STUDIES OF NUCLEAR PROCESSES

Progress Report

1 September 1992-31 August 1993

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TUNL XXXII
PROGRESS REPORT

1 SEPTEMBER 1992 - 31 AUGUST 1993

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, looks back on an interesting and productive 1992-1993. The following reports cover the final year of three-year grants between the U.S. Department of Energy and the three collaborating universities.

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

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

The results from the TRIPLE collaboration experiments at LANSCE/LANL continue to generate great interest, particularly the issue of sign correlations in ^{232}Th . Over a dozen theoretical papers discussing our results have been published. One review of our work has been published in the Soviet Journal of Particles and Nuclei and another will be included in the 1994 Annual Review of Nuclear and Particle Science.

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

We recently completed a measurement of the tensor mixing parameter in the n-p system. By scattering polarized neutrons from a polarized-proton target, we found the tensor force at low energies to be weaker than currently accepted, a result which should bring triton binding energy calculations into much closer agreement with the experimental value.

- **Observation of p-wave capture strength in 80 keV $^2\text{H-d}$ capture:**

Tensor analyzing power data show 50% of the cross section is due to p waves, indicating meson exchange currents are probably important in understanding low energy deuteron-deuteron fusion reactions.

- **$^8\text{Li}(\alpha, n)$ reaction and inhomogeneous big bang nucleosynthesis:**

From other reactions we have inferred the $^8\text{Li}(\alpha, n)$ reaction rate. We find this rate to be small, seriously reducing the possibility of heavy element production during an inhomogeneous big bang. Therefore, contrary to some expectations, observers will not be able to detect evidence for an inhomogeneous big bang by studying heavy element abundances.

- **Atomic beam polarized ion source:**

We brought into full operation one of the most intense polarized-ion sources in the world, complete with an innovative ECR ionizer. A recent proof-of-principle test has shown that a Lamb-shift spin filter on the source can provide for rapid on-line beam polarimetry, a major advance in the utilization of atomic-beam polarized ion sources for all users.

The TUNL research program focuses on several of the nuclear physics frontiers identified in the 1989 NSAC Long Range Plan. We are involved in and propose to continue research in the following areas:

- Precision tests of parity and time reversal invariance violation in resonance neutron scattering at LANSCE/LAMPF.
- Parity and time-reversal violation tests using charged particle resonances in $A = 20 - 40$ targets.
- Chaotic behavior in the nuclei ^{22}Na and ^{30}P from studies of eigenvalue fluctuations in nuclear level schemes.
- Nuclear astrophysics, using the refurbished Enge split-pole spectrometer at TUNL and the Radioactive Ion Beams facility at ORNL.
- Few-body nuclear systems, with specific experiments to address:
 - radiative capture reactions to investigate the D-state structure of ^3He , ^4He , and ^6Li , and the role of meson-exchange-currents
 - the role of three nucleon forces in the 3N continuum
 - the nature of the tensor force in the N-N interaction
 - charge symmetry breaking in the $^1\text{S}_0$ component of the N-N interaction and charge independence breaking in the ^3P components
 - delineation of the state structure of the low-energy $n\text{-}^3\text{He}$ continuum from scattering of polarized neutrons from a polarized ^3He target
 - p-d scattering lengths at very low energies
 - the quark structure of nucleons in experiments at CEBAF
- High-spin spectroscopy and superdeformation.

Developments in technology and instrumentation have been vital to our research and training program. We report:

- polarized ion source development,
- design of new cryogenic systems,
- improvement of the high-resolution beams for the KN accelerator,
- development of the Low Energy Beam Facility.

We plan to continue our innovative work in these areas. TUNL is recognized internationally for its development of polarized ion sources and low-temperature targets and detectors. We report plans to modify our ECR ionizer system to minimize radial loss of polarized ions, for adding a gridded electrode extraction system to improve overall beam brightness, and for permanent magnet sextupoles to improve our polarized beam formation system. We are currently building rapid-cycle cryogenic microcalorimeters – bolometers, which are devices that operate in the milliKelvin temperature regime to detect incident radiation with superb energy resolution. In the development of polarized targets, we are negotiating a collaboration which would bring a partially completed dynamically polarized proton target to TUNL. This target will be completed at TUNL and will allow the proton spin to be flipped in a short time,

thus reducing systematic errors. The target will also maintain high polarization in the intense neutron beams now available at TUNL.

The nuclear data evaluation project for nuclei with $A = 3$ to 20 was moved to TUNL during the last three-year grant period and continues to benefit our local research as well as providing a service to the nuclear physics community.

As one of the largest university-based nuclear physics laboratories, TUNL has special responsibilities and opportunities to lead in the training of young scientists. We recently hosted the 1993 National Nuclear Physics Summer School, at which approximately fifty students and postdoctoral research associates from the U.S. and overseas attended a two-week program of lectures. The school, located at North Carolina State University, was cosponsored by TUNL and the local nuclear theory faculty, and financially supported by NSF and DOE.

The TUNL seminar program continues with characteristic vigor. A related program, the Triangle Nuclear Theory (TNT) seminars, with presentations by 27 speakers in 1992-1993, is also beneficial to TUNL faculty and students.

The talents and enthusiasm of the 16 faculty members, 6 research staff and postdoctoral associates and approximately 30 graduate students from the three Triangle universities are responsible for the successes of our research program. We also benefit from the extensive skills provided by the TUNL technical support staff and from the large number of visitors and collaborators.

The TUNL Advisory Committee – Drs. David Balamuth (University of Pennsylvania), Gerald Garvey (Los Alamos National Laboratory), Wick Haxton (University of Washington), Steven Vigdor (University of Indiana) and Dirk Walecka (College of William and Mary) – continues to provide sound 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 state of a project, please contact the physicist whose name is underlined in the author list.

Triangle Universities Nuclear Laboratory

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1. FUNDAMENTAL SYMMETRIES IN THE NUCLEUS

1.1 Parity-Mixing Measurements

1.1.1 Parity and Time Reversal Symmetry Violation with Polarized Epithermal Neutrons--An Overview

*B.E. Crawford, C.R. Gould, D.G. Haase, L. Lowie, G.E. Mitchell, S.S. Patterson, N.R. Roberson and the TRIPLE Collaboration**

The nucleon-nucleon force is composed of two distinct parts: the strong, parity conserving (PC) interaction, and the weak, parity violating (PV) interaction believed to be transmitted by light mesons with different changes of isospin. Since the weak interaction violates parity conservation, it can be detected by measurement of pseudo-scalar observables of the type $(\vec{\sigma}, \vec{k})$, where $\vec{k}$ is the momentum and $\vec{\sigma}$ is the spin of the nucleon. In the absence of enhancements, the effects are expected to be small, as the PV interaction is known to have a strength of the order of 10^{-7} relative to the PC interaction. Polarized low-energy neutron scattering in the compound nucleon (CN) region has proven to be a rich field for testing PV. The weak interaction causes the mixing of nuclear levels of the same spin but opposite parity. Two CN mechanisms enhance the effects. Resonances are long lived (increasing the time for which the neutron interacts) and the levels are close together in energy. These features combine to magnify by 10^4 to 10^5 the effects in measurement of the helicity dependence of the cross section in the CN region in heavy nuclei.

The TRIPLE collaboration uses the high-flux epithermal neutron beam from LANSCE (Los Alamos Neutron Scattering Center) to study how the PV part of the NN interaction manifests itself. A series of measurements of the pseudo-scalar term $(\vec{\sigma}, \vec{k})$ in the total cross section of p-wave resonances, σ_p , have been carried out by determining the longitudinal asymmetry

$$p = (\sigma_p^+ - \sigma_p^-) / (\sigma_p^+ + \sigma_p^-)$$

up to neutron energies of several hundred eV. The asymmetries are analyzed using a model of CN state mixing and a simple expression of two-level mixing obtained from R-matrix theory.

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$$p = \frac{2M}{(E_p - E_s)} \left(\frac{\Gamma_n^s}{\Gamma_n^p} \right)^{1/2}$$

Here $M = \langle s | V^{PV} | p \rangle$ is the matrix element of the weak interaction between s -wave and p -wave compound states, $\Gamma_n^{s(p)}$ is the neutron width of the $s(p)$ -wave resonance and $E_{s(p)}$ is the corresponding resonance energy

The approach used by our collaboration treats the CN system as chaotic and assumes that the PV matrix elements are random variables. A statistical analysis of our results to date yields root-mean-squared matrix elements with values $M=1$ meV. These agree well with the expected estimate $M_{\text{theor}}=M_{\text{sp}}/N^{1/2}$ where the single particle matrix element is taken as ≈ 0.5 eV and $N \approx 10^6$ is the number of quasiparticle components in the wave function of a typical CN state.

The first measurements studied transmission of longitudinally polarized neutrons through ^{238}U and ^{232}Th . The ^{238}U was the first experiment to study PV for more than one resonance in a single nucleus and the data were consistent with the stochastic hypothesis. But the ^{232}Th measurement, which showed that PV in CN resonance is a universal phenomenon, revealed an unexpected correction in the sign of the longitudinal asymmetries. Many attempts to explain the sign effect, which appears to be non-statistical in nature, have not been successful. Clearly, more experimental data are needed to resolve the issue of whether the small number of nuclear levels studied have a common sign by chance.

Much of the last two years has been devoted to developing new equipment. This includes a new large-area, high-polarization hydrogen target for polarizing the neutron beam, a new large-area spin filter able to flip spins for neutrons with energies up to 1 keV, a new ^{10}B -loaded liquid scintillator for high concentrate transmission experiments and a large solid angle pure CsI detector for capture experiments with isotropic samples.

The new high count-rate detector is a 43 cm diameter ^{10}B -loaded liquid scintillator. The scintillator housing is divided into 55 cells, each viewed by a photomultiplier with a high current base. Fast discriminators (55) are used to produce a fixed shape pulse for each neutron detected. These pulses are summed to produce a slowly varying voltage signal whose amplitude is proportional to the total count rate in the detector. This voltage is digitized for each beam burst by a transient digitizer and the results stored in a summation memory.

The neutron-capture detector is now fully funded and under construction. The detectors are pure CsI, 12" long and approximately 4"x4" in cross section. The cross section is actually a partial wedge, so that 12 detectors will form a cylinder around the beam pipe. Two such cylindrical arrays (24 detectors) will provide a solid angle of approximately 2.8π . The 4" beam pipe which will hold the target will be covered with ^6Li -loaded (96% enriched, 10% by weight) polyethylene in the form of a hollow cylinder. This shielding was tested during the 1992 run cycle and worked quite well. The 24-detector array will be surrounded with 4" of lead and 6" to 8" of boron-loaded

polyethylene. The capture detector will be located in the 56-meter house. The evacuated beam pipe through which the polarized beam is transported from the spin-flipper to the target is being wrapped with wire. This long solenoid will provide a guide field to maintain the spin orientation of the neutrons.

We continue to discuss and plan for neutron tests of time reversal invariance (TRI). These experiments are challenging, since they require both a polarized neutron beam and a polarized or aligned target. They have attracted our interest because of the large enhancements associated with CN resonances. We have developed a holmium single crystal target which when cooled below 200 mK has suitable alignment to be used in a TRI test which searches for the term $(\vec{\sigma} \cdot \vec{K})$, $(\vec{\sigma} \cdot (\vec{K} \cdot \vec{T}))$. Here $\vec{T}$ is the target alignment. However, it is possible that magnetic domains in the holmium target will depolarize the neutron spins at low neutron energy. We have investigated this effect at 0.73 eV using ^{139}La as a novel polarization analyzer (see section 1.2.4). Measurement at higher energies are needed and we have started a collaboration with the Joint Institute for Nuclear Research at Dubna to study depolarization up to 30 eV. In addition, we are negotiating with the National Laboratory for High Energy Physics/KEK at Tsukuba, Japan, where we could utilize the unique capabilities developed there for polarizing and analyzing neutron spins with laser-pumped ^3He cells, to measure up to 60 eV.

Three review papers with TUNL authors are being prepared for publication. G.E. Mitchell is a co-author of a "Recent advances in the Study of Parity Violation in the Compound Nucleus," which will be published in the Annual Review of Nuclear and Particle Physics. C.R. Gould and D.G. Haase are preparing a review of Time Reversal Invariance Tests for Physics Reports. N.R. Roberson is a co-author of "Recent Developments in the Study of Parity Violation in Neutron p-Resonances," which is scheduled for publication in the August 1993 issue of the Soviet Journal of Particles and Nuclei.

1.1.2 Neutron Resonance Spectroscopy of ^{113}In and ^{115}In

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As a prospective target for study of parity violation, indium has many appealing characteristics. There is intense interest in obtaining parity violation data in other mass regions to supplement the uranium and thorium data. Indium is near the maximum of the 3p neutron strength function, enhancing the p-wave resonances. The isotopic abundance is 95.72% ^{115}In and 4.28% ^{113}In , which makes the use of natural samples feasible.

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A transmission experiment on natural indium has been performed at LANSCE. The energy range studied was 25-500 eV. Earlier measurements by Rainwater's group at Columbia [Hac74] reported 44 s-wave resonances in ^{115}In , 27 p-wave resonances in ^{115}In and 22 s-wave resonances in ^{113}In . Simple statistical arguments suggest that the set of p-wave resonances in ^{115}In and the set of s-wave resonances in ^{113}In are incomplete, since there should be about the same number of s-wave resonances in the two isotopes (both have $l = 9/2$ and the neutron separation energies are similar) and there should be many more p-wave resonances than s-wave. Statistical analysis of the ^{115}In s-wave resonances suggest that this data set is complete. In our transmission measurement we observed all of the previously reported resonances, plus 43 new resonances. This measurement alone cannot distinguish between p-wave resonances in ^{115}In and s-wave resonances in ^{113}In .

In the summer 1992 run, a highly enriched (99.99%) sample of ^{115}In was brought by our Dubna collaborators. The amount of material available, about 9 gm, was not sufficient to perform a transmission experiment, but was enough for study via the capture reaction. The gamma rays were detected with CsI detectors. All of the resonances previously identified as belonging to ^{115}In were observed. Preliminary analysis of the data indicate that of the 43 new resonances in natural indium, 20 are observed with the highly enriched ^{115}In target. From this fact alone, there are two choices -- either the missing resonances are not in ^{115}In (and therefore presumably in ^{113}In), or the missing resonances have strengths which are below our threshold for observability, and therefore could be in either isotope. Two weak resonances were observed which Hacken *et al.* had assigned as ^{113}In resonances; they were reassigned to ^{115}In . In addition, four more new resonances were observed in the capture spectra. These resonances have energies near large ^{113}In resonances and were obscured in the measurement with natural indium. An R-matrix analysis was performed and the resonance parameters determined for all the observed resonances. The strengths of the 49 new resonances were then ordered by size. The resonances which we observed in the highly enriched ^{115}In sample were randomly distributed with respect to strength; in fact, the weakest of the 49 new resonances was observed. Therefore, the resonances observed with the natural indium target but not with the highly enriched target are definitely not in ^{115}In . We assign these resonances to ^{113}In and tentatively label them as s-wave resonances. The s-wave level density is now similar for ^{113}In and ^{115}In .

Statistical analyses were performed on the three data sets: ^{115}In s-wave, ^{115}In p-wave, ^{113}In (presumed s-wave). For the ^{115}In s-wave set the Dyson-Mehta Δ_3 statistic, the nearest neighbor spacing distribution, and the reduced width distribution all agree well with the predictions of random matrix theory. Since some of these tests are extremely sensitive to missing or misassigned levels, this agreement suggests that the set of s-wave resonances in ^{115}In is essentially pure and complete. The set of p-wave resonances in ^{115}In is still very incomplete, but probably is rather pure. The set of presumed s-wave resonances in ^{113}In apparently has a number of p-wave resonances admixed. The s- and p-wave strength functions are consistent with other results on these

nuclei and in this mass region. The additional p-wave resonances in ^{115}In , when combined with the previously known resonances, yield a total of 50 p-wave resonances which are suitable for study of parity violation.

[Hac74] G. Hacken *et al.*, Phys. Rev. C10, 1910 (1974).

1.1.3 Neutron Resonance Parameters for ^{165}Ho

P. R. Huffman, C. M. Frankle¹, C. R. Gould, D. G. Haase, J. A. Harvey², R. S. Hoffenberg, S. Mioduszewski, and N. R. Roberson

A high resolution neutron transmission study of ^{165}Ho was performed at the Oak Ridge Electron Linear Accelerator (ORELA) to locate new weak resonances suitable for deformation effect and time reversal studies. Precise evaluation of resonance energies and neutron widths is necessary for such experiments in order to locate d-wave admixtures in s-wave resonances, and to set stringent bounds on T-violating interactions.

Neutron transmission through a 3.14-cm thick ^{165}Ho sample was measured for neutron energies between 5 eV and 10 keV. Data were taken using a ^6Li scintillator located at the end of an 80-m flight path. The sample was positioned 20 m from the source and was rotated into and out of the beam every 10 minutes. Spectra were taken with the ^{165}Ho sample in the beam, out of the beam, and with a 5-cm thick polyethylene filter used for background subtraction.

The data are presently being fitted with the multilevel, multichannel, R-matrix neutron resonance code SAMMY [Lar89]. Extraction of resonance energies and neutron widths is possible for all resonances within this energy region. These values will be a considerable improvement over those previously given by Mughabghab [Mug84]. Also, many new weak resonances have been located. A Bayesian analysis of these resonances indicated that in all likelihood they are weak s-wave resonances, but in principle could be strong p-wave resonances. Of particular interest for time-reversal experiments are the newly located 24.8-eV and 75.1-eV resonances. Future experiments using these resonances are under consideration.

A full analysis of the ^{165}Ho neutron resonance energies and neutron widths is currently in progress. These parameters will not only supercede previous values, but will provide information needed for future deformation-effect and time-reversal experiments involving ^{165}Ho .

[Lar89] N.M. Larson, ORNL/TN-9179/R2, 1989.

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² Oak Ridge National Laboratory

[Mug84] S.F. Mughabghab, "Neutron Cross Sections," (Academic Press, NY, 1984)
Volume 1, part B.

1.1.4 Parity Violation in Non-Resonant Neutron-Nucleus Scattering

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An unexpected experimental observation is that all seven asymmetries measured for p-wave resonances in ^{232}Th had the same sign, with statistical significance $> 2.4 \sigma$ had the same sign. This sign correlation is inconsistent with a purely statistical description. The data were then fit with two terms: a constant term and a fluctuating term. A number of authors have proposed explanations of this experimental observation. Some of these theoretical papers suggest that there might be a non-zero asymmetry for the non-resonant scattering. We therefore determined the experimental upper limit for the PNC longitudinal asymmetry measured for energies between resonances in the best available data, those for ^{232}Th .

The off-resonance data in ^{232}Th were analyzed following closely the spirit of the analysis of the resonance data. Since the time-of-flight is proportional to $E_n^{-1/2}$, the number of channels included in the analysis of on-resonance parity violation varied for each resonance. As natural units we chose channel-bin sizes determined from the widths of the resonances in a local region. We took the full width at 0.1 maximum as the local channel-bin size. A region of five natural channel-bin units was excluded above and below each resonance.

The transmission spectrum for ^{232}Th is shown in Figure 1.1-1, with the regions included in the analysis indicated. The prescription described above yielded 61 subregions suitable for analysis. Although the energy range for these intervals changes by a factor of seven, the statistical uncertainties in each region are comparable. For each of the 61 subregions i , and for each of the 355 data runs j , the transmission asymmetry $\epsilon_{ij} = (N^+ - N^-) / (N^+ + N^-)$ was determined. For each interval i an average value for ϵ_i was determined and the statistical error was obtained from the distribution of the 355 ϵ_{ij} values. The transmission asymmetry $\epsilon = -\tanh(n\sigma t f_n P)$, where n is the number density of the target, t the thickness of the target, σ the cross section, f_n the neutron polarization, and P the PNC longitudinal asymmetry. If the argument of the $\tanh$ is small, then $\epsilon \sim -n\sigma t f_n P$. This simple expression is adequate for the present purposes. The quantities n , t ,

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and σ are known, and the relative neutron polarization f_n was measured for each run. Therefore P can be obtained from the measured value of ϵ .

The weighted average value $\langle P_{\text{nonres}} \rangle = (9.8 \pm 21.7) \times 10^{-6}$. The ^{232}Th data are consistent with very small systematic errors; this conclusion agrees with all other previous evidence for these experiments. Possible energy dependence was examined by fitting the 61 values for the longitudinal asymmetry to the form $P = mE + b$. The best fit values for the constants m and b are consistent with zero. Of course, previously unobserved p-wave resonances could lead to local parity violation in presumably resonance-free regions. There is no strong evidence for a new $p_{1/2}$ resonance in the regions which we have studied.

The contributions to off-resonance parity violation due to neighboring s- and p-wave states should be very small, as should the potential-scattering contribution. The only remaining contributions are from distant states. These should be extremely small unless there is a sign correlation, with many distant states contributing coherently.

^{232}Th Transmission Spectrum

Figure 1.1-1 ^{232}Th transmission spectrum. The PNC longitudinal asymmetry was studied for non-resonant scattering in the regions indicated. The criteria for selecting these regions are described in the text.

Within the framework of the statistical approach, one expects an extremely small off-resonance PNC longitudinal asymmetry. Our data are consistent with this prediction, but are not sufficiently precise to provide a sensitive test. With improved experimental conditions we hope to reduce the present upper limit (2×10^{-5}) by an order of magnitude. At present the empirical upper limit for the off-resonance PNC longitudinal asymmetry of $\sim 2 \times 10^{-5}$ does not appear to distinguish between the various models of parity violation.

1.1.5 Possible Parity-Violation Tests with Charged Particles

J.F. Shriner, Jr.¹, E.G. Bilpuch, and G.E. Mitchell

We are examining the possibility of parity-violation tests with charged particles. Such tests would be in light- to medium-mass nuclei ($A \leq 60$) and complement the measurements with neutron resonances in heavy nuclei made by the TRIPLE collaboration. In principle, several measurements could be performed: either elastic scattering or a reaction could be studied. If a reaction were studied, either the differential or angle-integrated cross section could be measured. If the differential cross section is measured, either of the analyzing power components A_z or A_x reflects parity violation, but only A_z is non-zero for angle-integrated cross sections.

