and would also allow the measurement of additional analyzing powers, energies, and angles in a reasonable time.

- The $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction is an example of a higher-Z reaction which would become feasible to study at low energies with a more intense beam. As the slowest link in the main CN cycle, this reaction plays an important role in massive stars. The extrapolation to stellar energies is still quite uncertain. It is important to understand the capture mechanism to each of the seven states of ^{15}O which are populated. Experiments with polarized beams would allow one to see interference between the s -wave resonance at 278 keV and the p -wave direct capture for some of the final states. With a milliamperes of unpolarized beam and our large Ge detectors it would be possible to extend cross-section measurements to lower energies. The ground state channel is particularly interesting since a threshold state (of unknown width) is predicted to make an important contribution to the cross section at low energies.
- Our measurements of p - d elastic scattering angular distributions at 314 keV and 240 keV have shown promise for resolving the long-standing discrepancy between theoretical predictions of the ^2S and ^4S scattering lengths and the results of experiments at higher energies. It is now important to supplement our data with analyzing power angular distributions taken at energies near 600 keV in order to extract the relevant phase shifts. Previous measurements of these observables had been obtained at incident energies of several MeV. Values of vector analyzing powers are expected to be very small and a high count-rate, such as provided by an improved source, is necessary to provide the desired precision in a reasonable time.
- Our investigation of the $^3\text{He}(d,p)^4\text{He}$ reaction near the $3/2^+$ resonance at 430 keV has led us to consider two types of measurements which require increased polarized deuteron beams.

Notable in existing data are deviations from analyzing power angular distribution shapes that are expected based on the assumption of pure s -wave transitions. Measurements of vector analyzing power angular distributions at several energies will allow us to determine the contribution of p waves at low energies. Those analyzing powers are expected to be quite small.

A proposal by a group at Geneseo has now been funded to construct a proton polarimeter which will provide the means to undertake polarization-transfer measurements. The polarization of protons from the $^3\text{He}(d,p)^4\text{He}$ reaction when induced by polarized deuterons should yield unique information about the role of direct-neutron transfer at energies in a range around the resonance. We anticipate that the polarization of outgoing protons will be of opposite sign when neutrons are transferred directly as opposed to results expected when reactions proceed through the resonance. Polarization-transfer measurements will require at least ten times more polarized beam than presently available.

- Experiments at FN tandem energies

With our present polarized ion source we have performed a set of measurements to establish D-state parameters for ^3H and ^3He (tests of the NN tensor force) using (d,t) and $(d,^3\text{He})$ transfer reactions. The (d,t) reactions, measured at sub-Coulomb energies, have provided a means of determining η , the asymptotic D- to S-state ratio for the triton, with sufficiently small uncertainty so that predictions based on different methods of solving the Faddeev equations can be meaningfully tested. The situation for ^3He , however, is much more uncertain since we have had to perform these measurements at energies near or above the Coulomb barrier where the interpretation of analyzing power data is sensitive to the choice of optical-model parameters – especially the deuteron-nucleus tensor potential. At lower energies, where deuterons initiating the reaction are sufficiently sub-Coulomb, there are extremely small cross sections as well as smaller analyzing powers. In order to consider improving our η determination for ^3He it is necessary to initiate $(d,^3\text{He})$ reactions with more polarized beam than presently available.

- Beam Requirements

Low energy

- 100 μA of polarized D^- , H^- (provided the minitandem foils can survive this beam). More would be even better.
- 1 mA of unpolarized H^-

High energy - 50 μA of polarized D^- (radiation shielding would need improvement with these currents).

8.5 Polarimeters

8.5.1 Calibration of a $^4\text{He}(\vec{p},p)$ Proton Polarimeter

C.R. Brune, B.M. Fisher, K.A. Fletcher¹, W.H. Geist, H.J. Karwowski, D.S. Leonard, E.J. Ludwig, K.D. Veal, and M.H. Wood

A previously-existing proton polarimeter has been rebuilt and re-calibrated. It has been modified to use solid-state silicon detectors in place of its original CsI detectors. The polarimeter consists of a 2.54-cm-diameter ^4He gas cell enclosed in 2.54- μm Havar foil. Two detectors are positioned in the horizontal plane at $\theta_{lab} = 117^\circ$, and each has a solid angle of 7 msr. For energies of interest, the scattering of protons off of ^4He has, at this angle, a large analyzing power and a cross section ranging from 15 to 90 mb/sr. These features result in a very efficient polarimeter.

The polarimeter was calibrated by comparing its response to simultaneous polarization measurements performed with the same reaction in the 61-cm-diameter scattering chamber. The chamber detectors' geometry was defined very precisely, having an angular opening of 0.65° . Well established A_y values for $^4\text{He}(\vec{p},p)$ were used to determine the beam polarization in the chamber setup [Sch71]. Data were taken in both the chamber and the polarimeter for incident proton energies ranging from 4 MeV to 16 MeV. With 120 nA of 12 MeV incident protons, the polarimeter detectors each recorded roughly 5 counts per second. Background corrections were less than 4% at all energies.

The calibration results are shown in Figure 8.5-1.

Figure 8.5-1: Energy of the beam incident on the polarimeter vs. observed polarimeter analyzing power. The solid curve represents a quadratic fit.

For a wide range of energies, the effective proton analyzing power of the polarimeter is

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now known with an uncertainty of about 1%.

[Sch71] P. Schwandt, T. B. Clegg, and W. Haeberli, Nucl. Phys. **A163**, 432 (1971).

8.5.2 A Proton Polarimeter for Polarization-Transfer Studies

K.A. Fletcher¹, W.H. Geist, H.J. Karwowski, D. Kruse¹, E.J. Ludwig, R. Runkle, and K.D. Veal

A compact polarimeter has been constructed and calibrated to measure the polarization of 12.8 to 16.3 MeV protons, such as those emitted from the $^3\text{He}(d,p)^4\text{He}$ reaction near the 430 keV resonance. Measurement of the polarization-transfer coefficient K_y^y at 0° along with cross-section and analyzing power measurements allows one to completely determine the elements of the T-matrix. This places severe constraints on the reaction models for the $^3\text{He}(d,p)^4\text{He}$ reaction [San97].

The polarimeter is based on $p - ^4\text{He}$ elastic scattering. It consists of a helium-gas cell pressurized to 400 psi and a right-left pair of CsI detectors. The detectors are collimated by vanes oriented at an angle of 65° and spaced 0.58 cm apart, so that for protons along the central axis, the acceptance range is about 52° to 82° . A transmission surface barrier detector is mounted in the entrance snout, so that a coincidence requirement between this front and either side detector can be used to identify protons and to reduce background counts in the polarimeter spectra. A cross-sectional view of the polarimeter is shown in Figure 8.5-2.