While each of these possibilities offers potential advantages, here we focus on A_z for the (p, α) reaction, primarily because this measurement seems overall to offer the most advantages. High-resolution (p, α) resonance data from TUNL exist for 5 targets: ^{23}Na , ^{27}Al , ^{31}P , ^{35}Cl , and ^{39}K . We have searched these data for adjacent resonances which have the same spin but opposite parity, and which have a measured alpha width for the natural-parity resonance. Sixty-two pairs of resonances were identified which met these criteria. A_z was calculated for each of these pairs of resonances.

The calculations were performed by considering a Hamiltonian $H = H_0 + H_{PV}$, where H_0 is parity-conserving and H_{PV} is parity-violating. Perturbed reduced-width amplitudes were obtained using experimentally determined resonance parameters and first-order perturbation theory; we assumed only two states and only internal mixing. Differential cross sections were then calculated for a longitudinally polarized proton beam and convoluted with a 500-eV FWHM Gaussian to simulate finite-beam-energy resolution. Finally the calculated longitudinal analyzing power A_z was determined by

$$A_z = \frac{\frac{d\sigma}{d\Omega}(\rightarrow) - \frac{d\sigma}{d\Omega}(\leftarrow)}{\frac{d\sigma}{d\Omega}(\rightarrow) + \frac{d\sigma}{d\Omega}(\leftarrow)}$$

where $\rightarrow$ ($\leftarrow$) denotes polarization in the direction of (opposite the direction of) the beam. Since, to first order, A_z is proportional to V , the matrix element of H_{PV} , the ratio A_z/V is a suitable measure of the relative enhancements due to the resonances.

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The results depend dramatically on energy, angle, and the specific resonance parameters; results for four pairs of resonances are shown in Figure 1.1-2. The maximum magnitudes of A_z/V for each resonance pair range from 5×10^{-4} to 9×10^{-2} . However, a more meaningful quantity is $(A_z/V)^2(d\sigma/d\Omega)$, since maximizing this figure-of-merit minimizes the time to reach a given sensitivity in V , assuming all other experimental factors remain the same. This figure-of-merit is maximized for a pair of $J = 3$ resonances at $E_{cm} = 2.9399$ MeV and 2.9385 MeV in $p + {}^{31}\text{P}$, but other factors such as the level density and corresponding complexity of a given energy region must still be considered.

Figure 1.1-2 Values of A_z/V as a function of center-of-mass energy and angle for four pairs of compound nuclear resonances.

1.2 Time-Reversal-Invariance Measurements

1.2.1 Deformation Effect and Five-Fold Correlation Time-Reversal Test in Neutron Resonances Using Aligned ^{165}Ho

P. R. Huffman, C. M. Frankle¹, C. R. Gould, D. G. Haase, and N. R. Roberson

Neutron transmission tests of time-reversal invariance have attracted considerable attention because of the large enhancements in sensitivity associated with compound-nucleus resonances. A parity- (P -) even time reversal- (T -) violating neutron transmission test in the neighborhood of a d -wave resonance with interference from a nearby s -wave resonance would exhibit such an enhancement [Gou90]. We discuss how to use the deformation effect to identify ^{165}Ho resonances suitable for testing time reversal violation in the five-fold correlation (FC).

The FC test involves searching for a P -even, T -odd term in the neutron-nucleus forward scattering amplitude of the form $f_T \vec{s} \cdot (\vec{I} \times \vec{k}) (\vec{I} \cdot \vec{k})$. Here $\vec{s}$ is the neutron spin, $\vec{k}$ is the neutron momentum, and $\vec{I}$ is the nuclear spin. The FC term arises only if the beam is polarized and the target is aligned. An aligned target will also have a P -even, T -even term in the forward scattering amplitude of the form $f_D (\vec{I} \cdot \vec{k})^2$, known as the deformation effect (DE). The FC and DE have characteristic angular signatures, $\sin 2\theta$ and $P_2(\cos \theta)$ respectively, where θ is the angle between the beam direction and the alignment axis. Searching for these angular signatures was the basis of the time reversal test of Koster *et al.* [Kos91], carried out with a cryogenically aligned, rotating ^{165}Ho single-crystal target.

The FC and DE involve coupling the angular momentum of the neutron beam to the $K = 2$ rank of the oriented target. Neither effect will be observable on a pure s -wave resonance. But, if there is some d -wave admixture in an s -wave resonance, a deformation effect can be seen. In addition, if this d -wave admixture can interfere with a second nearby s -wave resonance, there will be enhanced sensitivity to time-reversal violation. Spin assignments are known for a number of s -wave resonances in ^{165}Ho . Locating a d -wave admixture in any s -wave resonance therefore immediately opens up the possibility of a sensitive time-reversal test. In principle, p -wave resonances can also exhibit a deformation effect and be suitable for a time-reversal-invariance test, but no p -wave resonances have been seen in ^{165}Ho .

The deformation effect cross section for an isolated resonance is [Huf93]

$$\sigma_{02}(J^\pi) = \pi \lambda^2 \hat{I} t_{20}(I) \frac{g_I \Gamma_I}{(E - E_I)^2 + \Gamma_I^2/4} C(J^\pi),$$

where the coefficient $C(J^\pi)$ is given by

$$C(J^\pi) = 4W(J \frac{1}{2} I 2; I \frac{3}{2}) g_h^I(0 \frac{1}{2}) g_h^I(2 \frac{3}{2}) - 2\sqrt{6} W(J \frac{1}{2} I 2; I \frac{5}{2}) g_h^I(0 \frac{1}{2}) g_h^I(2 \frac{5}{2}),$$

with W being the Racah coefficient and g_I the spin factor. The unpolarized resonance cross section is given by

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$$\sigma_{00} = \pi \lambda^2 \frac{g_J \Gamma_J}{(E - E_J)^2 + \Gamma_J^2/4} \sum_j [g_h^J(l, j)]^2.$$

To estimate the unknown neutron amplitudes $g_h^J(l, j)$, where $\Gamma_h^J(l, j) = [g_h^J(l, j)]^2$, we assume their widths depend only on l , and estimate them from the strength functions S_l and level spacings D_l . From the definition $\langle g_J \Gamma_h^J \rangle = (2l+1)D_l S_l$ [Mug84], and taking $D_l \sim D_0/(l+1)$, $\Gamma_n = \Gamma_h^J V_l E(\text{eV})^{1/2}$, $V_l \sim (kR)^{2l}$ (the penetrability), and $g_J \sim \frac{1}{2}$, we find for ^{165}Ho , $\Gamma_n(l=0) = 1.7 \times 10^{-3} E(\text{eV})^{1/2}$ and $\Gamma_n(l=2) = 2.2 \times 10^{-15} E(\text{eV})^{5/2}$. The deformation effect cross section also depends on the ratio of the $j = l \pm 1/2$ neutron amplitudes. We parametrize this unknown ratio via the j -spin mixing ratio

$$x_j = g_h^J(l, j = l - 1/2) / [\Gamma_h^J(l, j)]^{1/2} \text{ where } -1 \leq x_j \leq 1.$$

Two suitable weak s -wave resonances are located at energies of 24.8 and 75.1 eV [Huf93]. They may be candidates for a time reversal violation study if they exhibit a deformation effect. Figure 1.2-1 shows σ_{02} for the 24.8 eV resonance under the assumption that it is an s -wave with the admixture of d -wave given above. We take $t_{20} = \sqrt{\frac{7}{3}}$, corresponding to 100% alignment along the beam direction ($\theta = 0^\circ$). Two J values are possible (3 and 4) and the ratio $|\sigma_{02}/\sigma_{00}| \sim 10^{-3}$ for both possibilities. The small deformation effect can be detected with a rotating aligned target and an unpolarized neutron beam. From the $P_2(\cos\theta)$ dependence, the effect changes sign as θ goes from 0° to 90° , leading to a $0^\circ - 90^\circ$ transmission asymmetry $\varepsilon \sim 1 \times 10^{-3}$ for the 24.8 eV resonance. On-resonance asymmetries of order $\sim 10^{-4}$ have been measured at LANSCE [Fra92].

Figure 1.2-1 σ_{02} for the 24.8 eV resonance in ^{165}Ho .

If a ^{165}Ho resonance shows a small but non-zero deformation effect, then it is in all probability an s -wave with d -wave admixture, and, as such, is immediately suitable for a time-reversal-violation test with a polarized neutron beam.

In summary, we have estimated deformation effect cross sections for neutron resonances in an aligned ^{165}Ho target. For s -wave resonances with d -wave admixtures, the effects are small, but are still accessible to measurement. Locating a deformation effect opens up the possibility of a new test of time-reversal violation.

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- [Gou90] C.R. Gould, D.G. Haase, N.R. Roberson, H. Postma, and J.D. Bowman, *Int. J. Mod. Phys. A* **5**, 2181 (1990).
 [Kos91] J.E. Koster *et al.*, *Phys. Lett. B* **267**, 23 (1991).
 [Mug84] S.F. Mughabghab, "Neutron Cross Sections," (Academic Press, NY, 1984) Volume 1, part B.
 [Huf93] P.R. Huffman *et al.*, "Proceedings of the International Workshop on Time Reversal Invariance," (World Scientific Pub. 1993).
 [Fra92] C.M. Frankle *et al.*, *Phys. Rev. C* **46**, 778 (1992).

1.2.2 An Improved Direct-Reaction Test of Time Reversal Invariance

P. R. Huffman, C. R. Gould, D. G. Haase, C. D. Keith, N. R. Roberson, and W. S. Wilburn

An improved version of a previous TUNL test of time-reversal invariance is underway to search for the Parity- (P -) even, time reversal (T) odd, five-fold correlation (FC) term in the neutron-nucleus forward scattering amplitude. The FC has a vector dependence given by $\vec{s} \cdot (\vec{l} \times \vec{k}) (\vec{l} \cdot \vec{k})$, where $\vec{s}$ and $\vec{k}$ are the spin and momentum of the incident particle and $\vec{l}$ is the spin of the target. Polarized neutrons incident upon a cryogenically aligned, rotating ^{165}Ho target are used to search for the $\sin 2\theta$ angular dependence of the neutron total cross section that arises from the FC.

An asymmetry, ϵ , is formed by measuring the difference in transmission at $\theta = \pm 45^\circ$ over the total transmission. This asymmetry is directly proportional to the FC analyzing power, A_{FC} , where

$$\frac{\sigma_{\text{FC}}}{\sigma_0} = \sqrt{\frac{15}{2}} \sin \theta \cos \theta \hat{t}_{10} \hat{t}_{20} A_{\text{FC}}.$$

A_{FC} is independent of both the beam and target polarizations ($\hat{t}_{10}$ and $\hat{t}_{20}$) and the target angle. Previous measurements by Koster [Kos91] quote a limit $A_{\text{FC}} \leq 1.0 \times 10^{-4}$. A bound on $A_{\text{FC}} \sim 10^{-5}$ is expected from the present test.

Improvements in target polarization, beam polarization, and beam intensity account for the factor of 10 improvement. A new design for the thermal link between the ^{165}Ho cylinder and the mixing chamber of the dilution refrigerator will increase target alignment by a factor of 2. Improvements in the TUNL polarized ion source over the past

two years account for increased beam polarization. And, switching to the $D(\vec{d}, \vec{n})^3\text{He}$ polarization transfer reaction from the $T(\vec{p}, \vec{n})^3\text{He}$ reaction used by Koster, will increase the neutron flux by more than a factor of 10. These improvements, along with increased running time will account for the lower bound on A_{FC} .

Measurement of $A_{FC} \sim 10^{-5}$ will set an upper bound on $\alpha_T \sim 10^{-4}$, where α_T is defined as the ratio of the T-violating spreading, Γ_T , width divided by the T-invariant spreading width, Γ_{TRI} . A 10^{-4} bound on α_T is comparable to those set in P-even time-reversal tests using other systems. Results from this experiment are expected within the next year.

[Kos91] J.E. Koster *et al.*, Phys. Lett. **B267**, 23 (1991).

1.2.3 Time-Reversal Asymmetries from a Five-Fold Interaction in the Nucleon-Nucleus Optical Potential

V. Hnizdo¹, C.R. Gould

The total cross section for neutrons (spin $s = 1/2$) incident on a target nucleus of spin I , when the projectile and target are in polarization states described by statistical tensors that are diagonal in suitably chosen coordinate frames, $\tilde{t}_{kq}(s) = \tilde{t}_{k0}(s)\delta_{q0}$ and $\tilde{t}_{KQ}(I) = \tilde{t}_{K0}(I)\delta_{Q0}$, respectively, can be written as $\sigma_t = \sum_{kK} \sigma_{kK}$, where

$$\sigma_{kK} = 4\pi\lambda^2 \tilde{t}_{k0}(s) \tilde{t}_{K0}(I) \frac{\hat{k}\hat{K}}{\hat{s}\hat{I}} \text{Im} \sum_{\lambda} \hat{\lambda} C_{kK\lambda}(\hat{s}\hat{I}\hat{p})$$

$$\times \sum_{J|j|j'} (2J+1) \tilde{t}_{jj'}^{J'} \langle 1\lambda 00 | 1' 0 \rangle W(JjIK; Ij') \begin{Bmatrix} 1 & s & j \\ \lambda & k & K \\ 1' & s & j' \end{Bmatrix} T_{1'j',1j}^J,$$

with $C_{kK\lambda}(\hat{s}\hat{I}\hat{p}) = \frac{(4\pi)^{3/2}}{\hat{k}\hat{K}} \left[[Y_k(\hat{s}), Y_K(\hat{I})]_{\lambda}, Y_{\lambda}(\hat{p}) \right]_0$.

Here $T_{1'j',1j}^J = (1/2i)(S_{1'j',1j}^J - \delta_{1'j',1j})$ are elements of the elastic scattering T-matrix in the spin-orbit coupling representation, and the scalar quantities $C_{kK\lambda}(\hat{s}\hat{I}\hat{p})$ are the so-called correlation terms in the forward elastic-scattering amplitude, with $\hat{s}, \hat{I}$ and $\hat{p}$ being unit vectors along the z-axes of the frames in which the projectile and target statistical tensors are diagonal, and along the projectile beam direction, respectively. The correlation terms are real for $k + K + \lambda$ even and pure imaginary otherwise.

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The correlation terms are indicative of the presence of terms with the same spherical-tensor structure in the projectile-target interaction. For example, when both the projectile and target are vector polarized, the $k = K = 1$ cross section σ_{11} has spin-spin correlation terms $C_{11\lambda}(\hat{s}\hat{I}\hat{p}) = -\sqrt{1/3}\hat{s}\cdot\hat{I}$ and $\sqrt{3/2}[(\hat{s}\cdot\hat{p})(\hat{I}\cdot\hat{p}) - \frac{1}{3}\hat{s}\cdot\hat{I}]$ for the orbital angular momentum transfers $\lambda = 0$ and 2 , respectively. These reflect the presence of spherical and tensor spin-spin terms, $\mathbf{s}\cdot\mathbf{I}$ and $(\mathbf{s}\hat{\mathbf{r}})(\mathbf{I}\cdot\hat{\mathbf{r}}) - \mathbf{s}\cdot\mathbf{I}/3$ in the projectile-target interaction (here $\hat{\mathbf{r}}$ is a unit vector along the direction from the target to the projectile; an operator quadratic in $\hat{\mathbf{r}}$ transfers two units of orbital angular momentum, $\lambda = 2$). Another example is the case of $k = 0$ and $K = 2$, the deformation cross section σ_{02} for an unpolarized projectile incident on an aligned target. The deformation cross section σ_{02} has a correlation term with $\lambda = 2$: $C_{022}(\hat{s}\hat{I}\hat{p}) = (3/2)[(\hat{I}\cdot\hat{p})^2 - 1/3] = P_2(\hat{I}\cdot\hat{p})$ which corresponds to the tensor interaction $(\hat{\mathbf{I}}\cdot\hat{\mathbf{r}})^2 - I(I+1)/3$ of a nucleus with spin $I \geq 1/2$, or the quadrupole reorientation interaction of a rotational, statically deformed nucleus, which has the same tensor form.

The $k = 1$, $K = 2$ cross section σ_{12} is of interest in tests of time reversal invariance. The cross section σ_{12} has a parity-even, time-reversal-odd correlation term with $\lambda = 2$, which can be shown to have a "five-fold" form in terms of the Cartesian vectors $\hat{s}$, $\hat{I}$ and $\hat{p}$:

$$C_{122}(\hat{s}\hat{I}\hat{p}) = i\sqrt{3/2}\hat{s}\cdot(\hat{I}\times\hat{p})(\hat{I}\cdot\hat{p}).$$

Note that this correlation term is imaginary as here $k + K + \lambda$ is odd. A projectile-target interaction that has the same spherical-tensor structure is

$$T_5 = \frac{1}{2}[\mathbf{s}\cdot(\mathbf{I}\times\hat{\mathbf{r}})(\mathbf{I}\cdot\hat{\mathbf{r}}) + (\mathbf{I}\cdot\hat{\mathbf{r}})(\mathbf{I}\times\hat{\mathbf{r}})\cdot\mathbf{s}].$$

As $\mathbf{I}\times\hat{\mathbf{r}}$ and $\mathbf{I}\cdot\hat{\mathbf{r}}$ do not commute ($\hat{s}$, $\hat{I}$ and $\hat{p}$ are operators, unlike the "c-numbers" $\hat{s}$, $\hat{I}$ and $\hat{p}$ in the correlation terms), the five-fold operator T_5 is symmetrized as above. It conserves parity, but it anticommutes with the operator of time reversal. Its presence in the projectile-target interaction leads to a nonzero cross section σ_{12} , or a time-reversal asymmetry $\varepsilon = \sigma_{12}/\sigma_{00}$, which is measured as a ratio $(\sigma_{\uparrow} - \sigma_{\downarrow})/(\sigma_{\uparrow} + \sigma_{\downarrow})$, $\sigma_{\uparrow}$ ($\sigma_{\downarrow}$) being the total cross section for neutrons incident on an aligned target and polarized up (down) with respect to a direction normal to the alignment axis of the target spin $I > 1/2$ [Kos91].

Using the techniques of spherical tensor algebra [Bri68], the five-fold operator T_5 can be expressed as a scalar product of rank-2 spherical tensors

$$T_5 = -i\sqrt{4\pi}[[Y_2(\hat{\mathbf{r}}), \mathbf{s}]_2, [\mathbf{I}, \mathbf{I}]_2]_0,$$

and thus it is seen to be responsible for transfers $\lambda = 2$, $j_s = 1$ and $j_I = 2$ of the orbital, projectile-spin and target-spin angular momenta, respectively, in the spin-orbit coupling representation $\lambda + j_s = j_I$. The reduced matrix element of T_5 is then proportional to

$$-i\sqrt{4\pi}\langle s||s||s\rangle\langle I||I,1\rangle_2||I\rangle = -i\sqrt{\frac{2\pi}{3}}\hat{s}\hat{I}\sqrt{s(s+1)I(I+1)(2I+3)(2I-1)},$$

and a calculation of elastic-scattering S-matrix elements with the interaction T_5 included in the optical potential can be performed using a standard coupled-channels code. It should be noted that the reduced matrix element of T_5 is imaginary, in accordance with the operator being odd on time reversal and Hermitian.

Using the coupled-channels code CHUCK [Kun], calculations of the time-reversal asymmetry ϵ were performed for the system $n + {}^{165}\text{Ho}$ (spin $I = 7/2$) for neutron incident energies in the range 1-20 MeV. An energy-dependent spherical optical potential of the standard Woods-Saxon parametrization [Var87] was used, to which a five-fold interaction term $[V_0 f_V(r) + iW_0 f_W(r)]T_5$ with volume Woods-Saxon form factors $f_V(r)$ and $f_W(r)$ of the same geometries as the corresponding terms in the central potential was added. Figure 1.2-2 shows the time-reversal asymmetry as a function of energy, separately for a pure real five-fold term of strength $V_0 = +0.1$ MeV and a pure imaginary five-fold term of strength $W_0 = +0.1$ MeV. The calculations are for the alignment axis of the target spin set at an angle of 45° with respect to the beam direction, and the results are normalized to nominal $\bar{t}_{10}(s) = \bar{t}_{20}(I) = 1$. The asymmetries are seen to oscillate in a typical Ramsauer fashion.

Figure 1.2-2 Time-reversal asymmetry ϵ as a function of neutron incident energy E_n for $n + {}^{165}\text{Ho}$. The solid and dashed lines are for a real strength $V_0 = +0.1$ MeV and an imaginary strength $W_0 = +0.1$ MeV, respectively, of the five-fold interaction.

Performing calculations along the above lines, limits can now be placed on the strength of a time-reversal-violating five-fold term in the optical potential, using results of measurements of the time-reversal asymmetries in the MeV range. A remaining task would be to deduce quantitatively a five-fold term in the optical potential from a postulated time-reversal-noninvariant part in an effective nucleon-nucleon interaction, or to find a mechanism that would generate an effective five-fold interaction in the scattering process dynamically.

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1.2.4 Neutron Depolarization in Aligned Targets

C. R. Gould, D. G. Haase, N. R. Roberson, L. Pikel'ner, E. Sharapov, V. Skoy(JINR), A. Masaike(Tokyo), H. M. Shimizu (KEK)

The five-fold correlation test of time reversal violation (TRV) in neutron transmission involves the transmission of polarized neutrons through an aligned nuclear target. This experiment has been carried out at TUNL [Kos 91] with 2-MeV neutrons transmitted through a cryogenically aligned holmium target. There are plans for similar experiments at lower neutron energies where the dynamics of compound nuclear resonances may enhance any TRV effects.

Precession of the neutron polarization in the aligned target reduces TRV observables. An ideal aligned target should not cause neutron precession or depolarization, but the internal magnetizations of domains in the holmium crystal can significantly depolarize the neutron beam. This effect was investigated with 0.73 eV polarized neutrons in experiments at LANSCE [Haa92]. It was found that the depolarization was strongly dependent on the relative orientation of the neutron polarization and the holmium crystalline axes, and also on the average size of the holmium domains. Unfortunately in the five-fold geometry the 0.73-eV neutrons were completely depolarized, within the resolution of the LANSCE experiment.

The model used to describe the data shows that the depolarization in the crystal is proportional to a factor $\exp(-2D't)$. The depolarization parameter D' is in turn proportional to δ^2/E_n where δ is the average size of the magnetic domains and E_n is the neutron energy. The LANSCE measurements set a lower limit of $\delta = 11 \mu\text{m}$. Due to the $1/E_n$ dependence it may be possible to perform the five-fold measurement using 10 - 100 eV polarized neutrons and the same target.

We are collaborating with a group at the Frank Neutron Laboratory at the Joint Institute for Nuclear Research, Dubna, Russia, to determine the depolarization of neutrons in a holmium crystal for neutron energies to 30 eV. The purpose of this

measurement is to demonstrate the $1/E_n$ depolarization dependence. A diagram of the experiment is shown below. Neutrons from the IBR-30 pulsed reactor are polarized by transmission through a dynamically-polarized proton target. The neutrons then pass through a section of guide field to the holmium crystal which is cooled to 4.2 K. The crystal was grown at the Materials Preparation Center at the Ames Laboratory in Iowa using the same techniques that were used in producing the crystal used at TUNL and LANSCE. Therefore we expect the average domain size δ to be similar for both crystals. The neutrons transmitted through the holmium continue through the guide field through a 0.7-mm thick foil of erbium which is polarized in a magnetic field at 50 - 100 milliK. The neutron transmission through the foil at energies corresponding to nuclear resonances is highly spin dependent, so the foil acts as a spin analyzer at the erbium resonance energies 0.5, 6.0, 9.4, 20.3, 26.3 and 33.2 eV. The transmitted neutrons are finally detected in a ^3He gas ionization detector located at 0° . Energy analysis of the neutrons is made by time of flight technique.

Figure 1.2-3 Arrangement for neutron depolarization measurements at JINR, Dubna, showing relative orientations of neutron and target polarization axes.

Figure 1.2-4 Arrangement for neutron depolarization measurements at KEK, Tsukuba, showing relative orientations of neutron and target polarization axes.

We have been invited to participate in similar measurements at the neutron spallation facility at KEK, Tsukuba, Japan, in collaboration with researchers from KEK and the University of Tokyo. Using the same crystal measured in Dubna we will measure the depolarization up to 30 eV, using a ^3He gas target as the neutron spin filter. A diagram of the KEK experimental facility is shown below. The holmium target will be mounted with its cylindrical axis parallel to the neutron beam momentum. Instead of rotating the target, the polarization axis of the transversely polarized neutrons will be rotated. The KEK measurements will produce a higher resolution (1%) determination of the neutron depolarization, which will allow us to distinguish between various crystalline effects that were proposed in the original LANSCE analysis.

- [Kos 91] J. E. Koster, E. D. Davis, C. R. Gould, D. G. Haase, N. R. Roberson, L. W. Seagondollar, S. Wilburn, and X. Zhu, *Physics Letters B* **267**, 23 (1991).
 [Haa 92] D. G. Haase, *et al.*, *Phys. Rev. B* **46**, 11290 (1992).

1.2.5 Detailed-Balance Time-Reversal-Invariance Tests

J.M. Drake, E.G. Bilpuch, C.R. Bybee, G.E. Mitchell, and J.F. Shriner, Jr.¹

The results on parity violation in compound nuclear resonances have triggered much interest in whether time-reversal-invariance (TRI) violation also might be enhanced in the compound nuclear regime. A variety of experiments have been proposed. Bunakov and Weidenmüller [Bun89] suggested that large enhancements might be observed in tests of detailed balance near two interfering resonances. The expected degree of enhancement depends on the detailed spectroscopic properties of the resonances involved. We have utilized our large collection of (p,α) resonance data to consider the TRI violation enhancement in realistic circumstances. We identified 33 pairs of adjacent resonances which have the same (or probably the same) J^π for the targets ^{23}Na , ^{27}Al , ^{31}P , ^{35}Cl , and ^{39}K .

Although Bunakov and Weidenmüller considered the angle-integrated reaction cross section, the differential cross section seems more appropriate for (p,α) measurements. We define a quantity

$$\Delta(E, \theta) = 2 \frac{\frac{k_p^2}{g(p, \alpha)} \frac{d\sigma}{d\Omega_{(p, \alpha)}}(E, \theta) - \frac{k_\alpha^2}{g(\alpha, p)} \frac{d\sigma}{d\Omega_{(\alpha, p)}}(E, \theta)}{\frac{k_p^2}{g(p, \alpha)} \frac{d\sigma}{d\Omega_{(p, \alpha)}}(E, \theta) + \frac{k_\alpha^2}{g(\alpha, p)} \frac{d\sigma}{d\Omega_{(\alpha, p)}}(E, \theta)},$$

where $k = 2\pi/\lambda$ and g is the usual statistical factor. The collision matrix elements were evaluated by assuming a Hamiltonian $H = H_0 + iH'$ and – following the approach used by Moldauer [Mol68] – assuming only internal mixing and only two interfering states. Experimentally determined laboratory widths were then input to obtain the differential cross sections. To first order, Δ is proportional to the matrix element W of the time-reversal-violating part of the Hamiltonian (H').

The results are strongly energy- and angle-dependent, as illustrated for four pairs of compound states in Figure 1.2-5. The maximum values of Δ/W for a pair of resonances typically range from $\sim 10^{-4}$ to 10^{-1} eV^{-1} . Since the relative enhancement varies so strongly with energy, angle and resonance pair, in order to evaluate the merits of a detailed balance test of time reversal invariance, one must consider a specific pair of resonances and specific experimental conditions. Of course, a large value of Δ is not the only factor to be considered in evaluating the merits of a particular experiment, since

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(among other considerations) resonances with larger values of Δ have smaller cross sections, which are more difficult to measure accurately.

For a specific pair of 2^+ resonances in ^{32}S at $E_{\text{cm}} = 3.1356$ and 3.1490 MeV, the value of Δ/W is about 6×10^{-3} for back angles. If one assumes that a null value for Δ can be measured at the level of 10^{-2} (this is the limit obtained by Driller *et al.* [Dri79] in their

Fig. 1.2-5 Values of Δ/W as a function of center-of-mass energy and angle for four pairs of compound nuclear resonances.

classic detailed balance experiment), this implies an upper limit for W of the order of 2 eV. The strong interaction matrix element is of order MeV. The simplest estimate for the upper limit on α_T (the ratio of the strength of the T-violating interaction to the T-conserving interaction) is just the ratio of the two matrix elements, $\sim 10^{-6}$. It is conventional to express symmetry-breaking effects in terms of spreading widths. For time reversal invariance $\Gamma^{\text{TRIV}} = 2\pi \langle W^2 \rangle / D$. For this excitation energy in ^{32}S the average level spacing for 2^+ states is about 50 keV. This yields an estimate of an upper limit on Γ^{TRIV} of 5×10^{-4} eV. This is much smaller than obtained from previous measurements.

Although these considerations are preliminary, the results suggest the possible advantages of such experiments. It appears that the limits on time-reversal-invariance violation obtained from detailed balance tests can be significantly reduced.

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1.2.6 International Workshop on Time Reversal Invariance and Parity Violation in Neutron Reactions

C.R. Gould, D.G. Haase, G.E. Mitchell, N.R. Roberson

In collaboration with Los Alamos National Laboratory, and the Joint Institute for Nuclear Research (Dubna), TUNL recently helped organize the second international workshop on time reversal invariance and parity violation in neutron reactions. The workshop was held May 4-7, 1993 at the Neutron Physics Laboratory of the Joint Institute for Nuclear Research (JINR), Dubna, Russia. This was a successor to the highly successful TUNL-LANL workshop held in Chapel Hill in 1987, widely credited with stimulating much of the current work in symmetry tests with polarized neutron beams.

The workshop focused on the study of parity violation and time-reversal invariance in neutron physics. Emphasis was placed on measurements with polarized neutron beams and polarized targets, and on implication of recent theoretical developments for future progress in this constantly growing field of research. The workshop chairman was Yu.B. Popov (JINR, Dubna) and the organizing committee was J.D. Bowman (Los Alamos National Laboratory), C.R. Gould (North Carolina State University), A. Masaike (Kyoto University), Yu.B. Popov (JINR, Dubna), N.R. Roberson (Duke University), E. Sharapov (JINR, Dubna), S.J. Seestrom (Los Alamos National Laboratory)

The proceedings of the workshop are to be published by World Scientific, Singapore (C.R. Gould, editor). Travel support for faculty, scientists, post docs and graduate students from TUNL, LANL, and the University of Washington, was obtained

from the international programs division of the National Science Foundation. NSF is also supporting the cost of publication of the proceedings.

The attendance was excellent. Close to a hundred people were registered, including fourteen from the US and Canada, fifteen from Europe and Japan, thirty from Russia, and thirty six from JINR itself. The program of invited talks follows:

Opening of the Workshop

Chairman: V.L. Aksenov

V.E. Bunakov (Russia) Introductory overview

J.D. Bowman (Los Alamos) Data on PV in the compound nucleus and its interpretation

Session 2 : Invited papers

Chairman: P.D. Barnes

M.B. Johnson (Los Alamos) Sign correlation in PV effects

D.F. Zaretsky (Moscow) Valence and statistical mechanisms for parity violation

V.V. Flambaum (Kensington, Australia) Calculation of the weak matrix elements between compound states

Session 3: Invited papers

Chairman: P.A. Krupchitsky

G.A. Lobov (Moscow) PV potentials in N-N interactions

E.B. Davis (Stellenbosch, South Africa) Reactions test of TRI

S. Tomsovic (Seattle, USA) Strength and level densities: from compound nuclear spectroscopy to symmetries violations

G. Mitchell (Raleigh, USA) Charged particle tests of P and T violation with interfering resonances

Session 4: Invited papers

Chairman: J.D. Bowman

N. Auerbach (Tel Aviv) Doorway state approach to PV

A. Hayes (Chalk River) Mass dependence of the effective weak couplings

C.R. Gould (Raleigh, USA) Five-fold correlation and s-d mixing

J. Koster (Los-Alamos, USA) TUNL five-fold correlation experiments

Session 5: Invited and contributed papers

Chairman: V.A. Nazarenko

V.E. Bunakov (Gatchina, Russia) Statistical analysis for imperfect measurements of stochastic variables

F. Corvi (Geel, Belgium) The spins of U p-wave resonances

A. Masaike (Kyoto, Japan) P- and T-violation in neutron-nucleus reactions: experiments in Japan.

L.B. Pikelner (Dubna, Russia) PV study with polarized targets and nonpolarized neutrons

Session 6: Invited papers

Chairman: D.G. Haase

A.L. Barabanov (Moscow, Russia) P-even T violation from the energy shift in unpolarized (n, γ) reactions

I.S. Okunev (St. Petersburg, Russia) PV in neutron reactions with light nuclei

Session 7: Invited papers

Chairman: L.B. Pikelner

S.M. Beyer (Bonn, Germany) Test of TRI in proton deuteron transmission

K. Schreckenbach (Garching, Germany) TRI test in internal pair production with polarized neutrons

Y. Masuda (KEK, Japan) Neutron spin rotation and P,T violation KEK experiment

Session 8: Invited and contributed papers

Chairman: A. Msaikhe

A.P. Serebrov (Gatchina, Russia) New possibility for search P,T-violation

G.A. Petrov (Gatchina, Russia) Recent experimental data on parity violation in neutron induced fission

H.M. Shimizu (Tsukuba, Japan) Polarized target for T-violation experiment

D.G. Haase (Raleigh, USA) briefs on S.I. Penttila (Los Alamos, USA) Polarized neutron beam for parity violation measurements at LANSCE.

C.M. Frankle (Los Alamos) Measuring parity violation with the neutron capture reaction

J.D. Bowman (Los Alamos, USA) briefs on Yi-Fen Yen (Los Alamos, USA) Design and tests of a 10B liquid scintillator neutron detector

Session 9: Workshop Summary and Discussion

Chairman: N.R. Roberson

Yu.P. Popov (Dubna, Russia) IREN - Intense Resonance Neutron pulsed source at JINR (project)

F. Corvi (Geel, Belgium) IREN and GELINA complementary neutron sources

S.J. Seestrom (Los Alamos) Summary talk

1.3 Signatures of Quantum Chaos in Nuclei

Searches for chaos in the low-lying energy region in nuclei have focused mainly on statistical fluctuations. Many theoretical studies have been performed for both eigenvalues and eigenvectors, but the experimental analyses have been limited to eigenvalue analyses in the individual nuclides ^{26}Al [Shr90] and ^{116}Sn [Ram91], and in a

collection of data spanning many nuclei [Abu85, Shr91]. It is expected that chaotic systems will show statistical behavior agreeing with the Gaussian orthogonal ensemble (GOE) of random matrix theory, while regular systems will show behavior corresponding to Poisson statistics. Both ^{26}Al and ^{116}Sn have fluctuations which lie between these two extremes, while the more wide-ranging analyses suggest a mass dependence.

The major difficulty in analyzing eigenvalue fluctuations is the need for very high-quality data. Either missing or spurious levels can severely bias the results; this is the primary reason so few experimental analyses exist. Both additional data and alternate analysis techniques which have less stringent requirements are desirable. We describe below our efforts in these areas.

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[Ram91] S. Raman *et al.*, Phys. Rev. C 43, 521 (1991).

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[Shr91] J.F. Shriner, Jr., G.E. Mitchell, and T. von Egidy, Z. Phys. A 338, 309 (1991).

1.3.1 Resonances in ^{30}P

J.F. Shriner, Jr.¹, E.G. Bilpuch, C.R. Bybee, J.M. Drake, G.E. Mitchell, E.F. Moore, G.A. Vavrina, P.M. Wallace, and C.R. Westerfeldt

To acquire additional data suitable for a fluctuation analysis, we are studying the nuclide ^{30}P via the $p + ^{29}\text{Si}$ reaction. The preliminary task of studying the $^{29}\text{Si}(p,\gamma)$ excitation function using NaI detectors is complete and was reported in S.C. Frankle *et al.*, Phys. Rev. C45, 2746 (1992). The past year has been spent primarily in the final design and construction of a new spectrometer to study $^{29}\text{Si}(p,\gamma)$ with high-resolution γ -ray detectors at individual resonances. We have also worked extensively on analysis software. The program GELIFT, used to fit Ge spectra, has been modified to use the PGLOT graphics package. Another program has been written to perform analysis of information from singles spectra; it can suggest placement of γ -rays within the level scheme, calculate branching ratios once the γ -rays are placed, and even suggest J^π ; T assignments in some cases.

1.3.2 Shell-Model Calculations in ^{22}Na

A.A. Adams, E.G. Bilpuch, G.E. Mitchell, W.E. Ormand², and J.F. Shriner, Jr.³

As noted earlier, data to study the fluctuation properties of eigenvalues must be of extremely high quality. This restriction severely limits the systems which can be studied

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and also limits the statistical significance of those analyses which can be performed. Both additional data and suitable alternative methods of analysis are desirable. Shell-model calculations for ^{22}Na are being used to address both issues. Experiments are planned to study ^{22}Na via $p + ^{21}\text{Ne}$ at Bochum, and calculated level and decay schemes should be helpful in understanding the experimental data. Also, we wish to explore whether eigenvector distributions can be an appropriate experimental measure for chaos, and the shell-model transition strengths provide a useful starting point.

The lowest 25 positive-parity eigenvalues for each $J \leq 6$ and each isospin $T \leq 2$ have been determined. Then $B(M1)$ and $B(E2)$ were calculated for each pair of these states for which M1 and/or E2 transitions were allowed and for which at least one of the states have $J \leq 4$ (since we do not expect to populate states with $J > 4$ in $p + ^{21}\text{Ne}$). Next, we determined relative branching ratios for the $J \leq 4$ states below $E_x = 12.7$ MeV. Since the calculation does not include negative parity states, we cannot determine absolute branching ratios. An excitation energy of 12.7 MeV corresponds to an incoming proton energy of ≈ 6 MeV, which is well above the energies at which we hope to identify all of the resonance states. Thus, we have a "positive-parity decay scheme" for comparison with experimental data.

Previous analyses by Alhassid and Novoselsky with the interacting boson model [Alh92] and by Meredith with the Lipkin-Meshkov-Glick model [Mer93] have suggested that transition strengths in chaotic regions follow a $\chi^2(\nu=1)$ distribution and that the distribution moves toward $\chi^2(\nu<1)$ as the dynamics becomes regular. We are currently examining the statistical behavior of the $B(M1)$ and $B(E2)$ values calculated here, since this set of $\approx 85,000$ transition strengths should provide a fairly realistic representation of this nuclide with good statistics. We are especially interested in searching for any effects which can be attributed to a specific energy region or a specific electromagnetic transition character. A sample distribution is shown in Figure 1.3-1 for the 501 E2 decays from $J_i; T_i = 1; 1$ states to $J_f; T_f = 2; 0$ states. The best fit, corresponding to $\nu = 1.12 \pm 0.06$, is also shown for comparison.

The most complete experimental data of this type are for ^{26}Al [End88]; we plan to study the eigenvector distributions for those data in the future.

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- [Alh92] Y. Alhassid and A. Novoselsky, *Phys. Rev. C* **45**, 1677 (1992).
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 [End88] P.M. Endt, P. deWit, and C. Alderliesten, *Nucl. Phys. A* **476**, 333 (1988).

Fig. 1.3-1 Distribution of $B(E2)$ values for decays in ^{22}Na from $J_i; T_i = 1; 1$ states to $J_f; T_f = 2; 0$ states. The upper half of the figure shows the probability density; the lower half shows the cumulative probability. The smooth lines correspond to a χ^2 distribution with $\nu = 1.12$ degrees of freedom.

1.3.3 The Fourier Transform as a Signature for Quantum Chaos*C.R. Bybee, E.G. Bilpuch, G.E. Mitchell, and J.F. Shriner, Jr.¹*

In our search for alternative signatures other than eigenvalue fluctuations of quantum chaos, one candidate has been the Fourier transform. It was suggested by Leviandier *et al.* [Lev86] that the Fourier transform might be useful for this purpose. This approach has been used with some success on molecular spectra, but not on nuclear spectra. Therefore, we have modeled the behavior of the square of the Fourier transform for spectra of the size that seem appropriate for nuclear physics. Related work has been performed by Alhassid, Levine, and Whelan [Alh92, Alh93].

Our approach was to generate a spectrum of eigenvalues $\{E_i\}$, obeying either a GOE or Poisson distribution; from the eigenvalues, we form the spectrum $S(E)$, which has spikes of unit height at each eigenvalue and is zero elsewhere. The Fourier transform is defined as

$$\hat{S}(q) = \int_{-\infty}^{\infty} S(E) e^{-2\pi i q E} dE.$$

Following the suggestion of Leviandier *et al.*, we have examined the quantity $|\hat{S}(q)|^2$. If one considers an ensemble average, then spectra with GOE distributions show a "correlation hole" in $|\hat{S}(q)|^2$ for small q , while spectra with Poisson distributions do not. These two situations are illustrated in the top and center portions of Figure 1.3.2, where we have averaged $|\hat{S}(q)|^2$ for 500 different spectra of the appropriate type, each with 100 levels. The dependent variable is the dimensionless parameter q/ρ , where ρ is the level density. However, the practical concern is with the behavior of a single spectrum, since that is what is measured experimentally. There the situation is much less clear, as illustrated in the lower portion of Figure 1.3-2 where $|\hat{S}(q)|^2$ is plotted for a single GOE spectrum with 100 levels. In their early work Leviandier *et al.* discussed the need for some type of smoothing; however, we have found no smoothing method consistently appropriate for spectra of this size. We tentatively conclude that the Fourier Transform approach does not seem practical for spectra of the size typically encountered in nuclear physics.

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 [Alh92] Y. Alhassid and R.D. Levine, Phys. Rev. A **46**, 4650 (1992).
 [Alh93] Y. Alhassid and N. Whelan, Phys. Rev. Lett. **70**, 572 (1993).

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Fig. 1.3-2 (Top) The ensemble-averaged $|\hat{S}(q)|^2$ for GOE spectra with 100 levels. (Center) The ensemble-averaged $|\hat{S}(q)|^2$ for Poisson spectra with 100 levels. (Bottom) $|\hat{S}(q)|^2$ for a single GOE spectrum with 100 levels.

2. INTERNUCLEON INTERACTIONS

2.1 Neutron-Proton Interactions

2.1.1 Neutron-Proton Analyzing Power Data: π NN Form Factor and Charge-Independence Breaking of the 3P_J NN Interactions

R.T. Braun, C.R. Howell, W. Tornow and R.L. Walter

The motivation for a new series of accurate neutron-proton (np) analyzing power $A_y(\theta)$ measurements is two-fold. First, since the Nijmegen group published their sophisticated proton-proton (pp) phase-shift analysis where they claimed large breaking of charge independence (CIB) of the π NN coupling constants ($f_{NN\pi^0}^2 \neq f_{NN\pi^\pm}^2$), this issue has been of great interest and controversy [Sto93]. In the meantime, there seems to be some understanding that $f_{NN\pi^\pm}^2$ as determined by the Karlsruhe-Helsinki analyses [Koc80] from $\pi^\pm p$ scattering is too large. In fact, $f_{NN\pi^\pm}^2$ obtained in the analysis of the VPI & SU group [Arn90] using more recent $\pi^\pm p$ data is in agreement with the Nijmegen result for $f_{NN\pi^0}^2$. In addition, the most recent phase-shift analyses of the Nijmegen group of antiproton-proton, proton-proton, and neutron-proton data give consistent and equal results (within errors) for $f_{NN\pi^0}^2$ and $f_{NN\pi^\pm}^2$, therefore eliminating the earlier claim of large CIB of the π NN coupling constants [Sto93]. Furthermore, the values obtained by the VPI & SU group for $f_{NN\pi^0}^2$ and $f_{NN\pi^\pm}^2$ from their pp and np phase-shift analyses, respectively, support the results of the Nijmegen group [Arn92].

However, all of these analyses have been criticized for various reasons. As given in [Sto93], the Nijmegen np analysis depends heavily on the low-energy np $A_y(\theta)$ data. Here the np $A_y(\theta)$ data set of Holslin *et al.* [Hol88] at 10 MeV plays an important role. The recent TUNL np $A_y(\theta)$ data of Weisel *et al.* [Wei92] at 12 MeV, which are in good agreement with the Bonn B [Mac89] and Paris [Lac80] NN potential-model predictions, are somewhat lower in magnitude for $\theta_{c.m.} \geq 90^\circ$ than the Nijmegen np phase-shift analysis. In view of this discrepancy and the impact that a smaller π NN coupling constant implies for NN potential models in general, a new round of measurements of high-accuracy np $A_y(\theta)$ data was initiated at TUNL.