Figure 8.5-2: Cross-sectional diagram of the proton polarimeter.

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A Monte-Carlo code which uses $^4\text{He}(p,p)^4\text{He}$ cross-section data [Gar69], analyzing power data [Sch70], and the geometry of the polarimeter as input has been written to model the device and determine the effective analyzing power for various experimental conditions.

The results of the Monte-Carlo code can be tested experimentally under specific, limited conditions. The effective analyzing power for a highly collimated proton beam has been measured using polarized protons from the atomic beam polarized ion source. Because of the significant count rate when a proton beam directly enters the polarimeter, it was necessary to place a 0.0127-cm diameter, beam-limiting collimator in front of the polarimeter and to remove the front transmission detector for these tests. The polarization of the protons was simultaneously measured using $^4\text{He}(p,p)^4\text{He}$ scattering with a pair of well-collimated detectors placed at 115° .

A preliminary analysis of the calibration data is shown in Figure 8.5-3. The efficiency of the polarimeter in the middle of the energy range is estimated to be about 3×10^{-5} . The results of the Monte-Carlo simulation for the effective analyzing power with a collimated proton beam are also shown in Figure 8.5-3. The present simulation results represent the trend of the data fairly well, although there is a discrepancy in the overall normalization. The source of this discrepancy in the code is currently being identified.

Figure 8.5-3: The effective analyzing power (solid circles) of the polarimeter as a function of proton energy and the Monte-Carlo calculation (solid curve).

We have investigated various experimental designs using the polarimeter for zero-degree polarization-transfer experiments. Proof-of-principle has been demonstrated by accelerating polarized deuteron beams to 1.8 MeV through the tandem accelerator and reducing the beam energy to 430 keV in the ^3He gas cell using degrading foils. We have found that adequate count rates can be obtained through this method. Although these may not be the optimal experimental conditions, these initial tests demonstrate that the proton polarimeter can be used to measure polarization-transfer coefficients for this reaction.

[Gar69] D. Garetta *et al.*, Nucl. Phys. **A132**, 204 (1969).

[San97] F. D. Santos, private communication, 1997.

[Sch70] P. Schwandt *et al.*, Nucl. Phys. **A163**, 432 (1970).

8.5.3 Hall B Möller Polarimeter at JLAB

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The Radiative Capture Group at TUNL has been involved in building a Möller polarimeter for Hall B at Jefferson Laboratory for use with the Continuous Electron Beam Accelerator Facility (CEBAF). The polarimeter will measure the longitudinal polarization of the electron beam which will be important for many future experiments.

The polarimeter functions by measuring the Möller scattering of the polarized electrons from polarized electrons in a target. The targets are made of Permendur foils, annealed to increase the polarizability. The targets are tilted at an angle of 20° to the beam and placed in a magnetic field in order to have a longitudinal polarization component. The polarization along the beam direction is about 8%.

In the past year the polarimeter was installed and commissioned. The Helmholtz coils and target chamber were tested at TUNL and then shipped to Jefferson Laboratory in September 1997. The polarimeter was installed in the beam line near the entrance of Hall B. After the chamber there are two quadrupoles which can be adjusted so that the electrons scatter into the monitoring detectors. The monitoring detectors, made of scintillator embedded with lead fibers, were positioned symmetrically on each side of the beam line. The electronics were setup to require a coincidence between two electrons and reduce the contributions of background especially from Mott scattering.

Commissioning runs were made in April 1998 with a 2.5 GeV polarized electron beam. As a test of the sensitivity of the polarimeter, the polarization angle of the beam was rotated at the source, and the results were measured concurrently in Hall A and Hall B. The results are compared with the expected values in Figure 8.5-4. The polarimeter was even sensitive to a small offset (approximately 4°) in the zero-crossing point. These results agreed well with the measurements from Hall A.

The commissioning showed that good statistical accuracy could be achieved in a fairly short time. To make a measurement to 3% statistical accuracy required about ten minutes. The overhead for starting the measurement, e.g. putting in the target and powering the

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Figure 8.5-4: Measured and predicted beam polarization for different polarization angles at the source. The points are measured with the Möller polarimeter. The solid curve is the calculated polarization that would be measured in Hall B. The measured points are fit by a curve that is shifted by about 4°.

magnets, is about 15 minutes. The contamination of the data from accidental coincidences was measured during the commissioning run by looking at electrons that were coincident with a delayed gate. The real to accidental rate was measured to be better than 200:1.

The basic components of the polarimeter have been shown to work well. Currently, control of the individual components is being combined into one graphical user interface. This control should allow easy use of the polarimeter by all experimenters. The polarimeter will be ready for use in the first major measurement using polarized electrons.

8.6 Polarized Target

8.6.1 Calibrating Target Polarization in a Polarized Neutron - Polarized Proton Transmission Experiment

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We have recently measured the tensor contribution to the $\vec{n} - \vec{p}$ interaction for neutron energies between 1.9 and 20 MeV [Rai97, Wal98]. This contribution is characterized by the phase-shift parameter ϵ_1 which gives the mixing between the $^3S_1$ and $^3D_1$ states, and which can be determined from the spin dependence of the transmission cross section for $\vec{n}$ through a polarized proton target. Although standard NMR techniques were used to monitor the proton polarization, a neutron transmission measurement at 1.9 MeV was used to provide an absolute determination of the target polarization times thickness. This provided the opportunity to compare directly NMR and neutron measurements in precisely characterizing a proton target.

The target at the Triangle Universities Nuclear Laboratory (TUNL) was polarized in a ^3He evaporation cryostat based on a PSI design [vdB90]. The 1 to 2 mm diameter frozen beads of propanediol doped with EHBA - Cr^V complex were contained in a Kel-F box of inner dimensions of 1.4 cm $\times$ 1.4 cm $\times$ 1.4 cm. The nominal proton thickness of the target was 0.06 free H atoms/barn.

The spin dependence of the $\vec{n} - \vec{p}$ transmission for neutron energies near 1.9 MeV can be calculated with confidence from existing phase-shift analyses [Sto93]. This parameter was used as the basis of a determination of the product of target proton polarization times thickness, $P_t x$. The transmission was measured in two geometries. In the transverse (T) geometry the polarization axes of the neutrons and protons are perpendicular to the neutron momentum. In the longitudinal (L) geometry the neutron and proton polarization axes are co-linear with the neutron momentum. A transmission asymmetry

$$\epsilon_n = \frac{N_+ - N_-}{N_+ + N_-}$$

is then calculated. The determination of $P_t x$ depends on the knowledge of $\Delta\sigma_{T,L}$ and precise determinations of ϵ_n and P_n .

The polarization of the secondary $\vec{n}$ beam was calculated from the polarization of the proton beam and the polarization-transfer coefficient. That is $P_n = K_z^{z'} P_p$ in the longi-

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tudinal geometry and $P_n = K_y^{y'} P_p$ in the transverse geometry. The polarization-transfer coefficients have been measured at TUNL and elsewhere [Wil95].

The NMR absorption was measured using a Liverpool-type box [Cou93] connected to a PC-Labview based data-acquisition system. The polarization to area (P/A) ratio of the NMR measurement was determined from measurements of the thermal equilibrium signal at 530 mK and 930 mK. The target thickness itself was determined after the experimental cooldown by carefully removing the target beads from the cryostat, melting them and weighing the extracted material.

Figure 8.6-1: Comparison of determinations of $P_t x$ from four experiments. Circles indicate neutron transmission asymmetry results and squares results from NMR measurements.

While both the NMR and neutron asymmetry measurements of $P_t x$ are precise they disagree at the 1σ error limits. The NMR values of $P_t x$ are consistently 5 to 14% higher than the neutron transmission values if one ignores the June, 1997, point.

We have identified no specific measurement that could be responsible for the consistent offset between the NMR and neutron results, but we note that the NMR and the neutron asymmetry measurements do not necessarily sample the same volume of protons in the solid target. The lesson in these results is that it is always preferable to measure the target polarization through a nuclear scattering technique that is similar to the actual physics measurement of interest.

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8.6.2 Construction and Operation of a Dynamically Polarized Deuterium Target

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We have modified the existing TUNL dynamically polarized proton target for use as a dynamically polarized deuteron target. Vector polarizations of 13 - 15% were realized at 500 millikelvin in a 2.5 tesla magnetic field. The principal modifications to the target cryostat included the preparation of new target material and development of a separate deuteron NMR system.

The target material was partially deuterated 1,2 propanediol (D6) chemically doped with an EHBA Cr^V complex. The target therefore contains 75% deuterons and 25% protons, a property of some convenience in our experiments. The material was obtained commercially and manufactured at TUNL into 1 to 2 mm beads by the same methods used for our proton targets.

The polarization of the target could be determined by measurement of the deuteron NMR absorption signal centered at 16.55 MHz. The deuterium NMR signal is nearly 250 kHz in width and exhibits a Pake doublet structure produced by the interaction of the deuteron quadrupole moment with local electric field gradients. A separate Liverpool-type NMR Q-meter circuit was built to operate at this frequency and mounted on the target cryostat. The deuteron NMR box and $\lambda/2$ cable were mounted and powered so that the NMR system could be rapidly switched with the proton NMR system. To improve the system stability, all of the NMR components were temperature stabilized with a controlled temperature water circulation system.

Several tests of the microwave polarization and deuteron NMR systems were performed. Though the deuteron polarization could be determined through the measurement of the relative amplitudes of the Pake doublet peaks, it was found that the signal-to-noise of the deuteron NMR signals was poor. This was probably because the same low-Q two-turn NMR coil was used for both the deuteron and proton systems.

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It has been shown that nuclear spins in 1,2 propanediol obey the equal spin temperature hypothesis. Therefore it is possible to determine the deuteron polarization by measuring the proton polarization via NMR, which had a better signal-to-noise and which could be calibrated directly from the proton thermal equilibrium NMR signal. We are now investigating the use of a 100% deuterated propanediol (D8) target and modification of the NMR system to provide more reliable deuteron signals. We are also developing computer routines to improve the deuteron polarization determination by fitting the entire absorption line with a microscopic model of the NMR line shape.

8.7 Gas-Jet Target

8.7.1 Progress Towards an Operational Gas-Jet Target

B.M. Fisher, H.J. Karwowski, E.J. Ludwig, D.W. Schieber, and M.H. Wood

As has been previously reported in [Fis97], the Gas-Jet Target arrived from the University of Erlangen-Nürnberg, Germany in June of 1997. The target is to be used in elastic scattering experiments with polarized beams. Since its arrival, much progress has been made in getting the target, and its beam-line, operational.

All four "segments" of the target have been moved to Target Room One, where, after repairing some minor shipping damage, testing started on the rotary-piston pumps and roots blowers. The three rotary piston pumps have been reconditioned and are now operational. Testing of the roots blowers has started.

The system originally ran with 380V voltage in Germany. Conversion to a U.S. standard 208V proved problematic so a step-down transformer (to be used with an existing 480V main) has been ordered; it should be installed by the end of August, 1998.

A LabVIEW computer interface for the system is in early development. It will include controls for interlocks, gas-jet nozzle and catcher positions, safety monitoring systems (including room hydrogen monitors) and provide easy remote operation of all pumps along with the compressor/gas-cleaning assembly.

The 44-degree beamline of the 20-70 magnet has been reconditioned with a new 600 l/s turbo-pump and new beam scanner. The chamber has been aligned and connected to the beam line and preliminary leak tests have started. A new detector mount has been added to the chamber, allowing the use of numerous, pre-existing surface-barrier detector holders with the target.

We hope to have the chamber and pumping systems operational by the end of August, 1998, and have the entire system up and running by Spring, 1999. The whole system will then be tested with nitrogen or helium as the target gas and then, pending approval by the Duke Safety Office, experiments with hydrogen or deuterium as the target gas could begin. Possible initial experiments include p - p and p - d scattering experiments where the diminished backgrounds would greatly improve the precision of such measurements.

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8.8 HIGS Facility at the DFELL

8.8.1 Preliminary Plans for a Frozen Spin Deuteron Target at the HIGS Facility

D.G. Haase

We have begun design studies for a polarized deuteron target that will be used at the HIGS Facility at the Duke Free-Electron Laser Laboratory to investigate the Drell-Hearn-Gerasimov sum rule for the deuteron. The experiment involves directing a beam of circularly polarized gamma rays onto a longitudinally polarized deuterium target and detecting the total flux of neutrons produced from the deuteron breakup reaction. The target will be a 1 cm diameter by 5.1 cm long cylinder of a deuterated organic material polarized to 30 - 40% via the dynamic nuclear orientation process. The cylinder will be oriented with its axis parallel to the polarized gamma beam from the DFELL Compton Backscattering facility. The target cryostat will be a high-flow dilution refrigerator with a horizontal bore so that the gamma beam enters the cryostat along its main axis and encounters a minimum of extraneous material before reaching the deuterated target.