Our second motivation is based on the well-established neutron-deuteron (nd) $A_y(\theta)$ puzzle. It appears now that the $A_y(\theta)$ problem cannot be solved by adding 3N forces to the dominant NN interaction. Since it is well known that the low-energy nd $A_y(\theta)$ is the result of a complicated interplay between the three 3P_J (3P_0 , 3P_1 and 3P_2) NN force components, the only remaining issue is the question of the correctness of the 3P_J interactions. The present knowledge of the 3P_J phase shifts is based almost entirely on np

and $pp A_y(\theta)$ data and model assumptions, such as the One-Boson Exchange Potential. Experimentally, the three 3P_J phase shifts cannot unambiguously be determined from only a single observable, such as $A_y(\theta)$. Therefore, Witala and Glöckle [Wit91] performed the first combined analysis of NN and 3N data and, in fact, found 3P_J phase shifts that not only satisfactorily describe the nd and pd $A_y(\theta)$ data, but also give good fits to the NN data as well. However, these new 3P_J phase shifts exhibit a rather large breaking of CIB. The magnitude and the sign of the obtained CIB is not supported by recent meson-theoretical studies.

Although, in general, improved np $A_y(\theta)$ data alone cannot yield a better determination of the individual 3P_J phase shifts, they are instrumental for distinguishing between different phase-shift analyses and NN potential-model predictions. An improvement in accuracy of new np $A_y(\theta)$ data by a factor of two over that obtained recently at Wisconsin [Hol88] and TUNL [Wei92] is expected to have a dramatic impact on both the π NN coupling constant issue and the question of CIB of the 3P_J NN interactions.

The new TUNL setup for np $A_y(\theta)$ measurements is shown in Figure 2.1-1. It features a shielded neutron source, five pairs of neutron detectors, and a ^4He neutron polarimeter. Polarized neutrons are produced via the $^2\text{H}(\vec{d}, \vec{n})^3\text{He}$ polarization transfer reaction. In our first data taking run, polarized deuteron intensities on target were typically $1.5 \mu\text{A}$ and the neutron polarization was 0.58 as measured by the ^4He neutron polarimeter. The total uncertainty of the data is expected not to exceed ± 0.0005 . We plan to measure 15 data points each at 12 MeV, 7.5 and 5 MeV. At these low energies, the Nijmegen np phase-shift analysis deviates considerably from potential-model predictions. This energy range is also of special interest for the solution of the nd $A_y(\theta)$ puzzle, since the discrepancy between rigorous 3N calculations using realistic NN potential and nd $A_y(\theta)$ data is as large at 3 MeV as it is at 14 MeV.

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Figure 2.1-1 Five detector pair np $A_y(\theta)$ experimental setup including helium polarimeter.

2.1.2 Measurements of $\Delta\sigma_T$ for Scattering of Polarized Neutrons from Polarized Protons

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In an effort to determine the strength of the nucleon-nucleon (NN) tensor interaction, we have been making measurements at TUNL of the spin-dependent difference in total cross section $\Delta\sigma_T$. Previously, we have made measurements between 3.5 and 6.25 MeV to determine the zero-crossing energy of $\Delta\sigma_T$ [Wil93]. In the past year, measurements have been made in the energy region around 10 MeV where $\Delta\sigma_T$ exhibits the greatest sensitivity to the strength of the NN tensor interaction. Phase-shift analyses have been performed using these data. The results of the analyses indicate that the tensor force is weak for energies below 20 MeV. This conclusion is particularly important in the case of the triton as a weak tensor force will increase the triton binding energy as calculated by potential models, bringing them into closer agreement with the experimentally determined value [Mac89].

$\Delta\sigma_T$ is defined to be the total cross section with the neutron and proton spins anti-parallel minus the total cross section with the spins parallel:

$$\Delta\sigma_T = \sigma(\uparrow\downarrow) - \sigma(\uparrow\uparrow).$$

In both cases, the spins are transverse to the beam momentum. Measurements of $\Delta\sigma_T$ require that both the neutron beam and the proton target be polarized. The polarized proton target consists of titanium hydride, TiH_2 , which is cooled to approximately 15 mK in a 7 T magnetic field. Further details of the polarized target can be found in previous TUNL progress reports and in [Haa86]. The polarized neutron beam is produced through the $^2\text{H}(\vec{d}, \vec{n})^3\text{He}$ polarization transfer reaction. At energies below 30 MeV, $\Delta\sigma_T$ is very sensitive to the strength of the NN tensor interaction. This sensitivity is a maximum at approximately 10 MeV.

We have made three measurements of $\Delta\sigma_T$ between 7.5 and 11.5 MeV, in addition to six measurements made previously near the zero crossing. These data are shown in Figure 2.1-2 along with the predictions of the Bonn-B potential model [Mac89] and the phase-shift analysis, SP93, of Arndt [Arn93]. As can be seen from the figure, the measured values of $\Delta\sigma_T$ are substantially higher than predicted by Arndt's phase-shift analysis, indicating a weaker tensor force. The highest energy data are above even the Bonn-B prediction, a model having an already weak tensor force.

In terms of phase-shift parameters, the strength of the NN tensor force is indicated by the 3S - 3D mixing parameter ϵ_1 . In order to extract values of ϵ_1 from the $\Delta\sigma_T$ data, a phase-shift analysis (PSA) is performed. We have tried two PSA techniques. In the first, only the value of ϵ_1 is allowed to vary and all other phase-shift parameters are taken from the Bonn-B potential model. In the second, all phases for $J \leq 1$ are varied in order to fit all existing data. The results of both techniques are in agreement and those from the single-parameter analysis are shown in Figure 2.1-3. Also included in the figure are

Figure 2.1-2 Measured values of $\Delta\sigma_T$. The error bars represent the total uncertainty. The solid curve is the prediction of the Bonn B potential model, while the dashed curve is that of Arndt's phase-shift analysis SP93.

values of ϵ_1 from previous experiments [Sch88,Ock91a,Dol89,Ock91b] and the phase-shift analysis of Henneke at 25 MeV [Hen93]. The values of ϵ_1 below 20 MeV are consistently below those for SP93 and Bonn-B, indicating a weak tensor force in this energy range.

A weak tensor force has been shown to increase the triton binding energy as calculated by potential models. Since all realistic and local potential models presently underestimate the triton binding energy, this result will bring potential model predictions into closer agreement with the experimentally determined values. A manuscript has been submitted to Physical Review Letters.

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Figure 2.1-3 Values of ϵ_1 from analysis of the present data (diamonds) and from four previous measurements (crosses). The solid curve is from the Bonn B potential model, while the dashed curve is from Arndt's phase-shift analysis SP93. Henneck's phase-shift analysis at 25 MeV is also shown (square).

2.1.3 Determination of Neutron-Proton Scattering Length Parameter via Neutron-Deuteron Breakup Measurements

F. Salinas, C.R. Howell, W. Tornow, and H. Witala¹

The comparison of the neutron-neutron (n-n) and proton-proton (p-p) scattering length parameters a_{nn} and a_{pp} is one of the most basic tests of charge symmetry breaking (CSB). Though the evidence for CSB in the 1S_0 part of the nucleon-nucleon (NN) force is strong, discrepancies between the reported values of a_{nn} causes ambiguity in the interpretation of scattering length comparisons. The value of a_{nn} seems to depend on the

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reaction used in the determination. The value of a_{nn} extracted from reactions involving three or more nucleons in the exit channel, including the $n+d \rightarrow n+n+p$ breakup reaction, is around -16.6 ± 0.6 fm [Ter89], while the average value extracted from the $\pi+d \rightarrow n+n+\gamma$ reaction is -18.57 ± 0.34 fm [Mil90]. The Coulomb corrected value for a_{pp} is -17.15 ± 0.15 fm, which lies roughly midway between the two values for a_{nn} . According to the π -d capture results, the n-n force is stronger than the p-p force, while the values extracted using reactions having two or more nucleons in the exit channel suggest the opposite. The leading supposition is that the values for a_{nn} extracted from cross-section data for reactions involving three or more strongly interacting particles in the exit channel are influenced by three-nucleon (3N) forces [Sla89].

We are developing experimental techniques and equipment to determine the accuracy that NN scattering length parameters a_{NN} can be extracted from neutron-deuteron (n-d) breakup cross-section data. For this purpose, we will measure cross sections for the neutron-proton (n-p) final-state interaction (FSI) at four production angles of the n-p pair to an accuracy of $\pm 4\%$ per 0.5-MeV bin along the kinematical locus. According to sensitivity calculations, as shown in Figure 2.1-4, this accuracy should be sufficient to permit a determination of a_{np} to ± 0.5 fm at each production angle. The proposed experimental setup is shown in Figure 2.1-5. The detectors on the right side of the incident neutron beam axis will view the deuterated target scintillator (C_6D_{12}) through transmission detectors used in a concurrent a_{nn} measurement. The momentum of the two emitted neutrons will be measured in coincidence with the energy of the proton.

Initial measurements will be made at an incident neutron energy of 13.0 MeV. The breakup data will be normalized to n-d elastic scattering, which will be measured simultaneously with the breakup data. An absolute normalization requires knowledge of the neutron detector efficiency of one of the detectors in the coincidence pair over the neutron energy range covered by the kinematic locus. The relative efficiencies of the 8 detectors have been measured using a ^{252}Cf source embedded in an argon gas scintillator [How92]. Two independent methods will be used to determine the absolute detector efficiency of three of the detectors in the array. The 0° and 60° neutrons from the $^2\text{H}(d,n)^3\text{He}$ reaction, which has a well-known cross section, has been used to calibrate the detector efficiencies to an accuracy of $\pm 3\%$ at discrete energies in the range from 5.5 to 13.0 MeV. These results will be checked using the specially designed ^{252}Cf source, which is mounted inside a thin-walled ionization chamber, of the group at the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany. The detectors will be shipped to Braunschweig in July 1993 for calibration. In addition to the ^{252}Cf neutron source, the PTB group will use the monoenergetic neutrons from the $^3\text{H}(p,n)^3\text{He}$ and $^2\text{H}(d,n)^3\text{He}$ source reactions to check the TUNL results. W. Tornow and D. Gonzalez Trotter will travel to Braunschweig to assist in the calibration.

Since the value of the $^1\text{S}_0$ a_{np} is well known from n-p scattering using thermal neutrons [Koe75], our results will gauge the reliability of using n-d breakup cross sections to extract values for a_{NN} . According to Slaus *et al.* [Sla89], an angular dependence on the value of a_{np} would be the signature of 3N forces.

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Figure 2.1-4 Plot of calculated cross sections along the kinematic locus S for the n-p FSI as a function of a_{np} . The incident neutron energy is 13.0 MeV and the n-p pair goes to a laboratory angle of 30.0° .

a_{np} Detector Setup

Figure 2.1-5 Experimental setup for the n-p FSI cross-section measurements using the $^2\text{H}(n, np)$ breakup reaction. The scale is indicated on the drawing. Details are given in the text.

2.1.4 Deuteron Asymptotic S-Wave Normalization by n-d Elastic Scattering: A Test of Extracting Nucleon-Nucleon Force Details from Three-Nucleon Systems
C.R. Howell, H.R. Setze, W. Tornow, R.S. Pedroni¹, S.M. Grimes², C.E. Brient², G. Meriens³, and H. Witala⁴

The idea of using three-nucleon (3N) observables to probe details of the nucleon-nucleon (NN) force is attractive because of the possible amplification effect caused by interference between partial waves. The strong dependence of low-energy neutron-deuteron (n-d) elastic scattering vector analyzing powers $A_y(\theta)$ on the 3P_J NN partial waves illustrate the enhanced sensitivity of a 3N observable to a particular part of the NN interaction [How87]. Witala and Glöckle showed that the discrepancy between the n-d $A_y(\theta)$ data and calculations can be corrected by modifications to the 3P_0 NN force, without significantly affecting the description of two-nucleon data [Wit91a]. However, their modification resulted in charge independence breaking in the 3P_J partial waves, which is probably not supported by meson-exchange theory [Glö87]. The discrepancy between the n-d $A_y(\theta)$ data and calculations might be due to 3N forces, which is a possible complication that limits the robustness of extracting details of the underlying NN force from 3N data. Though clouded by the possibility of 3N forces, the use of 3N observables as a method for extracting details about the NN force should be developed.

An initial step in the development process is to test the accuracy with which 2N phase shifts and force parameters, which are well known from 2N data, can be determined using 3N data and calculations. In this work we use the determination of the asymptotic S-wave normalization of the deuteron A_s from elastic neutron-deuteron (n-d) scattering cross sections to measure the precision of the technique. Although done for a specific case, the results should be an indication of the accuracy one can expect when extracting 2N force information from 3N observables. The A_s of the deuteron wave function was chosen for this test for two reasons: 1) it is known to better than two parts per thousand from both electron-deuteron elastic scattering $A_s = 0.8802 \pm 0.0020$ [Eri84] and from low-energy neutron-proton scattering $A_s = 0.8846 \pm 0.0008$ [Eri83]; and 2) there is a strong correlation between A_s and the differential cross section $d\sigma(\theta)/d\Omega$ for n-d elastic scattering to backward angles [Koi86].

We have extended the original sensitivity study of Koike and Taniguchi [Koi86] to cover the entire angular distribution. The relationship between A_s and $d\sigma(\theta)/d\Omega$ for n-d elastic scattering to backward angles is shown in Figure 2.1-6 for an incident neutron energy $E_n = 10$ MeV. The symbols represent the predictions of rigorous n-d calculations and the curves are fits using a second order polynomial. The theoretical predictions were obtained by solving modified AGS equations with the two-body t-matrix being generated by the chosen NN interaction using the Lipmann-Schwinger equation. Details of the

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formalism and the numerical performance are in papers by Glöckle [Glö87] and Witala *et al.* [Wit88].

To predict $d\sigma(\theta)/d\Omega$ corresponding to different A_s values, the scattering equations were solved using different 3S_1 - 3D_1 force components while keeping all other NN partial waves equal to the one-boson equivalent of the Bonn-B potential (OBEPQ-B) [Mac89]. All calculations were done for a total NN angular momentum of $j \leq 3$. We checked that restriction to those states is sufficient at the energies used in the present work. The well-established charge-independence breaking in the 1S_0 NN force was taken into account [Wit91b]. Three calculations were done replacing the OBEPQ-B 3S_1 - 3D_1 NN force component with the 2T7 [Sve82], 4T4B [Cor81], and T4D [Dol74] potentials.

Figure 2.1-6 Relationship between A_s and $d\sigma(\theta)/d\Omega$ for n-d elastic scattering at 10 MeV. The data points are from calculations using four different potentials for the NN 3S_1 - 3D_1 force: 2T7 [Sve82], 4T4B [Cor81], OBEPQ-B [Mac89], and T4D [Col74]. The curves are second-order polynomial fits.

To resolve the discrepancy between low-energy $d\sigma(\theta)/d\Omega$ data for n-d elastic scattering [Koi86] and to provide reliable data for our determination of A_s , we have made $d\sigma(\theta)/d\Omega$ measurements to an accuracy better than $\pm 4\%$ for n-d elastic scattering to backward angles ($\theta_{cm}=140^\circ$ - 178°) at incident neutron energies of 8.0, 10.0, and 14.0 MeV. The results of our cross section measurements have been submitted for publication to Few-Body Systems [How93].

Figure 2.1-7 Plot of A_s versus $d\sigma(\theta)/d\Omega$ for n-d elastic scattering to $\theta_{cm} = 176^\circ$ at $E_n = 10$ MeV. The points without error bars and the curves are the same as in fig. 1. The open circles with the vertical and horizontal error bars represent the $d\sigma(176^\circ)/d\Omega$ data measured by Howell *et al.* [How93] and the corresponding A_s value extracted using the technique described in the text. The dashed line represents the value of A_s extracted from the $d\sigma(176^\circ)/d\Omega$ predicted using the OBEPQ-B 3S_1 - 3D_1 force.

The combination of our recent data and published data at the above three energies was used to extract a value for A_s . At each angle where n-d $d\sigma(\theta)/d\Omega$ data was available, a plot of A_s versus $d\sigma(\theta)/d\Omega$ was made as shown in Figure 2.1-7. The four calculated points were fit with a second-order polynomial. The polynomial function was used to determine the value of A_s corresponding to the measured n-d cross section. To gauge the absolute precision of the technique independent of the quality of the n-d data, the cross section predicted by the OBEPQ-B was projected onto the A_s axis to give a value for A_s . The dashed line in Figure 2.1-7 represents the extracted value of A_s using the OBEPQ-B at $E_n = 10$ MeV and $\theta_{c.m.} = 176^\circ$.

The A_s value extracted in our analysis of n-d data was $A_s = 0.9048 \pm 0.0053 \text{ fm}^{-1/2}$. This result is 1.4% higher than the control value of $A_s = 0.8923 \pm 0.0022 \text{ fm}^{-1/2}$ produced using the OBEPQ-B and 2.5% higher than the average value obtained from e-d and n-p scattering. A manuscript on these findings has been prepared and will be submitted to Phys. Rev. C.

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2.2 The Neutron-Neutron Scattering Length

2.2.1 Watson-Migdal Model Versus Rigorous Three-Nucleon: A Comparison of Neutron-Neutron Final-State-Interaction Cross Sections for $^2\text{H}(n,nn)p$.

W. Tornow, H. Witala, D.E. González Trotter

We consider the kinematical configuration in which the incident neutron breaks up a deuteron such that in the first step a free proton and a quasi-dineutron with low internal energy is created (amplitude T_0). In the second step the final-state-interaction

(FSI) of the neutrons is taken into account. The interaction between the proton and the two neutrons is ignored. The Watson-Migdal (WM) model gives the following cross section for the interacting neutrons [Wat52], [Mig55], [Bod89]:

$$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dS} = \frac{2\pi m_0}{\hbar k_0} |T_0|^2 F_{nn}(x) \rho(S, \vec{k}_1, \vec{k}_2) \quad (1)$$

where m_0 and k_0 are the mass and momentum of the incoming neutron, respectively. The production cross section $|T_0|^2$ is assumed to be constant around the FSI point for a fixed kinematical configuration. The enhancement factor $F_{nn}(x)$ is

$$F_{nn}(x) = \frac{1}{4} \frac{(x^2 + \alpha^2) r_{nn}^2}{\left(-\frac{1}{\alpha} + \frac{r_{nn} x^2}{2} \right)^2 + x^2} \quad (2)$$

$$\text{with } \alpha = \frac{1 + \sqrt{1 - \frac{2r_{nn}}{a_{nn}}}}{a_{nn}}$$

and the relative neutron momentum $\vec{x} = \vec{k}_1 - \vec{k}_2$, neutron-neutron (nn) scattering length a_{nn} , and the nn effective range r_{nn} .

The phase-space factor is given by [Mei83]

$$\rho(S, \vec{k}_1, \vec{k}_2) = \frac{M}{\hbar^2} \frac{k_1^2 k_2^2}{(k_1^2 (2k_2 - k_0 \cos\theta_2 + k_1 \cos\theta_{12})^2 + k_2^2 (2k_1 - k_0 \cos\theta_2 + k_2 \cos\theta_{12})^2)^{1/2}},$$

where S is the arc length described by the kinematical locus in the $E_{n1} - E_{n2}$ plane of the outgoing neutrons, M is the total mass of all outgoing particles (two neutrons and one proton), and $\cos\theta_{12} = \vec{k}_1 \cdot \vec{k}_2$.

In the past, the WM model has frequently been used to extract a_{nn} from the FSI peak of kinematically complete $^2\text{H}(n,nn)p$ experiments. The theoretical calculations based on eq. 1 were normalized at the peak height to the experimental data. In the fitting procedure of the FSI cross section, a_{nn} was treated as a free parameter. Due to its insensitivity to the FSI peak, r_{nn} was normally kept fixed at a reasonable value. Using this method, a_{nn} was obtained mainly from the width of the measured FSI enhancement.

The Bochum group [Wit92] and the Bonn group [Geb92] have observed that the Watson-Migdal method is in disagreement with rigorous three-nucleon (3N) calculations and the W-matrix approach, respectively. According to the rigorous 3N calculations performed with the code of the Bochum group, the magnitude of the FSI enhancement is sensitive to changes in a_{nn} and not so much its width, as can be seen from Figure 2.2.1.

FSI $E_n = 13$ MeV, $\theta_1 = \theta_2 = 25.0^\circ$, $\phi_{1,2} = 0.0^\circ$

Figure 2.2-1 Calculated FSI cross section for $E_n = 13$ MeV and $\theta_{n1} = \theta_{n2} = 25^\circ$ and $\Phi_{n1,n2} = 0^\circ$ using the Bonn B NN potential with modified 1S_0 forces to yield a_{nn} values between -17.5 and -19.5 fm.

The curves in Figure 2.2-1 were obtained using the Bonn B nucleon-nucleon (NN) potential with modified nn 1S_0 forces [Wit92] to yield a_{nn} values in the range from -17.5 fm to -19.5 fm. Figure 2.2-1 clearly shows that the determination of a_{nn} requires accurate absolute cross-section measurements. The lack of such accurate cross-section information is the main reason why published FSI spectra cannot be reanalyzed with rigorous 3N calculations and realistic NN interactions.

We calculated the FSI cross section at $E_n = 13$ MeV for $\theta_{n1} = \theta_{n2} = 25^\circ$ and $\Phi_{n1,n2} = 0^\circ$ using again the Bochum code and the Bonn B NN interaction with modified nn 1S_0 forces ($a_{nn} = -15$ fm and $a_{nn} = -18.5$ fm). These cross-section curves were then fitted with the WM expression of eq. 1, where we normalized the WM cross section to the rigorous 3N calculation at the peak height. It was found that rigorous 3N calculations with $a_{nn} = -18.5$ fm and $a_{nn} = -15.0$ fm correspond to WM calculations with $a_{nn} = -17.9$ fm and $a_{nn} = -14.6$ fm, respectively. Figure 2.2-2 shows one example. The magnitude and sign of the difference between WM and rigorous 3N calculations found in

the present work is different from those found with the W-matrix approach, where larger differences have been reported.

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Figure 2.2-2 The dots represent the FSI cross section using the rigorous approach of the Bochum group and a modified version of the Bonn B potential with $a_{nn} = -18.5$ fm. The solid line is a fit to this calculation using the Watson-Migdal model with $a_{nn} = -17.9$ fm.