Because the experiment requires neutron detectors located near the target in a low magnetic field the target will be held in the frozen spin mode. That is, the target will be polarized with microwaves while it is held at 500 millikelvin in a 2.5 tesla magnetic field from a superconducting solenoid located in a separate dewar system. Once the target is polarized the temperature will be rapidly reduced to near 50 millikelvin, and the microwaves turned off. A 0.5 tesla holding field will be provided by a small superconducting solenoid located in the target cryostat. At this low temperature the nuclear spin lattice relaxation time becomes of the order of several days, so the 2.5 tesla magnet can be rolled away and replaced with a bank of neutron detectors that fit closely around the target cryostat. The target polarization will be measured with an NMR Q-meter system, as used on our other polarized deuterium target. The drawback of this system is that to reverse the polarization direction the target must be repolarized with the 2.5 tesla magnet.

It is anticipated that the design, construction and testing of the cryostat at TUNL will require 12 to 18 months before its final installation at the DFELL.

8.8.2 Pair Spectrometer for the HIGS Facility at the DFELL

R.S. Canon, S.J. Gaff, J.H. Kelley, E.C. Schreiber, and H.R. Weller

An electron-positron pair spectrometer is being installed to measure the count rate and energy resolution of the γ -ray beam at the DFELL/TUNL High-Intensity Gamma-ray Source (HIGS). Our pair spectrometer will consist of a thin foil to convert γ rays to electron-positron pairs, a circular dipole magnet to focus the electrons and positrons onto separate

detector planes, and a series of position sensitive solid-state detectors to measure the degree of bending experienced by the electrons and positrons in the magnet field. A dipole magnet obtained last year from the Max Planck Institut in Mainz, Germany was measured and tested at TUNL. These tests, performed with electrons from a ^{106}Ru source and photons from $^7\text{Li}(p,\gamma)$ reaction, demonstrated the magnet to be inadequate for our requirements. An improved pair spectrometer system has been acquired from the Saskatchewan Accelerator Laboratory (SAL). This spectrometer has been demonstrated to accurately detect γ rays at the energies and count rates we will require as we further develop the HIGS system. The spectrometer arrived in mid Summer 1998 and is expected to be ready for the initial γ -ray tests later in the year.

8.9 KamLAND Detector

8.9.1 The Veto of KamLAND

L. DeBraekeleer, C.R. Gould, and W. Tornow

Our group has taken the responsibility for the veto counter of the KamLAND (Kamioka Liquid scintillator Anti-Neutrino Detector) experiment. Pending DOE funding for the U.S. contribution to the KamLAND project, this includes both the R&D, the mechanical engineering and the Monte-Carlo simulation, as well as the actual construction in Japan starting in January 2000. KamLAND is an experiment that will detect rare events such as antineutrinos emitted from nuclear reactors, from the Earth's radioactive elements, atmospheric neutrinos, solar neutrinos, and it will also include a search for nucleon decays.

The antineutrinos will be detected in a liquid scintillator by the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ with subsequent (delayed) capture of the neutron: $n + p \rightarrow d + \gamma$.

KamLAND consists of a 1,200 m³ spherical vessel filled with liquid scintillator fluid, viewed through a 2.5 m thick layer of isoparaffin (2,500 m³) by about 1200 phototubes, and finally the two concentric spheres are surrounded by a cylinder filled with pure water (3000 m³) and acting as a Čerenkov veto counter.

The success of the experiment and the quality of the data will heavily depend on how much the background can be suppressed and how well it will be understood. The water suppresses the background in several ways. Passively, it absorbs the radioactivity coming from the walls, which will be coated with a special paint. Also, the water degrades the energy of the fast neutrons originating from muon induced spallations in the wall material (rock). A priori, these neutrons can be quite a dangerous potential background. Once inside the detector, they can scatter on a proton and then slow down and capture on another proton. If pulse-shape discrimination between protons and electrons (positrons) is not perfect, the first proton might be misidentified as a positron and the whole scenario perfectly mimics an antineutrino reaction. Fortunately, only the neutrons produced in a 1 meter thick annulus of rock surrounding the detector volume contribute to the background. The others have their energy degraded too much to be a problem, and it has been estimated that this process will therefore not contribute to the background. Of course, the muons will also create neutrons by spallation in the water surrounding the spherical part of the detector. However, these neutrons will be in coincidence with the muon which can be detected because of the Čerenkov light that it emits in the water. Therefore, these events will be actively vetoed and it is evident that the efficiency for this active veto must be high. There is a major difference between the veto of KamLAND and the veto of the previous experiment Kamiokande. In the Kamiokande design, the Čerenkov light of the incoming muons was detected directly by an array of phototubes (PMTs) looking at the muons. They were mounted at the boundary of the fiducial volume and they were looking outside. The design

of KamLAND is different. Here, the PMTs of the veto are mounted on the cylindrical walls and the flat top and bottom surfaces, thus looking at the spherical detector which is covered by a highly reflective material. The Čerenkov light emitted by the incoming muons will be detected after reflection from the diffuse reflector. The PMTs of the Kamiokande experiment will be reused to build this veto. Several hundreds of them will be mounted on the top, the bottom and the inner surface of the cylinder, resulting in a total coverage of about 3%. The muons will cross the apparatus at a rate of about 0.4 Hz. They will typically go through 1 meter of water before entering the central detector. Assuming a 20% photocathode efficiency, one expects to detect about 100 photoelectrons, a number well above the expected dark current counting rate. However, there is a smaller gap at the equator of the sphere. Here, the water thickness is only 50 cm. The combination of this smaller path and the larger distance to the closest photocades might drastically reduce the efficiency of the veto. Of course, the rate of muons coming to the detector at large angles is much lower. Because of the chimney on top of the detector, there is a large unvetoes area right there where the cosmic-ray muon flux is the highest. Therefore, a 5 by 5 m² segmented plastic veto will be built on top of it. The side of the chimney will also be surrounded by plastic plates. A muon track going through the entire detector can be used to monitor the stability of the PMTs and the transparency of the scintillator. A few plastic detectors will be mounted on the floor of the veto counter, around the Čerenkov PMTs, and these detectors will be operated in coincidence with the segmented plastic detector located on top of the chimney. Such a coincidence will therefore identify well defined muon tracks and these events can be accumulated over the lifetime of the experiment to study the stability of the detector. The basic idea of the veto counter will be checked at TUNL using the coincidence between cosmic-ray muons entering a water tank and the Čerenkov light being reflected by a diffuser mounted on the floor of that tank. This device will also be used for other tests such as the study of the feasibility to shift the wavelength of the Čerenkov light by adding appropriate chemicals to the water. In principle, this can increase the number of photoelectrons since the bulk of the light is below the spectral efficiency of the photocathode. On the other hand, the attenuation length could be drastically reduced and this possibility must be carefully studied.