2.2.2 Determination of the Neutron-Neutron Scattering Length from Incomplete Neutron-Deuteron Breakup Experiments

W. Tornow, R.T. Braun and H. Witala¹

Although it has now been generally accepted that charge symmetry (CS) is broken in the 1S_0 nucleon-nucleon (NN) interaction, crucial questions remain unsettled. Since a suitable free neutron target is not available to study neutron-neutron scattering directly, these questions deal with the accuracy of the theoretical approaches used to obtain values for the neutron-neutron scattering length a_{nn} from multi-particle breakup reactions such as $n+d \rightarrow n+n+p$ and $\pi^+d \rightarrow n+n+\gamma$. According to Miller *et al.* [Mil90], the “recommended” value for the Coulomb corrected proton-proton scattering length (obtained from pp scattering) is $a_{pp} = -17.3 \pm 0.4$ fm, while the “recommended” value for the neutron-neutron scattering length is $a_{nn} = -18.5 \pm 0.3$ fm, thus clearly showing charge-symmetry breaking (CSB) in the 1S_0 NN interaction.

Figure 2.2-3 Calculated proton spectrum at $\theta_p = 4.0^\circ$ using 14.1 MeV incident neutrons for the original Bonn B potential (solid curve) and modified versions of Bonn B with $a_{nn} = -20$ fm (dashed curve) and $a_{nn} = -15$ fm (dotted-dashed curve).

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In this work we concentrate on the reanalysis of proton spectra measured near 0° in incomplete $n+d \rightarrow n+n+p$ breakup experiments in the incident neutron energy range from 11.0 to 62.8 MeV. Columns 1 to 5 in table 2.2-1 summarize the main features of the experiments, the results and the theoretical methods used for extracting a_{nn} . A striking feature seen in column 4 of Table 2.2-1 is that all experiments were analyzed with simplified and separable nucleon-nucleon (NN) forces acting in s-waves only.

Table 2.2-1 Summary of $^2\text{H}(n,p)2n$ data and analyses

E_n (MeV)	$\bar{\theta}_p \pm \Delta\theta_p$ (degrees)	Published a_{nn} (fm)	Theoretical Analysis	Ref.	Present Results for a_{nn} (fm)
11.0	2.5 ± 2.2	"supports" -16.6 ± 0.4	Doleschall code Yamaguchi form factor s-waves	[Kul81]	-18.54 ± 2.22
13.98	1.6 ± 1	-23.2 ± 3.6	Kloet code with RSC and MT I-III s-waves	[Hai77]	-22.08 ± 1.47
14.1	4.0 ± 2.2	-18.31 ± 0.22	Cahill code Yamaguchi form factor s-waves	[Shi73]	-16.00 ± 0.59
25.0	3.0 ± 2.5	"supports" -16.6 ± 0.4	Doleschall code Yamaguchi form factor s-waves	[Kul81]	-12.37 ± 2.67
49.6	$3.8^{+2.3}_{-2.8}$	-21.7 ± 1.2 -19.6 ± 1.2	Impulse approximation Code BREAK [Shi83] Yamaguchi form factor s-waves	[Str72] [Shi86]	-14.98 ± 0.76
62.8	2.66 ± 1.8	-18.8 ± 1.0	Code BREAK [Shi83] Yamaguchi form factor s-waves	[Koo86]	-14.09 ± 0.65

In the present work the 3N continuum Faddeev equations were solved rigorously using the meson-exchange based Bonn B NN potential [Mac89]. All NN force components with total angular momentum $j \leq 3$ were taken into account. The underlying theory and the numerical methods applied to calculate the 3N breakup amplitudes are outlined in detail in [Glö83] and [Wit88]. The well established charge-independence breaking of the 1S_0 NN interaction was treated exactly. Since the 1S_0 force component in

the Bonn B potential is fitted to the np 1S_0 scattering length ($a_{np} = -23.76$ fm), one normally assumes CS and takes for the nn 1S_0 force component a modified version of Bonn B with the σ -meson coupling constant changed to $g_\sigma^2 / 4\pi = 8.8557$ [Mac89]. This procedure adjusts the 1S_0 NN interaction to the pp system ($a_{pp} = -17.66$ fm). In order to construct 1S_0 NN potentials with a_{nn} different from the values given above for a_{pp} , we applied the same procedure and adjusted the σ -meson coupling constant to yield a_{nn} value of interest, typically from -12 fm to -24 fm. With these 1S_0 force components and all other NN force components as given in Bonn B, we calculated the 3N breakup amplitudes at the energies of interest. Finally, from the 3N breakup amplitudes proton spectra were calculated for a range of proton emission angles near 0° lab. The calculation of a single proton spectrum requires the proper integration over energy and angle of one of the unobserved two neutrons. The solid curve in Figure 2.2-3 shows a calculated proton spectrum for 14.1 MeV incident neutrons at a proton emission angle of $\theta_p = 4^\circ$ using the Bonn B potential ($a_{nn} = -17.66$). The enhancement of the cross section at the high-energy end of the spectrum is due to the nn final-state-interaction (FSI). It is this region of the proton spectrum that is sensitive to changes of a_{nn} , as can be seen from the dashed and dotted-dashed curves in Figure 2.2-3 which correspond to $a_{nn} = -20$ fm and $a_{nn} = -15$ fm, respectively.

The theoretical point geometry proton spectra were used in Monte Carlo codes written specifically for the experimental arrangements studied in the present work. As an example, Figure 2.2-4 shows our Monte Carlo simulation for three experiments at 13.98 MeV [Hai77], 14.1 MeV [Shi73] and 62.8 MeV [Koo86]. The different curves correspond to different values of a_{nn} . The results of our analysis are summarized in column 6 of Table 2.2-1. Clearly, a new experiment near 14 MeV is required to clarify the presently inconsistent experimental situation in this energy range. Our results for the experiment of Stricker *et al.* and Koori *et al.* are significantly smaller than the ones obtained in the earlier analyses. This finding can be traced back to the neglect of higher partial wave NN interactions in the original work. Column 6 of Table 2.2-1 indicates that the a_{nn} values obtained in our analysis cluster around -15.5 fm. This observation is completely unexpected and not understood. Following the estimates given in [Sla89], 3N force effects, which are not included in the present work, are small for this special configuration of the interacting nucleons studied in the present work. Assuming that the π -d result for a_{nn} (-18.6 ± 0.3 fm) [Mil90] is the "true" value for a_{nn} , one could conclude from column 6 of Table 2.2-1 that a_{nn} decreases with increasing incident neutron energy. As long as the controversial experimental situation at 14 MeV is not resolved and as long as the possible energy dependence of the extracted a_{nn} values cannot be explained satisfactorily, one should not use the present results and especially the average value ($a_{nn} = -15.6 \pm 0.4$ fm) calculated from the individual results given in column 6 of Table 2.2.1 as a new "recommended" value for a_{nn} obtained from incomplete n-d breakup experiments near 0° proton emission angle.

Figure 2.2-4 Monte Carlo simulation of proton spectra at 13.98 MeV (top), 14.1 MeV (center) and 62.8 MeV (bottom) incident neutron energy using the Bonn B potential (dashed curves) and modified versions of Bonn B with a_{nn} values given in the inserts (solid and dotted curves).

In summary, our reanalysis of published proton spectra for the incomplete nd breakup reaction using a realistic NN potential (Bonn-B and 1S_0 modified versions of Bonn-B) in rigorous 3N calculations yields, contrary to previous simplified analyses, a rather broad range of values for a_{nn} . The statistically significant proton spectra give a_{nn} values that are in clear disagreement with results obtained from the π -d breakup reaction.

The calculation of the 3N breakup amplitude and the point-geometry spectra required about 300 hours of Cray Y-MP CPU time. More than 1000 hours of μ Vax and SUN CPU time were used for the Monte Carlo simulations of the experimental arrangements.

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2.2.3 Determination of the Neutron-Neutron Scattering Length from Complete n-d Breakup Data: W-matrix versus Rigorous 3N Calculations

W. Tornow, H. Witala¹ and D.E. González Trotter

In order to accurately compare the results of complete nd breakup data with theoretical predictions, sophisticated Monte Carlo simulations are required to correct for finite geometry effects of the experimental setup. For this purpose, the nd breakup cross section must be calculated in small steps for the entire energy and angular range subtended by the actual experimental arrangement. It has been argued in [Bar87] and

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[Fra88] that the W-matrix formalism of the Bonn group [Bar86] provides an excellent way of representing the nucleon-nucleon (NN) interaction for neutron-deuteron (nd) elastic scattering and breakup calculations. In [Geb93] an uncertainty of 2-3% was assigned to W-matrix results. Since the W-matrix approach requires less computational resources than the rigorous calculations of the Bochum group [Glö83], the Erlangen group [Geb93] analyzed their nd breakup data in collaboration with the Bonn group using the W-matrix method. Here we focus on the Erlangen nd breakup data obtained at $E_n = 13$ MeV for the neutron-neutron (nn) final-state-interaction-configuration (FSI) at $\theta_{n1} = \theta_{n2} = 25^\circ$ (lab).

According to [Geb93], breakup cross sections were calculated using the W-matrix approach at 13,500 mesh points in the relevant region of the five-dimensional space spanned by the incident neutron energy E_n , the two neutron reaction angles θ_{n1} and θ_{n2} , the difference ϕ_{12} of the two neutron azimuthal angles, and the arc length S along the kinematical locus in the E_{n1} - E_{n2} plane. The Paris NN potential [Lac80] was used in

Figure 2.2-5 The Erlangen data (solid dots) for the FSI cross section at $E_n = 13$ MeV for $\theta_1 = \theta_2 = 25^\circ$ in comparison to theoretical calculations based on two different approaches. The solid curve is the best fit to the data using the W-matrix method of the Bonn group with $a_{nn} = -17.0$ fm. The dashed-dotted curve which overestimates the data slightly at the maximum, also obtained with the W-matrix method, is based on $a_{nn} = -17.6$ fm and shows the sensitivity of the calculations to changes of a_{nn} . The dashed-dotted curve is the result of a rigorous 3N calculation using the code of the Bochum group and the Bonn B potential. This curve is in complete disagreement with the data. The dotted curve shows a rigorous calculation with $a_{nn} = -15$ fm.

these calculations. Since the goal of the Erlangen nn FSI experiment was the determination of the nn scattering length a_{nn} , the 1S_0 phase shift of the originally charge-independent Paris potential, which is fitted to proton-proton (pp) data ($a_{pp} = -17.6$ fm), had to be modified to account for the neutron-proton (np) scattering length ($a_{np} = -23.76$ fm) and a_{nn} . This was achieved by replacing the 1S_0 contributions of the Paris interaction by expressions of Malfliet-Tjon [Mal70] type with parameters adjusted to reproduce both the experimental a_{pp} and a_{np} scattering lengths and to simultaneously give values of interest for a_{nn} .

The solid dots with error bars in Figure 2.2-5 present the Erlangen data for the FSI cross section at $\theta_{1n} = \theta_{2n} = 25^\circ(\text{lab})$ for 13 MeV incident neutrons. As can be seen, the data are in excellent agreement with the W-matrix approach calculations with $a_{nn} = -17$ fm (solid curve). In fact, the result quoted in [Geb93] is $a_{nn} = -17.0 \pm 1.0$ fm.

In preparation of the TUNL a_{nn} measurements we have performed extensive calculations with the rigorous 3N continuum code of the Bochum group using the Bonn-B NN potential. In Figure 2.2-5 the dashed-dotted curve, which deviates from the data by several standard deviations, presents one of the rigorous 3N calculations using the Bonn-B [Mac89] NN potential ($a_{nn} = -17.665$ fm). This curve can be directly compared with the dashed-dotted curve ($a_{nn} = -17.6$ fm) based on the W-matrix method which is in close agreement with the data. The comparison of these two curves with the Erlangen data indicates that a rigorous calculation with $a_{nn} = -15$ fm is expected to be in close agreement with the Erlangen data. In fact, this statement is supported by the dotted curve in Figure 2.2-5. Here a 1S_0 modified version of the Bonn-B potential with $a_{nn} = -15$ fm was employed. In order to modify 1S_0 of the original Bonn-B potential, the σ coupling was adjusted to give a_{nn} values of interest. This procedure effectively modifies 1S_0 below about 4 MeV.

In conclusion, we have shown that the W-matrix approach is not adequate for extracting accurate values for the neutron-neutron scattering length a_{nn} from complete nd breakup data. In this FSI configuration where the W-matrix approach differs from the rigorous result by more than 2 fm, the accuracy of the W-matrix approach calculation has been overestimated.

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2.2.4 Preparation for a_{nn} Determinations via Kinematically Complete n-d Breakup Experiment

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Model calculations predict that the value extracted for the 1S_0 neutron-neutron scattering length a_{nn} from kinematically complete $n + d \rightarrow n_1 + n_2 + p$ breakup experiments is not necessarily a true measure of the force between two neutrons due to the action of three-nucleon (3N) forces in the exit channel. Since 3N forces depend on the simultaneous coordinates of three nucleons, the presence of sizable 3N force effects must cause a_{nn} to be angular dependent, *i.e.*, the extracted a_{nn} values must depend on the production angle of the n_1n_2 pair in the nd breakup reaction. In order to investigate the influence of possible 3N force effects on a_{nn} determinations from kinematically complete nd breakup experiments, we plan to measure the 1S_0 nn final-state interaction (FSI) cross section simultaneously at several production angles of the n_1n_2 pair.

The experimental arrangement at TUNL has been finalized and is shown in Figure 2.2-6. The breakup process will be initiated by 13 MeV neutrons incident on a liquid deuterated scintillator (C_6D_{12}). Neutron pairs traveling to the right with respect to the incident neutron beam will be detected at 25° , 30° , 35° and 40° lab. Here, one of the two neutrons will be detected in one of the transmission detectors T_i , while the other neutron will pass through it towards the end detector D_i . Neutron pairs traveling to the left side will be detected at 15° , 22.5° , 30° , and 37.5° lab. Here, one neutron will be detected in the ring detector R_i , while the corresponding second neutron will pass through the central (open) part of the ring detector toward the associated end detector D_i . The transmission and ring detectors have been designed and constructed. These liquid scintillation (NE213) detectors are presently being tested. They are displayed in Figure 2.2-7. We will measure the neutron detection efficiency of these special detectors in August 1993 at the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany. There, the $^3H(p,n)^3He$ and $^2H(d,n)^3He$ monoenergetic neutron source reactions will be used to measure the absolute neutron detection efficiency above $E_n = 1.2$ MeV. For lower neutron energies we will use the calibrated ^{252}Cf fission source of the PTB. Figure 2.2-5 of Section 2.2.3 shows the sensitivity of the 1S_0 nn FSI cross section at 25° (lab) to changes in a_{nn} . As can be seen, the sensitivity $d\sigma(\theta)/da_{nn}$ at the peak of the FSI peak is about 1 mb/fm. However, due to the finite geometry of the experimental setup, the actual sensitivity is about a factor of two smaller, indicating that the absolute neutron detection efficiency must be known very well. The actual a_{nn} experiment is scheduled to run in 1994.

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Figure 2.2-6 Experimental arrangement for TUNL kinematically complete nd breakup experiment for determining the neutron-neutron scattering length a_{nn} .

Figure 2.2-7 Transmission detector (left side) and ring detector (right side).

2.3 Reactions between Deuterons and Very Light Nuclei

2.3.1 Three-Nucleon-Force Effects and the $A_y(\theta)$ Puzzle in n-d Elastic Scattering

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The extensive comparison of neutron-deuteron (nd) and proton-deuteron (pd) elastic scattering data with results of rigorous three-nucleon (3N) scattering calculations using realistic nucleon-nucleon (NN) interactions has convincingly revealed that the dynamics of such processes is governed by the simple mechanism of three pairwise interacting nucleons.[Glö90] The predictions of realistic NN potentials are in excellent agreement with nd total and differential cross-section data. Furthermore, if one neglects the forward scattering (Rutherford) angular range, pd data are equally well described, especially the tensor analyzing powers (in dp scattering) and polarization transfer data. The only exception is the nd (and pd) analyzing power $A_y(\theta)$ at energies below about 30 MeV. Here, a 25% discrepancy exists between data and 3N calculations at the maximum of $A_y(\theta)$ near $\theta_{c.m.} = 120^\circ$. This discrepancy, based almost entirely on TUNL nd $A_y(\theta)$ data, has recently been shown at Wisc to extend also below the nd breakup threshold, $E_n^{lab} = 3.33$ MeV [McA93].

It has been argued [Gib92] in the past that the nd $A_y(\theta)$ problem might be interpreted as a clear indication of the breakdown of the simple dynamical model of pairwise interacting nucleons and that additional dynamics, i.e., 3N forces, are required to solve the $A_y(\theta)$ puzzle. Very recently, the Bochum group presented the first rigorous calculations of 3N scattering observables [Hüb93] where the 2π -exchange based Tucson-Melbourne 3N force [Coo81] was added to the Bonn-B [Mac89] 1S_0 and 3S_1 - 3D_1 NN interactions. Some of the early calculations were performed by H. Witala in fall 1992 at TUNL on the Cray Y-MP at Research Triangle Park. During his recent visit at TUNL in the Spring of 1993, H. Witala extended these calculations and included 2N and 3N forces in all partial-wave states with two-nucleon total angular momentum $j \leq 2$. This breakthrough allowed, for the first time, the realistic calculation of $A_y(\theta)$ with a 3N force added to the dominating NN interaction. For computational reasons, these first calculations have been performed below the nd breakup threshold. Figure 2.3-1 shows the calculated $A_y(\theta)$ in comparison to the $A_y(\theta)$ data of [McA93] at $E_n = 3.0$ MeV. The dashed-dotted and dotted curves are results of calculations where the 2π -exchange 3N force was added to the Bonn-B NN interaction. Surprisingly, the addition of the 3NF makes the discrepancy between data and calculations even larger. Similar to 3N bound-state calculations, the effect of the 3NF depends on the cut-off parameter Λ_π used in the π NN form factor. Here μ denotes the pion mass. The solid curve is the result of a rigorous 3N calculation using the Bonn-B NN interaction only. The dashed curve is based on the modified 3P_J interactions as proposed by Witala, and Glöckle.[Wit91]

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However, these 3P_J interactions are characterized by a large CIB, in contradiction to recent meson-theoretical studies.[Li92]

In the future, these 3NF calculations will be extended to energies above the nd breakup threshold. In addition, the π -p and ρ -p 3NF will be included. Although these type of 3NF do not play a major role in 3N bound-state calculations, their influence on scattering observables is presently unknown.

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Figure 2.3-1 The nd analyzing power $A_y(\theta)$ (solid dots) at $E_n = 3$ MeV in comparison to theoretical predictions. The solid curve is the result of a rigorous 3N calculation using the Bonn B NN potential. The curve that reproduces the data almost perfectly is obtained from the charge-dependent pp and np modifications of the 3P_J phase shifts [Wit91]. Finally, the dashed and dashed (short dashes) curves are results obtained by adding to the Bonn B NN potential the 2π -exchange Tucson-Melbourne 3N force with $\Lambda_\pi = 4.1\mu$ and 5.8μ , respectively.

2.3.2 Resolution of Discrepancy Between Back-Angle Cross-Section Data for n-d Elastic Scattering

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The analysis of our differential cross-section measurements for neutron-deuteron elastic scattering at low energies is completed and a manuscript has been submitted to Few-Body Systems. The abstract for the paper follows.

High-accuracy differential cross-section $d\sigma(\theta)/d\Omega$ data for neutron-deuteron (n-d) elastic scattering to backward angles in the range from 140° - 178° c.m. have been measured at incident neutron energies of 8.0, 10.0, and 14.0 MeV. The measurements were made by detection of the recoil deuteron from a mixed CD_2 - CH_2 target foil. The data are compared to existing data and to three-nucleon calculations which use the Bonn-B nucleon-nucleon potential. We conclude that the present data unambiguously resolve the discrepancy between previously reported $d\sigma(\theta)/d\Omega$ data for n-d elastic scattering to backward angles.

2.3.3 Test of Nonrelativistic Rigorous n-d Elastic Scattering Calculations at Incident Neutron Energies above 70 MeV

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The analysis of our differential cross-section measurements for neutron-deuteron elastic scattering at incident neutron energies between 70 and 230 MeV is completed and a manuscript has been submitted to Physics Letters. The abstract for the paper follows.

Differential cross-section $d\sigma(\theta)/d\Omega$ data for neutron-deuteron (n-d) elastic scattering to backward angles in the range from 150° - 176° c.m. have been measured at incident neutron energies between 70 and 230 MeV using the continuous energy neutron beam at the LAMPF/WNR facility at the Los Alamos National Laboratory. For normalization purposes, the measurements were made by concurrent detection of recoil deuterons and protons from a CD_2 and a CH_2 foil mounted in a multi-target assembly. At neutron

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energies below 100 MeV the data were summed over a 5-MeV interval, between 100 and 160 MeV the data were binned in 10-MeV intervals, and above 160 MeV a 20-MeV energy bin was used. The data are consistent with existing nucleon-deuteron (N-d) elastic scattering data. The agreement between these data and nonrelativistic rigorous n-d calculations suggest that relativity is not important for the elastic N-d $d\sigma(\theta)/d\Omega$ up to a 3N c.m. energy of 150 MeV.

2.3.4 Monte Carlo Simulation of Kinematically Complete n-d Breakup

Experiment

W. Tornow

As outlined in detail in TUNL XXXI, p. 180, a sophisticated Monte-Carlo simulation of the experimental setup is required in order to compare the experimental data to rigorous three-nucleon (3N) calculations using realistic nucleon-nucleon (NN) interactions. By far the largest correction that has to be applied to the $n+d \rightarrow n_1+n_2+p$ cross-section data is due to the attenuation of both the incident neutron n and the breakup neutrons n_1 and n_2 . At TUNL the breakup reaction takes place in a C_6D_{12} liquid scintillator encapsulated in a cylindrical 4-cm diameter x 6-cm high glass container of wall thickness 0.15 cm. Figure 2.3-2 shows the calculated point-geometry cross section along the kinematically allowed locus (S-curve) for the space-star configuration of the three outgoing nucleons for $E_n = 13$ MeV using the Bonn-B NN potential. The rigorous 3N code of the Bochum group [Wit91] has been used for this calculation. Figure 2.3-3 (solid curve) displays the calculated Monte Carlo result for the total neutron transmission along the "average" S-curve using the TUNL geometry. As can be seen, correction factors of up to about 3 have to be applied to the data. In the calculations, the experimental 0.5-MeV bias has been used for the neutron detectors. Therefore, the calculated transmission is restricted to parts of the S-curve only. As expected, the largest correction is due to deuterium (dashed curve), while the air between the C_6D_{12} scintillator and the neutron detectors contributes only to a very small extent (dotted curve). Clearly, the glass container cannot be neglected, as can be seen from the second curve (from the top) in Figure 2.3-3. The structure in the total transmission is mostly due to the structure in the $n-^{12}C$ total cross section. The carbon contribution is shown by the dashed-dotted curve.

As can be seen from Figure 2.3-5, the correction factors are not as large for the collinear configuration of the outgoing nucleons. Nevertheless, correction factors up to 2.5 must be applied. Again, due to the 0.5-MeV bias in the neutron detectors, the left part of the S-curve (see Figure 2.3-4) is experimentally not accessible.

[Wit91] H. Witala, private communication, 1991.

Figure 2.3-2 Calculated point geometry nd breakup cross section for the space-star configuration of the outgoing nucleons.

Figure 2.3-3 Calculated neutron transmission factors for the space-star configuration using the TUNL nd breakup geometry.

Figure 2.3-4 Same as Figure 2.3-2 for collinear configuration.

Figure 2.3-5 Same as Figure 2.3-3 for collinear configuration.

2.3.5 Search for Three-Nucleon Forces Using the n-d Breakup Reaction

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Possible evidence for the influence of three-nucleon forces (3NF) dates back to the observation that two-nucleon (2N) force models fail to predict the triton binding energy, with realistic model underbinding it by about 1 MeV. The addition of three-nucleon (3N) potentials demonstrated that the problem could be remedied. However, because most 3N potentials that were able to fix the binding energy problem did not have firm connections to realistic nucleon-nucleon (NN) forces, the solution was not convincing evidence of 3N force effects. The more sophisticated 3N calculations that include 3NF underbind the triton even more than calculations using only 2N forces [Pic92]. This underbinding results from the competition between the repulsive Δ dispersive effects and the attractive 3NF. The triton binding energy has also been demonstrated to be sensitive to the strength of the NN tensor force, which is not well determined at low energies [Gib88]. Calculations using NN potentials with untraditionally weak tensor forces, such as the Bonn-A potential [Mac89], give an impressively close prediction of the triton binding energy. The situation surrounding the long-standing triton binding energy problem is quite controversial, with each proposed solution containing questionable speculations.

As an alternative to using the 3N bound system, attention has been given to 3N continuum observables for probing for 3N force effects. Huber, Witala, and Glöckle [Hub93] conducted a theoretical study of the influence of 3NF on cross sections for the $n+d \rightarrow n+n+p$ breakup reaction in several exit-channel configurations. Their calculations were done using the Bonn-B 2N potential and the Tucson-Melbourne 2π exchange 3NF. At an incident neutron energy of 10 MeV they found as much as a 10% effect in the space star configuration. The momentum vector of the three emitted nucleons in the star configuration have equal magnitude and are separated by 120° in the c.m. system. In the space star the momentum vectors lie in a plane perpendicular to the incident beam direction while in the coplanar star the plane formed by the momentum vectors contains the beam axis. Witala et al. [Wit88] showed that the cross section for the star configuration is insensitive to differences between realistic 2N potential models, thus making this observable a prime candidate for revealing the influence of 3NF. The cross-section data of Strate et al. [Str88] at an incident neutron energy E_n of 13.0 MeV for the space and coplanar star configurations are about 25% larger than predicted by calculations which use only 2N forces. If the data of Strate et al. are correct, this would be the most definitive evidence of 3N force effects.

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Figure 2.J-6 Experimental setup for the $^2\text{H}(n, nnp)$ cross-section measurements. The scale is indicated on the drawing. Details are given in the text.

In 1990 we started developing a collimated neutron beam facility to verify the results of Strate *et al.* [Str88] at $E_n = 13$ MeV. The experimental setup for the kinematically overdetermined cross-section measurements of the $^2\text{H}(n,nnp)$ breakup reaction is shown in Figure 2.3-6. The incident neutron beam is produced using the $^2\text{H}(d,n)$ source reaction. The neutron production target is a 3-cm long water cooled deuterium gas cell. The cylindrical wall is made of copper for good heat conduction to the water lines, and the beam stop is made of gold to provide good heat conduction with minimum background in the neutron beam. The beam was collimated to uniformly illuminate the scatterer while reducing the neutron flux outside the central beam by more than a factor of 5,000 for 13-MeV neutrons. The scatterer is a C_6D_{12} deuterated scintillator (NE-232) with dimensions 4-cm diameter x 6-cm high.

The production runs at TUNL, totaling 1465 hours of beam, are completed. We have measured relative cross sections for 46 kinematical configurations to a statistical accuracy of about $\pm 4\%$ for 0.5-MeV bins along the kinematic locus. The breakup data will be normalized to neutron-deuteron elastic scattering, which was measured simultaneously with the breakup data. An absolute normalization requires knowledge of the neutron detector efficiency of one of the detectors in the coincidence pair over the neutron energy range covered by the kinematic locus. The relative efficiencies of the 11 detectors have been measured using a ^{252}Cf source embedded in an argon gas scintillator [How92]. Two independent methods will be used to determine the absolute detector efficiency of three of the detectors in the array. The 0° and 60° neutrons from the $^2\text{H}(d,n)$ reaction, which has a well-known cross section, has been used to calibrate the detector efficiencies at discrete energies in the range from 5.5 to 13.0 MeV. The results obtained using neutrons from the $^2\text{H}(d,n)$ reaction are shown in Figure 2.3-7. These results will be checked using the specially designed ^{252}Cf source, which is mounted inside a thin-walled ionization chamber, at the Physikalische-Technische Bundesanstalt in Braunschweig, Germany. The detectors will be shipped to Braunschweig in July 1993 for calibration. W. Tornow and D. Gonzalez Trotter will travel to Braunschweig to assist in the calibration.

Monte Carlo codes are being developed to simulate the experiment. These codes will be used to smear the 3N calculations into the finite geometry and energy resolution of the experimental setup so that the data and calculations can be projected onto the point-scattering locus using the same algorithm. Since the data and theory will be projected in the same way, the normal ambiguities in regions along the locus where one kinematic variable changes rapidly as a function of the others will be avoided.

Our schedule is to finalize the analysis of the star and collinear (the three outgoing nucleons form a line in the c.m. system) configurations during the fall 1993. The analysis of the other configurations will start in the Spring 1994.

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Figure 2.3-7 Neutron detector efficiency data measured using the $^2\text{H}(d,n)$ source reaction. The curves are predictions using the Monte-Carlo code from the PTB group in Braunschweig, Germany. The calculations represented by the solid and dashed curves have been multiplied by 1.05 and 0.95, respectively, to fit the data.

2.3.6 Proton-Deuteron Elastic Scattering at Very Low Energies***T.C. Black, H.J. Karwowski, E.J. Ludwig, W.J. Thompson***

Within the past decade, advances in computational techniques have made it feasible to perform exact calculations of a large number of observables for three-body systems which manifest the Coulomb interaction. These have included calculation of ^3He wavefunctions and related observables [Pay80, Fri88A, Fri88B, Fri88C, Doy92] and low-energy proton-deuteron elastic scattering parameters and observables [Fri90, Ber86, Ber90, Che89, Che91, Ber88, Fri83].

Of all these observables, the set of low-energy proton-deuteron scattering lengths present the theorist with the smallest number of uncertainties, ambiguities and computational complications. Furthermore, the success of the neutron-deuteron scattering length calculations in replicating the experimental data suggest that the nuclear component of the calculation is well-understood. A similar success in replicating experimentally determined p-d scattering lengths would inspire confidence that the Coulomb interaction can be reliably treated in the framework of the Faddeev equations.

A number of calculations of the low-energy proton-deuteron elastic scattering parameters have been performed over the last ten years, primarily by the Los Alamos-Iowa collaboration, who employed a configuration-space method [Fri83, Che88, Che89, Fri90, Che91] and by the group at Graz, whose calculations were rendered in momentum space [Ber86]. The results of these calculations are remarkably consistent—The Graz group calculated the scattering lengths using a set of parameterized Yamaguchi potentials which incorporated tensor forces. The set of parameters which best replicates the accepted neutron-deuteron scattering lengths yielded spin doublet and quartet proton-deuteron scattering lengths of $^2a_{pd} = 0.257 \pm 0.098$ fm and $^4a_{pd} = 13.68 \pm 0.12$ fm.

The Los Alamos-Iowa collaboration has reported a number of values. A representative set of scattering lengths was obtained by extrapolating calculations performed at finite energies to the two-body threshold, utilizing the MT I-III potential [Che89]. These are $^2a_{pd} = 0.17$ fm and $^4a_{pd} = 13.8$ fm.

On the basis of such energy-dependent calculations, both groups predict the existence of a pole in the doublet S-wave effective range function, analogous to a pole which is known to exist in the neutron-deuteron doublet S-wave effective range function at a virtual state energy of $E_v = -160$ keV. The Los-Alamos group estimates the p-d pole to lie at -25 keV, whereas the Graz work reports the pole lying at -37 keV. The corresponding values of these scattering parameters obtained from extrapolating to zero energy the results of phase shift analyses of the existent experimental data are:

Analysis	$^2a_{pd}$ (fm)	$^4a_{pd}$ (fm)	Minimum energy included in analysis
[Van67]	1.3 ± 0.2	$11.4 + 1.8 - 1.2$	1.51 MeV
[Arv74]	2.73 ± 0.10	$11.88 + 0.4 - 0.1$	1.0 MeV
[Hut83]	$4.0 + 1.0 - 0.67$	$11.11 + 0.25 - 0.24$	0.4 MeV

If, as the Faddeev calculations suggest, there exists a pole in the effective range function for the doublet S-wave phase shift, then this parameter cannot be reliably extrapolated to zero energy without considering data in the energy regime where the curvature in the effective range function becomes evident; namely at proton energies below 300 keV.

Therefore, to obtain an accurate determination of the doublet scattering length, (and the quartet scattering length as well, since an error in determining one can be largely compensated in the spin-averaged cross section by an error in the other), it is necessary to measure differential cross-sections at proton energies below 400 keV to a very high accuracy. In addition, it may be necessary to measure polarization observables as well.

In the past year, we have performed computer simulations of differential cross-sections, using the various sets of scattering lengths. These indicate that it will be necessary to measure the absolute differential cross-sections to an accuracy of better than 3% in order to unambiguously discriminate between the competing sets of scattering lengths. Since the cross-sections are very large, it is predicted that statistical accuracy will not be a limiting factor. Systematic errors will dominate, owing to the confluence of the difficulties inherent in measurement of absolute cross-sections for elastic scattering processes.

The systematic errors arising from uncertainties in the determination of beam integration, solid angle and target thickness, as well as the errors associated with the finite energy spread of the beam and energy loss and straggling in the target can be minimized by measuring the cross-section of interest with respect to the cross-section of some other reaction whose angular distributions are well known. The reference reaction we have chosen for this purpose is the elastic scattering of protons from ^{12}C . Very thin solid hydrocarbon targets can be made (though not easily) and since the resonance structure of the $^{12}\text{C}(p,p)^{12}\text{C}$ reaction has been mapped out extensively [Ajz91], it is possible to use R-matrix theory to obtain a reliable determination of these cross-sections.

In the past year we have made a number of measurements of the $^{12}\text{C}(p,p)^{12}\text{C}$ angular distribution at various energies in order to verify the utility of the existing R-matrix parameters in predicting proton-carbon cross-sections at lower energies. The agreement of our data with single-level theory is only marginally adequate. We are currently working to modify our R-matrix code so as to incorporate the influence of more distant levels, especially the ^{13}N ground-state level, which has been found by other

workers to be important in obtaining a good fit to the data at low energies [Mey76]. The difficulty is compounded by the presence in our carbon targets of un-identified contaminants. We hope to be able to produce carbon foils free of heavy contaminants by the same method we have developed to produce our deuterated targets.

Although systematic errors can be minimized by utilizing the "comparison method", diligence must be applied in further reducing their influence if we are to achieve the requisite accuracy. The most disruptive source of error we have yet identified is the finite energy width of the beam, due to energy straggling in the minitandem accelerator stripper foil and straggling in the target itself.

The simpler task has been to limit the energy spread of the beam incident upon the target. By appropriate adjustment of the analyzing magnet object and image slits, we have been able to achieve a substantial increase in the ratio of signal-to-background in our spectra. Limiting straggling in the target is a far more difficult task, but we can report substantial progress in this area as well. Our initial efforts focused on attempts to produce very thin deuterated polyethylene films. Unfortunately, we were never successful in making such films sufficiently thin.

Our more recent efforts have concentrated upon the production of amorphous hydrogenated carbon films, known colloquially as "cracked ethylene" foils. Very thin films prepared by cracking a hydrocarbon gas in a DC glow discharge have been used for many years now as stripper foils for heavy-ion accelerators. These films are known to contain a substantial complement of hydrogen, are very durable under ion irradiation, and can be made very thin [Huc81]. A DC glow discharge reactor has been built and is now operational. We have very recently been successful in producing thin self-supporting films by this method. Preliminary analysis of the composition and thickness of these films indicate that they will be sufficient for our purposes. Provided that more detailed analysis sustains this judgment, we will be ready to begin acquisition of production data in the very near future.

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Table 2.3-1 List of coincidence particle-angle pair settings in the $\vec{d}+d \rightarrow d+p+n$ asymmetry measurements. The + and - refer to left and right scattering respectively and the angle θ is the lab scattering angle.

Deuteron-Proton		Deuteron-Neutron		Proton-Neutron	
θ_d (deg)	θ_p (deg)	θ_d (deg)	θ_n (deg)	θ_p (deg)	θ_n (deg)
± 17.0	± 17.0	± 17.0	± 17.0	± 17.0	± 17.0
± 19.4	± 19.4	± 17.0	± 34.5	± 17.0	± 34.5
		± 19.4	± 28.9	± 19.4	± 28.9
± 10.0	± 10.0				
± 10.0	± 41.2				
± 17.0	± 17.0				
± 17.0	± 34.5				
± 34.5	± 17.0				

2.3.7 Analyzing Powers in the $\vec{d}+d \rightarrow d+p+n$ Reaction at 12 MeV

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We have made measurements at TUNL of the vector and tensor analyzing powers A_y , A_{yy} , and A_{zz} for d-p and d-n quasi-free scattering (QFS) in the $\vec{d}+d \rightarrow d+p+n$ breakup

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reaction. Although there exist cross-section data for deuteron-nucleon QFS in the d+d system [Val72, Fuk89], prior to the present work and the recent d-p A_y measurements of Fukunaga *et al.* at 60 MeV [Fuk89], data for spin observables for this reaction did not exist. The present measurements were conducted using a 12-MeV tensor-polarized deuteron beam incident on a deuterium-filled gas cell. The momenta of two (d-n, d-p, or p-n) of the three outgoing particles were measured in coincidence, thereby completely defining the reaction kinematics. A list of the angle pairs measured in this work is shown in Table 2.3-1. A portion of these data were used in a charge-symmetry breaking study [How93].

The proper interpretation of these data requires 4N continuum calculations. Such calculations for spin observables are presently unavailable. Two groups, one at the University of Lisbon and the other at the University of Bochum, are independently working on solving the 4N problem at energies above the deuteron breakup threshold. We are collaborating with both groups. Antonio Fonseca from Lisbon visited TUNL in February 1993 to continue development on his 4N code. While at TUNL he assisted in the development of a computer code to calculate spin observables using a plane-wave impulse approximation (PWIA) for the $d+d \rightarrow d+p+n$ breakup reaction. The code is an improvement over our other PWIA codes [How91] because it uses the full spin and momentum space of the 4N system with the correct symmetry properties for interchange of particles. With the new code the spin observables can now be calculated correctly. After testing is completed, this code will be used to analyze our breakup data.

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2.3.8 A Novel Probe of Charge Symmetry Breaking: Deuteron-Induced Breakup

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The analysis of the charge-symmetric analyzing power data for the $\vec{d}+d \rightarrow d+p+n$ breakup reaction at an incident deuteron energy of 12 MeV is completed. A manuscript has been submitted to *Phys. Rev. C*. The abstract for the paper follows.

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The present paper identifies unique symmetry properties of the $\vec{d}+d \rightarrow d+p+n$ breakup reaction that make it an excellent probe for studying charge-symmetry breaking. Measurements were made for two configurations of the ejected particles in the breakup reaction to obtain values of the spin observables A_y , A_{yy} and A_{zz} . These observables are compared for the mirror reactions ${}^2\text{H}(\vec{d},dp)n$ and ${}^2\text{H}(\vec{d},dn)p$ for the two reaction conditions $(\theta_d, \phi_d; \theta_N, \phi_N) = (17.0^\circ, 0^\circ; 17.0^\circ, 180^\circ)$ and $(17.0^\circ, 0^\circ; 34.5^\circ, 180^\circ)$ for an incident deuteron energy of 12 MeV. Similarities of the observables for these reactions are noted. In addition, spin observables for the ${}^2\text{H}(\vec{d},pn)d$ reaction at $\theta_p = \theta_n$ and $\phi_p = \phi_n + 180^\circ$ are shown to provide a particularly good test of charge symmetry. Our A_y , A_{yy} , and A_{zz} data for the ${}^2\text{H}(\vec{d},pn)d$ reaction at $(\theta_p, \phi_p; \theta_n, \phi_n) = (17.0^\circ, 0^\circ; 17.0^\circ, 180^\circ)$ are used to illustrate this latter point. Of the ten charge-symmetric sets of observables measured, two were found to differ by 2.5 standard deviations, suggesting a need for further studies.

3. DYNAMICS OF VERY LIGHT NUCLEI

3.1 Measurements of D States of Very Light Nuclei by Transfer Reactions

Reactions in which one or more particles are transferred to incident tensor-polarized deuterons to form composite-light nuclei can be analyzed to test models of the wave functions of the nuclei involved. These reactions have strong sensitivity to the non-spherical or D-state components of the composite nuclei. Parameters which have been found to be dependent on the D state are the asymptotic D- to S-state ratio, η , and the D_2 parameter. Theoretical predictions of η and D_2 for tri-nucleon systems have improved dramatically over the last decade, and very precise measurements are now required to distinguish between the various nucleon-nucleon (NN) interaction models.

One component of our program involves the precise determination of η for mass-3 nuclei using measurements of tensor-analyzing powers for (d,t) and (d, ^3He) reactions at sub-Coulomb energies. The α -particle D state is still difficult to parameterize, although (d, α) reactions can be analyzed using realistic α -particle wavefunctions to check the validity of D-state predictions. We have tested calculations of these D-state components in cases where there is already sufficient information about the structure of the target nucleus.

3.1.1 The D State of ^3H Using Sub-Coulomb (d,t) Reactions. B. Kozłowska, Z. Ayer, H.J. Karwowski, E.J. Ludwig

Our purpose is to obtain a precise determination of the D- to S- state ratio, η , for the triton using (d,t) reactions at sub-Coulomb energies. In the past year most of the effort was spent on theoretical analysis. The only angular distribution measurement taken this year was for A_{zz} in the $^{149}\text{Sm}(d,t)^{148}\text{Sm}$ reaction at a deuteron bombarding energy of 6 MeV, 43% below the Coulomb barrier, which completed the data set.

The analysis was done using exact finite-range DWBA calculations performed with the code PTOLEMY. It is well known that tensor analyzing powers (TAP) calculated in the DWBA framework are sensitive to the choice of parameters for the T_R tensor potential in the entrance channel. This sensitivity of calculated TAP to T_R parameters lessens with decreasing deuteron bombarding energy. The starting point for the sub-Coulomb analysis was the folding model T_R [Kea73] which yields for depth, radius and diffuseness: $V = 7.6$ MeV, $r = 1.14$ fm, $a = 1.02$ fm, $W = 1.0$ MeV, $rw = 1.29$ fm, $aw = 0.87$ fm.

In studies of (d,d) and (d,p) sub-Coulomb reactions the strength of the calculated real or imaginary part of the folding-model potential is often reduced or set to zero [Rod90, Kam85]. In our studies of (d,t) reactions at energies about 40% below the Coulomb barrier (V_C) different modifications of the folding model T_R cause a 2% uncertainty in the determination of η , but at energies about 13% below V_C this

uncertainty rises to ~10% with the extreme – and perhaps unrealistic – variations mentioned above. Since our data were taken within the range 13-43% below V_C , it is necessary to perform a careful investigation in order to find the consistent set of tensor potential parameters.

A reasonable approach to determine the unambiguous optical model potential parameters is to fit the calculated cross section and TAP to deuteron elastic scattering data. There exists very limited (d,d) data sets at sub-Coulomb energies as listed below:

Reaction	Energy [MeV]	Reference
$^{208}\text{Pb}(d,d)^{208}\text{Pb}$	8.9,10	[Kam85],[Knu75], [Mur88]
$^{90}\text{Zr}(d,d)^{90}\text{Zr}$	5.5	[Knu75]
$^{136}\text{Xe}(d,d)^{136}\text{Xe}$	5.5	[Rod90]

We found that in order to fit the elastic scattering data the strength of the tensor potential calculated from the folding model needs to be reduced either in the real or imaginary part while keeping the geometry fixed. By fixing the real part and varying the imaginary part and vice-versa we extracted the limits on the potential depths which give reasonable fits to the data: $V_1 = 7.6$ MeV, $W_1 = 0.3$ MeV and $V_2 = 3.0$ MeV, $W_2 = 1.0$ MeV. The T_R potentials with V and W varying smoothly between these limits also yielded similar quality fits (see Figure 3.1-1). At present we are calculating the uncertainty in the value of η caused by using the different sets of T_R potential parameters described above.

At very low deuteron energies used in this work there is an additional effect which has to be taken into account. The Coulomb tensor potential (V_Q) [Knu75] arises from the interaction of the deuteron quadrupole moment with the electric field of the target nucleus. The strength of this potential at $r \sim 10$ fm is only few tenths of a percent in comparison with the central Coulomb potential part. For (d,t) reactions carried out at sub-Coulomb energies, the neutron transfer takes place far outside the nuclear surface, where the effects of nuclear forces are small and the projectile is subject mainly to Coulomb distortions. The presence of V_Q increases calculated A_{zz} by 2.5-7% for the sub-Coulomb (d,t) reactions under study, depending on bombarding energy.

Taking into account effects with T_R and V_Q described above, the A_{zz} experimental data for (d,t) reactions on ^{95}Mo , ^{119}Sn , ^{149}Sm , ^{208}Pb for several sub-Coulomb energies have been reanalyzed. These improved analyses will be finished in the near future and the new, highly precise experimental η parameter will be determined.