8.10 Detector Developments

8.10.1 Analog Fiber-Optics Pulse Transmission Circuitry

C. McKinney¹ and H.J. Karwowski

A simple, three-component system for transmitting detector pulses from inside a high-voltage field to ground potential over fiber-optics cables has been developed and tested. This system will replace the existing transmission link in the High Voltage Chamber at the LEBAF facility, which suffered from narrow dynamic range and deteriorating reliability.

The system consists of a transmitter, receiver, and DC baseline restorer. The transmitter utilizes a Hewlett-Packard LED optical transmitter module driven by a high-speed, high-current amplifier with gain and offset controls. The input impedance of the amplifier is high (100 k Ω) and may be either AC or DC coupled as set by an internal jumper. The receiver consists of a matching Hewlett-Packard optical receiver module that drives a high-speed amplifier capable of providing an output current of up to 100 mA in order to easily drive 50 Ω loads. AC or DC interstage and output coupling can be jumper-selected. An active unity-gain buffer stage is used to provide input offset voltage adjustment to the high-speed amplifier while maintaining amplifier stability by elimination of parasitics through a very low output impedance.

The high-speed amplifiers (220 MHz gain bandwidth product) used in both the transmitter and receiver circuits were designed specifically for amplification of high speed AC signals and thus have not been optimized for DC stability. Therefore, the system will have the highest pulse-height stability when AC coupling is used throughout. This, however, causes DC baseline shifts to occur at high pulse repetition rates, severely affecting pulse-height measurements. Therefore, a baseline restoration circuit was designed to maintain amplitude stability.

The restoration circuit used here inverts the input signal, rectifies it, and sums the error signal back to the original signal to correct for the baseline shift. The circuit consists of a high-speed summing amplifier with the non-inverting input connected to the output of the receiver circuit. A low-pass filtered precision active rectifier preceded by an inverting amplifier feeds the inverting input. The error amplifier input is jumper-selectable to provide either open-loop (passive) or closed-loop (active) baseline correction. In the active mode, a feedback loop around the high-speed amplifier is established, thus correcting for system baseline errors.

Tests of the transmission system have shown that it is capable of reproducing Gaussian pulses with pulse widths down to 1 μ sec at periodic repetition rates of over 20 kHz while driving a 50 Ω load to over 8 V without pulse degradation. Random pulse tests using a ⁶⁰Co source and a Ge detector show no change in the energy resolution of 1.33 MeV peak

¹Department of Radiology, Duke University, Durham, NC.

for rates up to 5 kHz and a slight increase in energy resolution for rates above 10 kHz. Further tests of the system are in progress.

8.10.2 Digital Triggers for Low Count Rates

A.E. Champagne and S. Seagroves

Cross-section measurements at low energies can be complicated by backgrounds from a variety of sources such as cosmic rays, target contaminants, etc. If the signals of interest have low energies, electronic noise can also be a problem. Usually, the analog filters built into amplifiers are adequate for dealing with environmental noise sources, but if the count rate is low, then spurious signals can be a problem. However, low count rates allow us to carefully look at detector pulses as they are generated, for example by digitizing the preamp output.

To test this idea, we have collected digitized preamp signals generated by α -particles from ^{241}Am and the reactions $^{nat}\text{Li}(p,\alpha)$, and $^{10}\text{B}(p,\alpha)$. The reaction data were collected at $E_p = 80$ keV. The data-acquisition software (written in LabVIEW) was set up to collect valid event triggers as well as background after every 8th event. False triggers from noise can be clearly discerned within the group of valid events. We tried several techniques to remove these bad events. Discrimination of the basis of power spectra was not successful because the background had a large bandwidth. The sizable low-frequency component also rendered "optimal" filtering less than optimal.

Although there are other techniques for digital filtering, analog filtering is perfectly adequate provided that unwanted signals can be removed. Standard pulse-shape discriminators can be adapted for this purpose, at least for some applications, but we desire a simpler alternative. Consequently, we have constructed a crude software discriminator based on risetime and this does an excellent job of removing bad events, some of which would appear as background in our α spectrum. We are now working to convert this technique to real-time discrimination. Again using LabVIEW, we are constructing a trigger based on a sample risetime derived from an ensemble of ideal pulses. This module is also designed to produce a measurement of the risetime that can be stored along with the energy signal to facilitate offline analysis.

8.11 Data-Acquisition Systems

8.11.1 New Data-Analysis and Data-Acquisition Systems for TUNL

R.T. Braun, R.S. Canon, S.E. Edwards, and C.R. Howell

The upgrade of the data-analysis computer resources at TUNL is proceeding on schedule and slightly below cost. Most of the savings on the data analysis stations come from our decision to build some stations using personal computers (PCs) instead of Sun workstations. The Fortran compiler by Asoft was installed on the cluster to offer users a robust Fortran compiler for Linux that features most of the DEC extensions to Fortran-77. A fully equipped (Pentium II processor with a clock speed equal to or greater than 300 MHz, 64 MB RAM, 6 GB hard disk storage, an 8-mm Exabyte tape drive, 17-inch color monitor, SCSI interface, a CD drive and Linux OS) PC-based data-analysis station costs about \$3k less than an equivalently instrumented Sun station with a 167-MHz processor clock speed. Ten stations were added to the cluster last year. Five use 167-MHz Ultra-1 Sun workstations, and the others use Gateway PCs with 300-MHz Pentium II processors. In addition, two stations are being prepared to be placed at NC State University and at UNC in Chapel Hill. Each station has a Dell PC, equipped as described above, with a 19-inch color monitor. The Fortran compiler by Asoft will be bundled with data-analysis software installed on each remote station.

The savings accrued by using the lower-cost PC stations are being used to add more stations to the system and to enhance the analysis infrastructure in the laboratory. For instance, five network printers (four HP laser writers and one HP color ink jet), a 20-disk CD tower, a color scanner and a station for writing CDs has been added to the system as part of the upgrade. The storage capacity of a CD (about 0.6 GB uncompressed and nearly 2 GB compressed for TUNL data) is well matched to the volume of data from a TUNL experiment. The Parallel Virtual Machine software package from Oak Ridge National Laboratory has been installed on the cluster to provide parallel computing capabilities. This software has enabled users running Monte-Carlo simulations to make efficient use of the enormous aggregate processing power of our present data-analysis cluster. We anticipate this software will provide important data-processing options for the group in the CLAS collaboration at Jefferson Laboratory. Their experiment starts in August this summer and will run until mid November. After one or two passes through the data using the CPU at Jefferson Laboratory, the sifted data will be brought to TUNL for final analysis in the Spring of 1999. There remains the issue of whether a computer server, like a workstation with a dual 400-MHz DEC Alpha processor, is needed to analyze the large volumes of complex data from CLAS at a practical speed. The decision will be postponed until some experience with replaying CLAS data is acquired.

In addition to the above enhancements, the TUNL local-area network (LAN) was up-

graded. It has been fully converted to a star topology. The University Office of Information Technology (OIT) installed new high-performance 100Base-T wiring in the TUNL building and in the main physics building. The network is segmented into working groups using the 24-port Ethernet switch, which was provided by the OIT. The LAN is connected to the physics department network with a 100Base-FX fiber up link from the switch. Our plan is to use the 100Base-T down-link port on the switch for the Solaris server and eventually for a high-speed web server. The LAN now has the bandwidth to make effective use of the high-speed bus structure of modern computers.

Two prototype data-acquisition (DAQ) stations were assembled last year and have been used to benchmark system parameters, to test component performance and to develop software. A Sun workstation with a 167-MHz Ultra-1 processor was used in each prototype to configure the system and to perform online data analysis. The first prototype was built in the first quarter of 1997 and has VME and CAMAC readout capability. The readout controller is a Motorola MVME-162 single-board computer for VME with a 68020 (33 MHz) processor with 8 Mbytes of RAM. It runs the VxWorks (version 5.1) real-time UNIX operating system and is interfaced to CAMAC using a Kinetic Systems (KS) 3912 VME-CAMAC interface. The data are buffered in the MVME-162 memory and transferred to the data acquisition workstation over Ethernet using standard TCP/IP protocol. The software engine for the system is CODA2.0, which was developed and is maintained by the DAQ group at Jefferson Laboratory. The first experiment to use the prototype started taking data in July 1997 and has taken data throughout the year. The system is robust, but its speed is inadequate to meet the general DAQ needs at TUNL. Most experiments at TUNL have one- or two- parameter data at high trigger rates (several hundred Hz). Therefore, the minimum speed requirement for the new system is two-parameter (2P) CAMAC readout at a rate of 15 kHz (400 Hz trigger rate with a deadtime of 3%). The speed of the prototype for 2P readout is about 4 kHz, a factor of almost four short of the requirement. The main limitations are the latency time (about 200 μ s) of the 3912 VME-CAMAC interface and its intrinsic speed when operated in single-step mode (about 35 μ s for each CAMAC instruction) as done in the CODA software. The system is being optimized to squeeze a bit more speed out of this hardware combination. For instance, the 3912 is strobed by the module with the fastest conversion time to reduce the effective latency time of the 3912. Also, we hope to shave a little time off the 35 μ s instruction time by loading the address of each CAMAC module prior to starting data collection.

The intrinsic hardware limitations were reduced in the second prototype by replacing the KS 3912 CAMAC-VME interface with the 8210 VME-based CAMAC branch drive by Creative Electronic Systems (CES). The interrupt latency of the CES 8210 is about 60 μ s and each CAMAC instruction takes about 15 μ s. The maximum 2P readout rate with this hardware configuration is about 10 kHz, about 35% shy of the design goal of 15 kHz. We are confident that another factor of two in speed can be achieved through software modifications. For instance, the CAMAC addresses of all active modules will be stored

before commencing data acquisition. In addition to the faster processing speed over the KS interface, the CES 8210 is compatible with the A-2 CAMAC crate controller, which is the type used with our existing MBD-VAX systems, and gives users the capability to do LAM grading. The KS 3912 requires a special parallel crate controller and does not give access to the LAM signals. Though too slow for normal DAQ at TUNL, the system based on the KS 3912 interface can be used as a detector development DAQ station or as a small portable DAQ station. The timeline is to install the first station for general laboratory DAQ this fall.

Appendices

I. Graduate Degrees Awarded

Ph.D. Degrees

1. Dinko González Trotter, "Extraction of the $^1S_0$ Neutron-Neutron Scattering Length from a Kinematically Complete n - d Breakup Experiment," Duke University, *Supervisor*: W. Tornow.
2. Qiankun Chen, "Extraction of the $^1S_0$ Neutron-Neutron Scattering Length from the Reaction π - $d \rightarrow \gamma nn$ Using Monte Carlo Simulations," Duke University, *Supervisors*: R.L. Walter and C.R. Howell.
3. Joseph R. Walston, "Determination of the Nucleon-Nucleon Tensor Force Through $\bar{n}$ - $\bar{p}$ Scattering Measurements," North Carolina State University, *Supervisors*: C.R. Gould and D.G. Haase.
4. Richard Braun, "The Neutron-Proton Analyzing Power at $E_n = 7.6$ and 12 MeV and the πNN Coupling Constant," Duke University, *Supervisor*: W. Tornow.
5. Bryan J. Rice, "The $^4\text{He}(\gamma, dd)$ Reaction at $E_\gamma = 150$ –250 MeV" Duke University, *Supervisor*: H.R. Weller.
6. Frank Salinas, "Extraction of the $^1S_0$ Neutron-Proton Scattering Length from a Kinematically Complete n - d Breakup Experiment," Duke University, *Supervisor*: C.R. Howell.
7. William H. Geist, "The $^3\text{He}(d, p)^4\text{He}$ Reaction at Low Energies," University of North Carolina, *Supervisor*: E.J. Ludwig.