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Figures 3.1-2 and 3.1-3 show preliminary results of our A_{zz} measurements as a function of c.m. angle for the $^{63}\text{Cu}(d,^3\text{He})^{62}\text{Ni}$ and the $^{89}\text{Y}(d,^3\text{He})^{88}\text{Sr}$ reactions, respectively. The solid curve represents the best fit to the data using the optical-model parameters of Daehnick *et al.* [Dae80]. The result of this preliminary analysis yields $\eta(^3\text{He}) = -0.040 \pm 0.007$ from the fit to the $^{63}\text{Cu}(d,^3\text{He})^{62}\text{Ni}$ data, and $\eta(^3\text{He}) = -0.039 \pm 0.005$ from the fit to the $^{89}\text{Y}(d,^3\text{He})^{88}\text{Sr}$ data. The error in the value of η reflects the uncertainty associated with the measurement only and neglects uncertainties due to the choice of optical potentials including the tensor potential. The preliminary result we obtained previously from A_{yy} and A_{zz} measurements for the $^{93}\text{Nb}(d,^3\text{He})^{92}\text{Zr}$ reaction at $E_d = 12$ MeV was $\eta(^3\text{He}) = -0.037 \pm 0.003$.

During the past year we completed measurements of the differential cross section, VAP and the TAPs A_{yy} and A_{zz} in $^{93}\text{Nb}(d,d)$ elastic scattering at 12 MeV. We are in the process of analyzing the data so as to estimate the effects that the choice of optical potential, including the tensor potential, have on our measurement of $\eta(^3\text{He})$.

Figure 3.1-2 The tensor analyzing power A_{zz} as a function of c.m. angle for the $^{63}\text{Cu}(d,^3\text{He})^{62}\text{Ni}$ reaction at $E_d = 8$ MeV. The solid curve is the result of a finite-range DWBA calculation using $\eta = -0.0399$.

Figure 3.1-3 The tensor analyzing power A_{zz} as a function of c.m. angle for the $^{89}\text{Y}(d, ^3\text{He})^{88}\text{Sr}$ reaction at $E_d = 10.5$ MeV. The solid curve is the result of a finite-range DWBA calculation using $\eta = -0.0392$

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3.1.3 Tests of D State Wavefunctions for ^4He Using (d, α) Reactions

E.R. Crosson, A. Eiro(Lisbon), G. Graw(Munich), S.K. Lemieux, E.J. Ludwig, F.D. Santos(Lisbon) and W.J. Thompson

We have published one paper [Cro92] and had another accepted [Cro93] describing our efforts to investigate realistic microscopic wave functions [Sch86] for the α particle, with emphasis on the D-state component arising from the overlap of the two deuterons. We measured and analyzed TAP in (d, α) reactions that proceed by unnatural-parity transitions without L mixing. Reactions analyzed using exact finite-range DWBA include $^{58}\text{Ni}(d, \alpha)^{56}\text{Co}$ at 16 and 22 MeV, $^{50}\text{Ti}(d, \alpha)^{48}\text{Sc}$ at 16 MeV and $^{48}\text{Ti}(d, \alpha)^{46}\text{Sc}$ at 22 MeV. We find that DWBA analyses of tensor analyzing powers produce satisfactory agreement with the data and that A_{xx} is especially sensitive to the D-state component of α -particle wave functions generated by different realistic nucleon-nucleon interactions.

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3.2 Nuclear Reactions Between Very Light Nuclei

3.2.1 A_{zz} and $A_{xx}-A_{yy}$ for $D(d,p)^3H$ and $D(d,n)^3He$ at 25, 40, 60, and 80 keV K.A. Fletcher, E.J. Ludwig, H.J. Karwowski, W.J. Thompson

We have completed our study of tensor analyzing powers for the $D(d,p)^3H$ and $D(d,n)^3He$ reactions at very low energies and are preparing a manuscript for publication. These data are among the lowest energy analyzing powers ever measured. Most of this work has been described in previous TUNL Progress Reports, so we supply only a brief summary here.

The complexity of the four-nucleon system, even at very low energies, has hindered the development of a satisfactory understanding. Broad and overlapping energy levels in 4He [Til92] permit P waves and D waves to compete with S waves in the $D(d,p)^3H$ and $D(d,n)^3He$ reactions at deuteron energies below 100 keV. Evidence for the P-wave and D-wave contributions includes the angular anisotropy of differential cross section measurements at energies as low as 15 keV [Bro90, Kra87], and the sizable values of vector analyzing powers near 30 keV [Tag92, Bec92]. In past attempts to describe the low energy data, sixteen complex matrix elements have been included [Lem90]. To untangle the numerous matrix elements contributing to these reactions, precise measurements of polarization observables are required to supplement the unpolarized data. To this end, several groups have reported recently on measurements of the vector and tensor analyzing powers at very low energies [Tag92, Bec92, Pfa85].

Such investigations have also been fueled by the suggestion that polarizing the nuclei in a $^3He(d,p)^4He$ fusion reactor might suppress the less efficient $D(d,p)^3H$ and $D(d,n)^3He$ reactions, resulting in a neutron-lean or even neutron-free fusion reactor [Kul82]. For this suggestion to be true, entrance channel quintet S state transitions must be vanishingly small. Analyzing power data provide an indirect means of determining the validity of such a scheme.

We have measured angular distributions for A_{zz} and $A_{xx}-A_{yy}$ at deuteron energies of 25, 40, 60, and 80 keV at the Low Energy Beam Facility (LEBF). Polarized beam was extracted from the TUNL atomic beam polarized ion source, with the beam energy determined by the source frame potential. For this investigation, thin-film targets of deuterated parapolyphenyl (for the 25 keV measurements) and deuterated titanium (for the 40, 60, and 80 keV experiments) were manufactured. The deuterated parapolyphenyl was obtained in powder form from Y. Tagishi of the University of Tsukuba, Japan. To compensate for depletion of deuterium from the targets under bombardment from our 1 to 2- μA beams, the polarization states were switched rapidly. The beam polarization was

monitored continuously by a polarimeter placed at the exit port of the reaction chamber. The polarimeter [Fle93] was based on the $D(d,p)^3H$ reaction and calibrated using the data of [Tag92].

Our results are displayed in Figures 3.2-1 and 3.2-2. These values are consistent with the results of [Tag92], where the complete set of analyzing powers was measured for the $D(d,p)^3H$ reaction only, but disagree somewhat with [Bec92], where all four discrepancies are with the observable $A_{xx}-A_{yy}$ reported in [Bec92]. A comparison between the two reactions based on our data reveals quite small differences throughout our range of energies, as shown in Figure 3.2-3.

With the guidance of G.M. Hale, we have included these data in the R-matrix analysis of the four nucleon system at Los Alamos National Laboratory [Hal91, Hal90] to see how these results affect this global parametrization. The results are shown in Figures 3.2-1 and 3.2-2. The *dashed* lines indicate R-matrix predictions made *before* our data were included, and the *solid* lines indicate R-matrix calculations made *after* our data were included in the parametrization. Based on this R-matrix parametrization with our data included, we have determined that the entrance channel quintet S states are as important to the reaction mechanisms as transitions from the singlet S states, thus supporting the conclusion of other previous analyses [Hof86, Lem90, Sch92] that polarizing the nuclei would not suppress the $D + D$ reaction rates in a fusion plasma.

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Figure 3.2-1 Angular distributions of A_{22} for the $^2\text{H}(d,p)^3\text{H}$ and $^2\text{H}(d,n)^3\text{He}$ reactions at laboratory bombarding energies of 25, 40, 60, and 80 keV. Due to energy-averaging in the targets, the appropriate reaction energies are 21, 39, 55, and 75 keV respectively. The angles are measured in the CM frame. The error bars indicate statistical errors only, and the overall normalization error is 4%. The *dashed* lines indicate the R-matrix predictions made *before* our data were included in the data set. The *solid* lines indicate the R-matrix calculations for this observable *after* our data are included in the parametrization.

Figure 3.2-2 The same as in figure 3.2-1 for the observable $A_{xx}-A_{yy}$. Because of differences in target thicknesses, the bombarding energies 25, 40, 60, and 80 keV correspond to reaction energies of 21, 38, 56, and 76 keV for this observable.

Figure 3.2.3 Comparisons of Legendre function fits to our A_{zz} and $A_{xx}-A_{yy}$ data for ${}^2\text{H}(d,p){}^3\text{H}$ (solid lines) and ${}^2\text{H}(d,n){}^3\text{He}$ (dotted lines).

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3.2.2 ^4He Scattering States from $n\text{-}^3\text{He}$ Spin-Spin Cross Sections

C.D. Keith, D.G. Haase, P.R. Huffman, C.R. Gould, N.R. Roberson, W. Tornow, W.S. Wilburn

We are making measurements at TUNL of spin-dependent total cross section differences, $\Delta\sigma$, for polarized neutrons scattered from a polarized ^3He target. This quantity is expected to provide new information on the structure in the four-nucleon continuum. Results of a comprehensive, charge-independent R-matrix analysis of the $A=4$ system reveal a complicated system of many broad, overlapping states [Til92]. Whether these states are really virtual levels of the ^4He nucleus, or simply artifacts of the partial-wave scattering amplitudes, is not clear. However, polarization experiments can typically provide additional information not available from unpolarized experiments and are necessary for a better understanding of the four-nucleon continuum.

$\Delta\sigma$ is defined as the difference in total cross section between parallel spins minus anti-parallel spins

$$\Delta\sigma = \sigma(\uparrow\uparrow) - \sigma(\uparrow\downarrow).$$

The experiment may be performed with the spins longitudinal or transverse to the incident beam momentum. As detailed in the 1991-1992 TUNL Progress Report, $\Delta\sigma$ may be expressed as a linear combination of the integrated partial wave cross sections. In general the linear combinations are different for the longitudinal and transverse spin geometries. By taking appropriately weighted combinations of $\Delta\sigma_L$, $\Delta\sigma_T$, and the total unpolarized cross section, σ_0 , one can in principle extract information about specific partial waves. For example, we have shown that in the $n\text{-}^3\text{He}$ system, the combination $(\Delta\sigma_T - \Delta\sigma_L)$ is particularly sensitive to the 3P_0 partial wave. Different combinations can be made to emphasize the contribution of other partial waves as well.

$\Delta\sigma$ is determined by measuring the spin-spin asymmetry ϵ . Polarized neutrons are transmitted through a polarized target and detected by liquid scintillators located at 0° with respect to the beam axis. An asymmetry is measured in the number of neutrons detected when the spin of the neutrons is reversed,

$$\epsilon = \frac{N(\uparrow\uparrow) - N(\uparrow\downarrow)}{N(\uparrow\uparrow) + N(\uparrow\downarrow)}.$$

ϵ is typically of order 10^{-2} or less, and it can be shown that

$$\epsilon = -\frac{1}{2} \Delta\sigma \times P_n P_t.$$

Here x is the target thickness expressed in atoms/barn, and P_n and P_t are the polarizations of the beam and target, respectively. To maximize the observed asymmetry, it is necessary to use a relatively thick target. A thickness of $2/\sigma_0$ is ideal. In the case of $n\text{-}^3\text{He}$ scattering, σ_0 is of order 2bn in the 1 - 10 MeV neutron energy range. Gas targets of polarized ^3He typically have thicknesses of 10^{-4} atoms/bn or less, and are unsuitable for the TUNL experiment. The density of solid ^3He is approximately 0.12 g/cm^3 , so that a 2.5 cm long target has an effective thickness of 0.06 atoms/bn; two orders greater than a gas target. Using the brute force method, the solid can be polarized to approximately

40%. Polarized neutrons are obtained using either the $^3\text{H}(\bar{p}, \bar{n})^3\text{He}$ or $^2\text{H}(\bar{d}, \bar{n})^3\text{He}$ reaction.

In order to estimate $\Delta\sigma$ for $n\text{-}^3\text{He}$ scattering, exact calculations have been made based on the scattering matrix elements obtained from the previously mentioned R-matrix analysis [Hal92]. Results are shown in figure 3.2-4. for both the longitudinal and transverse geometries. Similar calculations using the Breit-Wigner single level approximation were presented in the 1991-1992 TUNL Progress Report. Agreement between the BW and exact calculations is qualitatively good. Both indicate a striking difference between $\Delta\sigma_L$ and $\Delta\sigma_T$, centered around 0.6 MeV. This difference is attributable to the $^3\text{P}_0$ partial wave, or, in the BW calculation, to a 0^- resonance located 21 MeV above the ^4He ground state. The emergence of higher partial waves, notably $^3\text{P}_1$ and $^3\text{P}_2$, is reflected in the increase of both $\Delta\sigma_L$ and $\Delta\sigma_T$ to positive values. We believe that a systematic study of these spin-spin observables will provide valuable information on the physics of the ^4He scattering states.

Figure 3.2.4 The spin-dependent, total cross section differences, $\Delta\sigma_L$ and $\Delta\sigma_T$, for polarized neutrons incident on polarized ^3He . Calculated from the R-matrix analysis of the $A = 4$ system [Hal92].

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3.2.3 Realistic Four-Nucleon Calculations: Bound and Scattering States

H. Kamada¹, W. Glöckle¹, C.R. Gould, W. Tornow

The rigorous theoretical treatment of the four-nucleon (4N) system is expected to provide an even more stringent test of our present knowledge of the nucleon-nucleon (NN) interaction than has been obtained from three-nucleon (3N) studies. In contrast to the bound states of the 3N system, the ^4He ground state is characterized by a spatially rather dense nucleon distribution. Furthermore, ^4He is the lightest nucleus with excited states. These states are located above particle thresholds and have rather large widths. While these states are not excited, bound states in the same sense as in heavier nuclei, reproducing the experimentally known level scheme of ^4He using exact few-nucleon techniques is an exciting theoretical challenge.

The theoretical approach of the Bochum group involves the rigorous solution of the 4N Yakubovsky equations using the most realistic NN interaction available. Very recently [Kam93], results for the ^4He ground state have been obtained for the Nijmegen, Paris, Argonne, Bonn-B and Bonn-A NN potentials. Whereas the calculations for the Bonn potentials are in close agreement with the experimental ^4He binding energy, the other NN potentials underbind the ^4He ground state considerably, a result already estimated from variational Monte-Carlo studies [Wir91]. With the availability of rigorous 4N bound state calculations it is now possible to compare the two-body correlation functions for the deuteron, ^3He and ^4He . It turned out that their short-range behavior is nearly identical once the three correlation functions are normalized to each other at their maxima.

The next logical extension of the present 4N studies is the theoretical description of low-energy n - ^3He and d - d scattering below the dnp threshold. A convenient set of coupled equations of the Yakubovsky type has been formulated for the scattering processes of interest. These equations have been extracted from the asymptotic behavior of the 4N Yakubovsky components. Although the equations are equivalent to the well-known AGS formulation, the present approach is a better way of solving the 4N problem, because it does not involve any type of separable approximation. The theoretical studies underway have concentrated on the calculation of the energy dependence of the low-energy (0-8 MeV) n - ^3He phase shifts. The goal is to locate the resonant structures (excited states of ^4He) that have been observed from R-matrix analyses [Hal92]. In the spring of 1993, H. Kamada spent three weeks at TUNL and installed the 4N codes of the Bochum group on the local Cray Y-MP. Similar to the TUNL 3N projects, a close collaboration on 4N projects has been initiated with the Bochum group.

¹ Ruhr-Universität Bochum, Germany

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 [Wir91] R.B. Wiringa, Phys. Rev. C43, 1585 (1991).

3.3 Radiative Capture Reactions with Polarized Sources

3.3.1 Radiative Capture of Protons by Deuterons at Low Energies at $E_d \leq 80$ keV *G.J. Schmid, R.M. Chasteler, M.A. Godwin, B. Rice, D.R. Tilley, H.R. Weller*

We are currently setting up an system to study the $d(\bar{p},\gamma)^3\text{He}$ reaction in the energy region $E_p(\text{lab})=80$ to 0 keV. The motivation for our study is to determine the ratio of E1 to M1 strength in this reaction at stellar energies, where E_p is around a few keV. A previous $d(p,\gamma)^3\text{He}$ experiment to determine this ratio was done in 1963 [Gri63] where unpolarized beam in the energy region $E_p=24$ to 48 KeV was used. The results of this study were extrapolated to stellar energies. Our current work will improve upon this previous work in the sense that we will use polarized beam, and thus be able to measure observables, such as A_y , that are especially sensitive to E1/M1 interference. Previous measurements of the $d(\bar{p},\gamma)^3\text{He}$ vector analyzing power A_y have been made, but the lowest energy measurement [Kin84] was at $E_p=770$ KeV. Our goal is to measure the cross section and vector analyzing power for this reaction in the energy region $E_p=80$ to 0 keV, and then deconvolute the results to produce values of A_y and $\sigma(\theta)$ as a function of energy below 80 keV. This should allow the calculation of the E1/M1 ratio in the stellar energy region. The deconvolution process will be made possible by the use of a high resolution High Purity Germanium (HPGe) detector. The sensitivity of our experiment to the E1/M1 ratio is also greatly aided by the fact that we plan to measure not only the vector analyzing power of the outgoing γ -rays, but also the γ -ray polarization by means of a Compton polarimeter.

The cornerstone to this low energy $d(\bar{p},\gamma)^3\text{He}$ experiment is the HPGe detector that we have recently obtained from ORTEC. The relative efficiency of this HPGe detector, as compared with a $3''\times 3''$ NaI detector, was measured at the ORTEC factory to be 128%. In a test run that we performed in June of 1993 with a ^{60}Co source, the 1.33 MeV line gave a FWHM resolution of 2.0 keV. A sample spectrum from this test run, showing the 1.17 and 1.33 MeV ^{60}Co lines along with the 1.44 MeV ^{40}K line, is shown in Figure 3.3-1. If we assume a $\sqrt{E}$ energy dependence for the FWHM resolution, this would translate into a resolution of about 4.0 keV for the 5.5 MeV γ -rays from the $d(\bar{p},\gamma)^3\text{He}$ reaction. This resolution should allow a deconvolution of the $d(\bar{p},\gamma)^3\text{He}$ γ -ray spectrum that results from the 80 to 0 keV protons stopping in the deuterium target. The result should be a set of data representing $A_y(\theta)$ and $\sigma(\theta)$ in the energy region $E_p(\text{lab}) = 0$ to 80 keV. Note that the $A_y(\theta)$ data, being ratios of cross sections, will be independent of calculations of energy loss, process, while the cross section requires a knowledge of the energy loss as the 80 -keV beam stops in the target.

Figure 3.3-1 High Purity Germanium spectrum for the ^{60}Co lines (1173 KeV and 1332 KeV) and for the ^{40}K line (1460 KeV). The resolution for the 1332 KeV ^{60}Co line was measured to be 2.0 KeV.

The feasibility of using our HPGe detector in a low-energy experiment at TUNL has been demonstrated by a second test run that we also performed in June of 1993. We used the HPGe detector to measure the γ -ray spectrum that results from the $^7\text{Li}(p,\gamma)^8\text{Be}$ reaction, where the beam used was produced by the TUNL atomic beam polarized ion source [Cle90] in an unpolarized mode. The resulting spectrum, obtained in about 6 hours, is shown in Figure 3.2-2. The ground state peak ($E_\gamma = 17.3$ MeV) and the first two escape peaks ($E_\gamma \approx 16.8, 16.3$ MeV) are clearly visible, as is the γ -ray strength leading to the broad 2^+ first excited state at 14.3 MeV. The presence of an anomalous “ghost peak” in the vicinity of the second escape peak is also noted, and we are currently investigating this.

Obtaining an E1/M1 ratio from the $^2\text{H}(p,\gamma)^3\text{He}$ data can be accomplished by an analysis process that involves expanding $\sigma(\theta)A_\gamma(\theta)$ in terms of associated legendre polynomials. If we consider solely E1 and M1 radiation, the expansion for A_γ involves only the b_1 and b_2 coefficients, for which the corresponding associated legendre polynomials have a $\sin\theta$ and a $\sin\theta\cos\theta$ dependence respectively. Using the formalism of [Sey79], it can be shown that the b_1 coefficient for this reaction depends entirely on the interference of E1 and M1 transition matrix elements. Thus, if we measure A_γ at

$\theta_{\text{lab}}=90^\circ$, the result that we get is due entirely to E1-M1 interference, and we can then use the formalism of [Sey79] to determine what E1/M1 ratio gives the observed A_y .

In order to help determine a unique E1/M1 ratio while using the above procedure, we have the advantage of being able to measure the polarization of the outgoing γ -rays by means of a Compton polarimeter. We can also expand the observed γ -ray polarization in terms of the matrix elements present in the $d(\bar{p},\gamma)^3\text{He}$ reaction, and thus we will have additional constraint equations to use in determining the E1/M1 ratio. The Compton polarimeter that we will use is a cylindrical, segmented NaI detector which consists of four equal sized segments (up, down, left, right). The polarimeter will detect Compton scattered γ -rays from the HPGe detector. This Compton polarimeter will surround the HPGe detector, which is also cylindrical, and works by using the sensitivity of the Compton effect to the orientation of the $\vec{E}$ -field vector of the incoming γ -ray. The segmented NaI detector will detect a left-right/up-down asymmetry in the Compton scattered photons (which will be measured in coincidence with the HPGe γ -rays) which is proportional to the γ -ray polarization.

Figure 3.3-2 High Purity Germanium spectrum for the $^7\text{Li}(p,\gamma)^8\text{Be}$ reaction. The ground state peak is visible at ~ 17.3 MeV, the first escape peak at ~ 16.8 MeV, the second escape peak at ~ 16.3 MeV, and the wide first excited state at ~ 14.4 MeV.

This $d(\bar{p},\gamma)^3\text{He}$ experiment, using the HPGe detector and the Compton polarimeter, is scheduled to begin trial runs in the next few months. Preliminary count rate calculations, based on extrapolations of the cross section data of [Gri63], indicate that a count rate on the order of 30 counts per hour for the total, unconvoluted spectrum of γ -rays should be achievable for our experimental set up.

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3.3.2 $H(\vec{d},\gamma)^3\text{He}$ Experiment at $E_d = 80\text{-}330\text{ keV}$

Lijun Ma, H. J. Karwowski, and E. J. Ludwig

The measurement of vector and tensor analyzing power of $H(\vec{d},\gamma)^3\text{He}$ reaction at low energies has great importance for providing insight into the nuclear structure of the few body system, nuclear reaction mechanism, and astrophysical processes [Leh93]. The experiment has been in progress since the assembling and the testing of two large BaF_2 γ -ray scintillators in summer 1992 [Ma92].