II. Publications

Articles Published

1. ${}^7\text{Li}(\vec{p},\gamma){}^8\text{Be}$ Reaction at $E_p = 80\text{--}0$ keV, M.A. Godwin, C.M. Laymon, R.M. Prior, D.R. Tilley and H.R. Weller, *Phys. Rev.* **C56** 1605 (1997).
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8. Measurements of Reaction Rates Relevant to Abundances in Globular Clusters, S.E. Hale, D.C. Powell, A.E. Champagne, C. Iliadis, J.C. Blackmon and V.Y. Hansper, Proceedings of 2nd Oak Ridge Symposium on Atomic and Nuclear Physics in the Universe.
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10. Polarized Protons and Heavy Ions, T.B. Clegg and W. Haeberli, Handbook of Accelerator Physics and Engineering, World Scientific.
11. Parity Nonconservation in Neutron Capture on ^{113}Cd , S.J. Seestrom, J.D. Bowman, B.E. Crawford, P.P.J. Delheij, C.M. Frankle, C.R. Gould, D.G. Haase, M. Inuma, J.N. Knudson, P.E. Koehler, L.Y. Lowie, A. Masaike, Y. Masuda, Y. Matsuda, G.E. Mitchell, S. Penttilä, Yu.P. Popov, H. Postma, N.R. Roberson, E.I. Sharapov, H.M. Shimizu, D.A. Smith, S.L. Stephenson, Yi-Fen Yen and V.W. Yuan, Phys. Rev. C.
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3. Determination of the ^3P_j Phase Shifts from Nucleon-Nucleon Data: A Critical Evaluation and a Surprising Result, T. Tornow and W. Tornow, Few-Body Syst.
4. Toward a Global Exciton Model: The Equilibrium Component, C. Kalbach, J. Phys. G.
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7. Error Estimates of Resonant Thermonuclear Reaction Rates, W.J. Thompson and C. Iliadis, Nucl. Phys. A.

III. Conference Reports

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4. Model-Independent Determination of the ϵ_1 Phase Shift Parameter with Low Energy $\vec{n}\text{-}\vec{p}$ Scattering, B.W. Raichle, C.R. Gould, D.G. Haase, M.L. Seely, J.R. Walston, W. Tornow, W.S. Wilburn, G.W. Hoffmann and S.I. Penttilä, Bull. Am. Phys. Soc. **42** 1649 (1997).

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41. Sub-Coulomb α Transfers on ^{12}C and the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ Reaction Rate, C.R. Brune, W.H. Geist, R.W. Kavanagh and K.D. Veal, Proceedings of the 5th International Conference on Nuclei in the Cosmos, Volos, Greece (1998).
42. Sodium and Aluminum in Globular Clusters: Reaction Studies, A.E. Champagne, S.E. Hale, D.C. Powell, C. Iliadis, V.Y. Hansper and J.C. Blackmon, Proceedings of the 5th International Conference on Nuclei in the Cosmos, Volos, Greece (1998).
43. Commissioning of the Daresbury Recoil Separator for Nuclear Astrophysics Measurements at the Holifield Radioactive Ion Beam Facility, M.S. Smith, J.C. Blackmon, P.E. Koehler, T.A. Lewis, J.W. McConnell, W.T. Milner, D.E. Pierce, D. Shapira, D.W. Bardayan, A.A. Chen, P.D. Parker, K.B. Swartz, D.W. Visser, R.L. Kozub, B.A. Johnson, M.E. Roettger, A.E. Champagne, Z. Ma, U. Greife, F. Strieder, A.N.

James, M.A. Hofstee and M. Allen, Proceedings of the 2nd Oak Ridge Symposium on Atomic and Nuclear Physics in the Universe (1998).

IV. Invited Talks and Seminars

1. The Nucleon-Deuteron Analyzing Power Puzzle, W. Tornow, Institute for Nuclear Theory, Seattle (1997).
2. Recently Solved and Currently Unsolved Problems in Low-Energy Few-Nucleon Physics, W. Tornow, International Workshop on Few-Body Problems in Nuclear Physics and Related Fields, Trento, Italy (1997).
3. The Triangle Universities Nuclear Laboratory: Recent Scientific Results and Future Directions, W. Tornow, University of North Carolina at Chapel Hill (1998).
4. Few-Nucleon Physics with Hadronic Probes, W. Tornow, 16th European Conference on Few-Body Problems in Physics, Autrans, France (1998).
5. Parity and Time Reversal Tests in Nuclear Physics, C.R. Gould, University of Notre Dame (1997).
6. Symmetry Tests and the Compound Nucleus, C.R. Gould, Oak Ridge National Laboratory (1997).
7. Some Open Questions in Explosive Nucleosynthesis, A.E. Champagne, Michigan State University (1997).
8. Sodium and Aluminum in Globular Clusters: Reaction Studies, A.E. Champagne, Nuclei in the Cosmos, Volos (1998).
9. Measurements of Reaction Rates Relevant to Abundances in Globular Clusters, S.E. Hale and D.C. Powell, 2nd Oak Ridge Symposium on Atomic and Nuclear Physics in the Universe (1998).
10. Two-Neutron HBT Interferometry to Measure Time-Scales in the Reaction $^{40}\text{Ar} + ^{165}\text{Ho}$ at $E/A = 25$ MeV, S.J. Gaff, 2nd Catania Relativistic Ion Studies, Catania, Italy (1998).
11. Experimental Tests of Random Matrix Theory in Nuclei, G.E. Mitchell, Wigner Symposium V, Vienna, Austria (1997).
12. Parity Violation in Complex Nuclei, G.E. Mitchell, Lund University, Sweden (1997).
13. Broken Symmetries in Chaotic Nuclei, G.E. Mitchell, New Spectroscopy and Nuclear Structure 1997, Copenhagen, Denmark (1997).

14. Chaos in Quantum Many Body Systems, G.E. Mitchell, Southeastern Section of the American Physical Society, Nashville (1997).
15. Parity Violation in Neutron Resonances, G.E. Mitchell, Institut des Sciences Nucleaires, Université J. Fourier, Grenoble, France (1997).
16. Parity Violation in Charged Particle Resonance Reactions, G.E. Mitchell, Parity Violation in Hadronic and Nuclear Systems, Institute for Nuclear Theory, Seattle (1998).

V. Seminars at TUNL

1. Tom Clegg, University of North Carolina (9/4/97)
Options for Producing More Intense Polarized H and D Beams
2. Diane Markoff, University of Washington (9/11/97)
Measurement of the Parity-Nonconserving Spin-Rotation of Transmitted Cold Neutrons through a Liquid Helium Target
3. Blayne Heckel, University of Washington (9/18/97)
Time Reversal Symmetry Violation: New Pieces to an Old Puzzle
4. Dinko González Trotter, Duke University (10/2/97)
Results of the TUNL $^1S_0$ Neutron-Neutron Scattering Length Experiment
5. Carl Brune, University of North Carolina (10/16/97)
Proton-Deuteron Scattering at Low Energies
6. J. Scott Price, TJNAF (10/30/97)
Polarized Beam on Target: A Review of Polarized Electron Beam Production and Delivery at TJNAF
7. Alejandro Kievsky, Istituto Nazionale di Fisica Nucleare (11/2/97)
Progress in the Description of Three- and Four-Nucleon Scattering States
8. Kamal K. Seth, Northwestern University (11/12/97)
Charmonium - In and Out of the Nucleus
9. Bruce Vogelaar, Princeton University (11/20/97)
Can't Fix It? Prove It's Broken: Borexino and the Be-7 Neutrino Flux
10. Xiaodong Jiang, University of Massachusetts at Amherst (11/25/97)
The Out-of-Plane Spectrometer (OOPS) Project at MIT/Bates
11. Steve Churchwell, University of Massachusetts at Amherst (12/2/97)
The Spin Structure of the Neutron: Results from SLAC Experiment E154

12. John Hardy, Texas A&M University (12/11/97)
Superaligned Beta Decay: A Nuclear Probe of the Electroweak Standard Model
13. Mark Roberts, Lawrence Livermore National Laboratory (1/22/98)
The Lawrence Livermore National Laboratory Ion Microprobe
14. Charles Perdrisat, College of William and Mary (1/29/98)
Proton Electric Form Factor with Polarized Electrons at TJNAF
15. Joseph Walston, North Carolina State University (2/5/98)
Determination of the Nucleon-Nucleon Tensor Force through $\vec{n}-\vec{p}$ Scattering Measurements
16. Stanley Kowalski, MIT/Bates (2/12/98)
Spin Observables in High Energy Electron Scattering
17. Petr Vogel, California Tech (2/26/98)
Neutrinos and the r-Process Nucleosynthesis
18. Richard Braun, Duke University (3/5/98)
The Neutron-Proton Analyzing Power at $E_n = 7.6$ and 12 MeV and the πNN Coupling Constant
19. Uli Giesen, TRIUMF (3/12/98)
Traps and Dragons: Physics with Radioactive Beams at TRIUMF
20. Carl Gagliardi, Texas A&M University (3/26/98)
Asymptotic Normalization Coefficients and ${}^7\text{Be}(p,\gamma){}^8\text{B}$
21. Sam Austin, Michigan State University (4/2/98)
Spin Strength and Supernovae
22. Moshe Gai, University of Connecticut (4/9/98)
Nuclear Astrophysics with Secondary (Radioactive) Beams
23. Lynn Knutson, University of Wisconsin (4/16/98)
Some Comments on the Nuclear Three-Body Force
24. Frank Salinas, Duke University (4/23/98)
Use of the ${}^1S_0$ Neutron-Proton Scattering Length as a Probe for Three-Nucleon Forces
25. Willem Van Oers, University of Manitoba (4/28/98)
Proton-Proton Parity Violation Experiments

26. Rick Casten, Yale University (4/30/98)
Physics Opportunities with Radioactive Beams
27. Giorgio Gratta, Stanford University (5/13/98)
Doing Science with Neutrinos: The KamLAND Experiment
28. Steve Sterbenz, LANSCE (5/14/98)
The Los Alamos Neutron Science Center (LANSCE) and Stockpile Stewardship
29. Antonio Fonseca, University of Lisbon, Portugal (5/21/98)
How Realistic Interactions Fail to Describe Low-Energy Four-Nucleon Observables
30. Alexander Barabash, ITEP, Moscow (7/7/98)
Double Beta Decay to Excited States of Daughter Nuclei
31. Yuri Kamyshev, University of Tennessee (7/13/98)
Search for (B-L) Nonconservation: Proton Decay and Neutron Oscillation in the Kamland Detector
32. Henryk Witala, Jagellonian University, Cracow (8/20/98)
On the Application of $3N$ Scattering States

Advances in Physics Seminars

1. Ludwig DeBraekeleer, Duke University (6/18/98)
The Superkamiokande Experiment: Clear Evidence for Neutrino Mass
2. Carl Brune, University of North Carolina (6/25/98)
Big Bang
3. Chris Gould, North Carolina State University (7/2/98)
Parity Violation
4. Richard Prior, North Georgia College and State University (7/9/98)
Angular Momentum
5. Calvin Howell, Duke University (7/16/98)
Nuclear Physics and Society
6. Hugon Karwowski, University of North Carolina (7/22/98)
Nuclear Physics and the Arts
7. Diane Markoff, North Carolina State University (7/30/98)
The Deuteron Playground: Understanding the Nucleon-Nucleon Interaction

TUNL Safety Talks

1. Terry Yoshizumi, Brenda Pulliam and Kelly Ryan, Radiation Safety Office, Duke University (6/1/98)
Overview of Radiation Health Issues, Dosimetry and Operational Health Physics at TUNL
2. Scott Alderman, Occupational & Environmental Safety Office, Duke University (6/1/98)
Chemical Safety
3. Aaron Weinbaum, Occupational & Environmental Safety Office, Duke University (6/4/98)
Fire Safety
4. Larry Lloyd, Occupational & Environmental Safety Office, Duke University (6/4/98)
Lockout/Tagout Procedures and General Occupational Hazards
5. Chris Westerfeldt, TUNL, Duke University (6/5/98)
Laboratory Safety at TUNL
6. Paul Carter, TUNL, Duke University (6/5/98)
Emergency Procedures at TUNL

TUNL Introduction Lecture Series

1. Paul Carter, TUNL (6/9/98)
Vacuum Systems in an Accelerator Lab
2. Chris Westerfeldt, TUNL (6/9/98)
Principles of Accelerator Control Circuits
3. Sidney Edwards, TUNL (6/9/98)
The TUNL Electronic Shop: Primary Functions and Practical Electronic FYIs
4. Robert Timberlake, Duke University (6/9/98)
The Physics Instrument Shop: Capabilities, Resources, and Procedures
5. Richard O'Quinn, TUNL (6/9/98)
Local Research-Materials Stores and Recommended Steps for Ordering Materials and Mechanical Instrumentation
6. Tom Clegg, UNC/TUNL (6/10/98)
The Physics of the TUNL Polarized Ion Source and Online Beam Polarimetry

7. John Dunham, TUNL (6/10/98)
Operation of the TUNL Polarized Ion Source
8. Steve Hale, UNC/TUNL (6/10/98)
Cross-Section Measurements with the TUNL Enge Split-Pole Spectrometer
9. Denise Powell, UNC/TUNL (6/10/98)
Thin-Target Fabrication
10. Mark Mikolajewski, Raleigh Valve and Fitting Company (6/11/98)
Tube and Pipe Connections
11. Dinko González Trotter, Duke/TUNL (6/11/98)
Neutron Measurements
12. John Kelley, TUNL (6/11/98)
Gamma-Ray Measurements
13. Mike Wood, UNC/TUNL (6/12/98)
Charged-Particle Measurements
14. David Haase, NCSU/TUNL (6/15/98)
Polarized Target Technology