In spring 1993, we obtained good quality spectra for $D(p,\gamma)^3\text{He}$ at 80 keV, as shown on Figure 3.3-3 and Figure 3.3-4. The background is largely due to cosmic rays and natural activity of the detector itself. Most of the effort since has concentrated on building the new beamline, target production, and system testing.

The target for the experiment was chosen to be deuterated or hydrogenated titanium, because titanium is good hydrogen absorber and it can bear the high beam current required in this experiment. Two techniques have been used to make the targets. The first one is heating the pure titanium foil inside the evaporator chamber to about 470°C , while bleeding in pure hydrogen gas. The second method is ion-beam implantation. The 8-keV H^+ beam from the UNC sputter-bell facility was used to strike the 1-micron-thick titanium foil to form a titanium hydride target. Both these two methods have advantages and disadvantages. The first is easy to operate, but it is hard to monitor the profile of the hydrogen inside the matrix. The second one was more often used because it can provide a good estimate of the hydrogen concentration in the target. The hydrogen depth profile of the target can be measured by p-p elastic scattering.

All experiments were done using the newly constructed and modified LEBF beam line and scattering chamber, which provided better beam quality and solid angle efficiency for the detectors.

Figure 3.3-3 The $D(p,\gamma)^3\text{He}$ in-beam spectrum with BaF_2 detectors.

Figure 3.3-4 The 5.54 MeV gamma ray peak for $D(p,\gamma)^3\text{He}$ at 80 keV using BaF_2 detectors. The solid curve is the best Gaussian fit of the spectrum after background subtraction.

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3.3.3 Radiative Capture of Tensor Polarized Deuterons on Protons

G.J. Schmid, R.M. Chasteler, M.A. Godwin, D.R. Tilley, H.R. Weller

In the past few years, exact, three body continuum Faddeev calculations have been available for the $p(\bar{d},\gamma)^3\text{He}$ reaction through the work of Lehman and Fonseca [Fon91]. In particular, calculations have recently been performed at $E_d(\text{lab}) = 10, 19.8, 29.2, 45.3$ and 95 MeV in order to compare with data taken at these energies [Goe92, Vet85, Jou86, Pit88]. These calculations were intended to show the necessity of treating both the continuum and final states exactly when doing three body calculations. In addition, the calculations have helped explore the nature of the ^3He D-state, which is responsible for the observed tensor analyzing powers in the $p(\bar{d},\gamma)^3\text{He}$ reaction, and have helped test the sensitivity of observables to the nucleon-nucleon p-wave interaction, which is small compared with the nucleon-nucleon s and d wave interactions. The current experimental work underway is concerned with augmenting existing $T_{20}(\theta)$ data at 19.8 MeV and adding new $T_{21}(\theta)$ data at 18.8 MeV.

Figure 3.3-5 TAC (Time to Amplitude Converter) spectrum for the $p(\bar{d},\gamma)^3\text{He}$ reaction at $E_d(\text{lab})=19.8$ MeV, where the peak position represents the time difference between the detection of the γ -ray and the ^3He recoil. The dashed lines represent the gate that has been set on this peak in order to create a TAC gated energy spectrum.

Figure 3.3-6 The TAC gated energy spectrum for the NaI detector in the $p(\bar{d},\gamma)^3\text{He}$ reaction at $E_d(\text{lab}) = 19.8$ MeV. The γ -ray peak is clearly visible at 12 MeV.

The experimental set up for this $p(\bar{d},\gamma)^3\text{He}$ experiment is based on detecting the outgoing γ -ray and the outgoing ^3He recoil in coincidence. This system, which utilizes a 10"x10" cylindrical NaI crystal complete with anti-coincidence shield and paraffin covering to detect the γ -rays and a fast plastic scintillator to detect the ^3He recoils, can greatly reduce the otherwise large neutron background in our energy spectra. We carry out the coincidence procedure as follows. After the incident deuteron beam passes through the hydrogen gas target, a magnet bends the recoiling ^3He nuclei out of the beam and into the plastic scintillators. We then have a TAC circuit set up between the NaI crystal and the plastic scintillator such that when a γ -ray produced in the $p(\bar{d},\gamma)^3\text{He}$ reaction hits the NaI it will start the TAC and when the corresponding ^3He recoil hits the plastic scintillator it will stop the TAC. The resulting TAC spectrum that is produced (Figure 3.3-5) has a peak whose position represents the time difference between the detection of the γ -ray and the detection of the ^3He recoil, about 70 ns. By gating on this TAC peak, we can choose to look only at γ -rays that have a corresponding ^3He recoil which is detected 70 ns later. Figure 3.3-6 shows the energy spectrum obtained after gating on the TAC peak. The γ -ray peak is quite prominent at 12 MeV.

In 1985, Vetterli published the results of a $p(\bar{d},\gamma)^3\text{He}$ experiment at $E_d(\text{lab})=19.8$ MeV, where $T_{20}(\theta)$ was measured at various angles[Vet85]. This particular beam energy was chosen because it represents the peak of the $p(\bar{d},\gamma)^3\text{He}$ cross section.

Vetterli's data are shown in Figure 3.3-7, represented by the square data points, along with a full, three body Faddeev calculation, represented by the solid line. This Faddeev calculation [Leh93] was done using the Paris potential in the EST approximation [Ern73], and included only the E1 operator. This particular calculation seems to be insensitive to the presence of the nucleon-nucleon p-wave interaction [Leh93]. Calculations using the Born approximation, which do not take into account the initial state scattering, have not been able to match the data nearly as well as this full calculation [Leh93]. The discrepancies between the data and the full Faddeev calculation at front and back angles are thought to be due to the absence of the M1 and E2 terms.

Before the Faddeev calculation is redone with these effects included, which is planned, we plan to remeasure some of the forward-angle data with smaller error bars in order to provide a more stringent test for the forthcoming calculations. To try out our experimental set up, we have already taken some data at the midangles, shown by the open circle data points in Figure 3.3-7, where comparison with theory has been very good. The 19.8-MeV polarized deuteron beam in this experiment was provided by the TUNL atomic beam polarized ion source [Cle90], and was prepared to have a pure t_{20} beam polarization at the target.

Figure 3.3-7 The $T_{20}(\theta)$ data of Vetterli et al. [Vet85] shown along with the current data for the $p(\bar{d},\gamma)^3\text{He}$ reaction at $E_d(\text{lab}) = 19.8$ MeV. The solid line is the exact Faddeev calculation of [Leh] which uses the Paris potential in the EST approximation [Ern73].

Figure 3.3-8 The Faddeev calculation [Leh] of $T_{21}(\theta)$ for the $p(\bar{d}, \gamma)^3\text{He}$ reaction at $E_d(\text{lab}) = 19.8$ MeV. The hypothetical data point at 50° shows the error bars that should be obtainable in about three days of running time ($\Delta T_{21}(50^\circ) = .01$).

In the near future we also hope to measure the $T_{21}(\theta)$ tensor analyzing power at $E_d(\text{lab}) = 18.8$ MeV. This analyzing power, which has been measured at other energies, most recently at $E_d(\text{lab}) = 10.0$ MeV, will be measured at $E_d(\text{lab}) = 18.8$ MeV, as opposed to $E_d(\text{lab}) = 19.8$ MeV because the accelerator stability is currently better at this energy. Having measured the angular distribution for this observable, we will then be able to compare it with the results of a full Faddeev calculation at this energy. A full Faddeev calculation which has already been done at 19.6 MeV for this observable [Leh] indicates an insensitivity to the nucleon-nucleon p-wave interaction, as was the $T_{20}(\theta)$ calculation. This Faddeev calculation for $T_{21}(\theta)$ is shown in Figure 3.3-8, along with a hypothetical data point which shows the error bars that we can expect to obtain in about three days of running time with $\Delta T_{21}(50^\circ) = 0.01$.

Our measurement will, in concert with the $T_{20}(\theta)$ measurement at $E_d(\text{lab}) = 19.8$ MeV, provide a further test for the three-body dynamics in the full Faddeev calculations that are being done. Time permitting, we would also like to take a very accurate data point for $T_{20}(\theta)$ at $E_d(\text{lab}) = 14.0$ MeV for $\theta(\text{c.m.}) = 90^\circ$. These data will help to confirm the role of the p-wave part of the N-N interaction. This is shown in Figure 3.3-9, where the solid line represents a full Faddeev calculation done with

nucleon-nucleon p-waves, and the dashed line without p-waves. Both calculations are from [Leh]. Two data points that have been previously taken, from [Goe92] and [Vet85], indicate that the N-N p-waves are essential here. Additional data should make a quantitative comparison possible.

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Figure 3.3-9 The Faddeev calculation [Leh] of $T_{20}(90^\circ)$ for the $p(\bar{d},\gamma)^3\text{He}$ reaction for a range of possible energies. The solid line represents a calculation that was done that included the n-n p-wave interaction, while the dashed line represents a calculation that did not include the n-n p-wave interaction. The data points are from [Goe92] and [Vet85].

3.3.4 The ${}^4\text{He}(\vec{d}, \gamma){}^6\text{Li}$ Radiative Capture Reaction

M. A. Godwin, R. M. Chasteler, G. J. Schmid, D. R. Tilley, H. R. Weller

We are continuing to study the ${}^4\text{He}(\vec{d}, \gamma){}^6\text{Li}$ reaction. Our first goal is to measure $\sigma(\theta)$, $A_y(\theta)$ and $T_{20}(\theta)$ at $E_d \sim 20$ MeV. Even though this reaction is dominated by E2 radiation at this energy, there are indications of E1 radiation as well [Rob81]. The origin of the E1 radiation is not fully understood, however, it may arise from charge polarization of the deuteron by the ${}^4\text{He}$ target nucleus, as well as the spin-flip ($\Delta S = 1$) isoscalar part of the E1 operator. Knowledge of the angular distribution of the cross section and vector analyzing power should allow us to study the E1-E2 interference effects.

The ground state of ${}^6\text{Li}$ has been investigated theoretically by using a three-body model and leads to a reasonable understanding of the static properties of the system and the ground-state wave function [Leh78, Leh83]. Model calculations show that the α -d cluster consists of both $L=0$ and $L=2$ (D-state) partial waves, with the D-state being sensitive to the tensor force in the nucleon-nucleon interaction, as well as to the $s_{1/2}$ alpha-nucleon interaction. A measurement of the tensor analyzing power $T_{20}(\theta)$ should provide information about the D-state admixture. It is interesting to note that at present there are contradictory theoretical estimates of η , the asymptotic D/S state ratio (intimately related to the

Figure 3.3-10 Top view of the target chamber to be utilized.

quadrupole moment), not only in magnitude but even in sign, and that empirical results are not accurate enough to determine the sign. We hope to shed some light on this situation.

Originally we had planned to utilize a shielded NaI detector in coincidence with two fast plastic scintillators, one to detect ${}^6\text{Li}$ recoils, one to veto scattered deuterons, 2 m downstream of the target [Kra90]. This system was built and tested at $E_d \sim 16$ MeV, but it proved to be too difficult to detect the recoil particles. Even though we now may run beams close to 20 MeV, this technique has still been unsuccessful. It appears that the recoil lithium particles (which come out at ~ 6.5 MeV) lose much of their energy in the target (mostly in the exit window), straggle, and spread out so much that clear identification of them in these scintillators is not possible.

With this in mind, we have developed a new detection technique, where the recoil particles are bent immediately after being produced and are detected using silicon-barrier solid-state detectors, while still in the gas target, as depicted in Figure 3.3-10. Notice the use of two solid-state detectors in a ΔE -E telescope set-up, where the first will detect the ${}^6\text{Li}$ recoils and the second will veto out scattered deuterons and other background. Preliminary Monte-Carlo simulations have been run in an attempt to understand the trajectories of the incident beam and the recoil ${}^6\text{Li}$ nuclei. With a gas pressure of 0.33 atmospheres, the deuteron beam will exit the chamber at a 15° angle and the recoils at a

Figure 3.3-11 Overview of the experimental set up. The lithium recoils will be magnetically deflected and then detected by the solid state detectors, and the deuteron beam will be directed into a beam dump.

30° angle. This corresponds to separation of 3.17 cm at the chamber wall, which provides enough room for detection. Installation is underway and we hope to finish installation and testing and begin data taking by fall 1993. Figure 3.3-11 shows a conceptual view of the apparatus.

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3.3.5 Gamma-Ray Capture of Protons on ^7Li at 80-0 keV

R.M. Chasteler, M.A. Godwin, G.J. Schmid, D.R. Tilley, and H.R. Weller

Since the preliminary feasibility tests mentioned in [Cha92], angular distribution measurements have been made on the $^7\text{Li}(p,\gamma)^8\text{Be}$ reaction. Angles of 0°, 45°, and 90° in the lab frame have been measured. The relative cross sections observed were not isotropic, as previously indicated by Cecil *et al.* [Cec92]. These researchers have interpreted this reaction in terms of pure s-wave (E1) radiative capture. When our data were fit to an expansion in terms of Legendre polynomials ($\sigma(\theta) = A_0[1 + a_1P_1(\cos(\theta))]$) an a_1 coefficient of 0.21 ± 0.022 was extracted.

Measurements of the analyzing power, A_y , were then performed to learn more about the contributing transition-matrix-elements and their relative phases. Negative polarized proton ions were extracted from the ABPIS and their polarization determined by accelerating them through the TUNL FN tandem accelerator and analyzing them with a carbon-foil charged-particle polarimeter [Wil93]. Once the polarization was determined the negative ion beam was steered down the Low Energy Capture Line (LECAL). Fast-spin-flip was used to measure the analyzing power, which switched between opposite spin states every 100 msec. Measurements were performed at 90° and 30° in the lab frame. Analyzing powers, A_y , of 0.259 ± 0.037 and 0.233 ± 0.049 , respectively, were measured. These results, along with the cross section measurements, indicate that the reaction has a substantial non-E1 contribution, since pure E1 would give $A_y(90^\circ) = 0.0$.

Further analyzing powers have been measured at 15° steps from 15° to 120° (all angles in the lab frame). These measurements were sped up by first tuning up the atomic-beam polarized ion source transition units using negative ion beam and using the high energy charged-particle polarimeter [Wil93]. Then the ABPIS was switched to positive ion beam, taking care not to adjust any of the polarization units, and the positive beam tuned down the LECAL where the analyzing power at 90° mentioned above was duplicated. Doing this allowed >6 times the amount of beam on target compared to that obtained using the negative-ion beam. These measurements have yet to be fully

analyzed. Further unpolarized cross section measurements were made in 15° steps at angles between 0° and 120° , to determine the angular dependence of the cross section to higher accuracy.

Preliminary results of these new analyzing power and relative cross section data have given two solutions for the transition-matrix-element fit with similar chi-squares. One result gave an E1 strength of $33.1 \pm 8.6\%$ and M1 strengths of $12.6 \pm 2.3\%$ and $54.3 \pm 9.9\%$, for p-waves of channel spin 1 and 2 respectively, and the other result gave an E1 strength of $6.7 \pm 0.8\%$ and M1 strengths of $17.0 \pm 5.0\%$ and $76.3 \pm 8.4\%$, for p-waves of channel spin 1 and 2. Both results exhibit p-wave strength in disagreement with the interpretation of Cecil *et al.* [Cec92]. These results also show strengths of the p-waves in a ratio of 1/5, within experimental error, as was seen by Mainsbridge [Mai60] at the 441-keV (M1) resonance and down to 200 keV proton lab energy.

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3.3.6 Radiative Capture of Polarized Deuterons by ${}^7\text{Li}$ G.J. Schmid, R.M. Chasteler, H.R. Weller, D.R. Tilley

Our work on this experiment is scheduled to be published in the July 1993 issue of Physical Review C. The abstract is:

The differential cross-section, $p(\theta)$, the vector analyzing power $A_y(\theta)$ and the tensor analyzing power $A_{yy}(\theta)$ have been measured for the ${}^7\text{Li}(\vec{d}, \gamma){}^9\text{Be}$ reaction at $E_d(\text{lab})=6.0$ MeV. The angle-integrated cross section at this energy is estimated to be 4.8 ± 1.0 μb . A transition matrix element analysis has been performed on the data. In addition, a direct-capture calculation has been performed, and is compared to the data.

4. THE MANY NUCLEON PROBLEM

4.1 Nuclear Astrophysics

4.1.1 The $^{17}\text{O}(\text{p},\alpha)^{14}\text{N}$ Measurement

J.C. Blackmon, A.E. Champagne, M.A. Hofstee, M.S. Smith¹, R.G. Downing², R.K. Das

The $E_p = 70$ keV resonance in the $^{17}\text{O}(\text{p},\alpha)^{14}\text{N}$ reaction dominates the reaction rate at stellar energies. A knowledge of this reaction rate would allow one to use observations of the $^{17}\text{O}/^{16}\text{O}$ abundance ratio in the atmospheres of red giant stars to draw conclusions about mass flow and mixing in main-sequence stars. Due to the extremely small proton width, high beam current, target density and detection efficiency are required to measure the resonance strength. A recent search for the resonance [Ber92] reports an upper limit on the proton width of $\Gamma_p \leq 3$ neV, in disagreement with the width, $\Gamma_p = 70 \pm 40$ neV, deduced from the proton stripping reaction $^{17}\text{O}(^3\text{He},\text{d})^{14}\text{N}$ [Lan89]. We wish to measure the proton width of the resonance with neV sensitivity.

Since enriched ^{17}O is in scarce commercial supply, we produced a target by implanting 2×10^{18} oxygen atoms/cm² into a 2mm-thick aluminum backing. With an implanted dose of greater than about 8×10^{17} atoms/cm², it has been shown that a subsurface layer of amorphous Al_2O_3 is formed [Mus85]. Analysis of the target by Cold Neutron Depth Profiling (CNDP) at the National Institute of Standards and Technology showed a uniform layer of $\text{Al}_2[^{17}\text{O}]_3$ with 30-keV thickness for protons. This target was analyzed by CNDP after an accumulated charge of 7 and 24 Coulomb on target. After 7 Coulomb of charge there was no appreciable change in the target composition, but after 24 Coulomb the total oxygen concentration in the target had dropped to less than 3×10^{16} atoms/cm².

The limited data taken with this target, however, have shown that electronic and mechanical improvements have reduced background levels sufficiently to allow neV sensitivity. These improvements include evaporating an aluminum dead layer directly onto the surface of the detectors, cooling the detectors to liquid nitrogen temperatures, and better shielding of the chamber. We have also changed the software to allow anticoincidence to be demanded between all detectors. Demanding anticoincidence results in the rejection of a relatively flat background over most of the entire energy spectrum. Data taken with a ^{10}B target has shown that there is insignificant rejection of real events. With these improvements, the background rate in the region of interest was about 10 counts/keV/Coulomb for the sum of all the detectors, sufficient to allow neV sensitivity in a reasonable amount of beam time.

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Figure 4.1-1. Alpha particle elastic scattering from a WO_3 target at $E_\alpha = 2 \text{ MeV}$ and $\theta_{\text{lab}} = 165^\circ$. The oxide layer (between channels 1300 and 1850) has a thickness of 500 keV for the alpha particles corresponding to a thickness of about 1300 keV for low energy protons.

In addition, the CNDP showed that there exists a small boron contaminant in our beam which is not removed by the TUNL polarized ion source inflection magnet. The buildup of boron in the target over time leads to background from the $^{10}\text{B}(p,\alpha)^7\text{Be}$ reaction in the region of interest in the charge-particle spectrum. We have found that using the Wien filter on the TUNL atomic beam polarized ion source with increased field settings has reduced the beam contaminants significantly, while only decreasing the total beam current by roughly 10%.

We are currently studying oxide targets produced by resistive heating of a metallic backing in an oxygen atmosphere. Targets of Ta_2O_5 have been shown to be stable to very intense proton beams [Bcr92], but the targets are not preferred, since boron is a common contaminant in tantalum. With tungsten backings, we have produced very thick and uniform WO_3 layers, which are believed to be relatively free of boron contamination, but we have found that the oxide layer dissipates under high beam currents due to the localized heating in the first micron of the target. By further cooling the target, we may be able to minimize the oxygen loss in the target.

Such targets are advantageous since the thickness of the oxide layer is easily determined by Rutherford Back-Scattering (RBS) of alpha particles. To assist in the analysis of these targets we have refurbished the TUNL helium negative ion source. This

allows us to analyze targets by RBS of alpha particles while low-energy data are being taken. A sample of such a spectrum is shown in Figure 4.1-1 for a WO_3 target. We are currently working with both of these backings in trying to produce a oxide target which is free of boron contamination and also stable against high beam currents. Use of such a target with the present beam currents and detector efficiencies should give neV sensitivity to the proton width of the $E_p = 70$ keV resonance.

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4.1.2 Explosive Nucleosynthesis

A.E. Champagne

During astrophysical explosions, temperatures are on the order of $(0.2 - 1.5) \times 10^9$ K and average densities can be $10^3 - 10^6$ g/cm³. Under these extreme conditions, nuclear reactions will proceed on time scales of ns - min (though more typically sec - min). Thus, any nuclei produced with comparable half lives will become targets for subsequent nuclear reactions. Measurements of at least some of these reactions are desirable, both from an astrophysical and from a nucleosynthetic perspective: Cataclysmic binaries and Type-I supernovae are powered by these reactions, and so a knowledge of their rates is crucial to an understanding of the outburst mechanism. We are also interested in elemental abundances, particularly of spectroscopic tracers such as ^{22}Na , ^{26}Al and ^{44}Ti . In Type-II supernovae, these reactions are incidental to the outburst, but again nucleosynthesis can provide clues as to the physical conditions during an explosion.

Explosive hydrogen burning will proceed via several reaction cycles and sequences. The CNO isotopes will be processed within the Hot CNO (HCNO) cycles and heavier elements will be produced as a consequence of the rp-process (Figure. 4.1-2) [Wal81].

Crude estimates of reaction rates suggest that the HCNO cycles are responsible for classical novae, while the rp-process produces more energetic outbursts such as fast novae and x-ray bursts. The rp-process is initiated by the sequence $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}(p,\gamma)^{21}\text{Mg}$. Recent progress in our understanding of these two reactions is summarized below.

Figure 4.1-2 The transition from the HCNO cycles to the rp-process. More detailed reaction paths may be found in [Cha92].

4.1.3 Calculation of the $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$ Reaction Rate

B.A. Brown¹, A.E. Champagne, H.T. Fortune² and R. Sherr³

Above the $^{19}\text{Ne} + p$ threshold at 2199 keV, the first known state [Kub89, Lam90, Smi92] is at 2646 keV. This state, which is presumed to be the strongest (p,γ) resonance, is strongly populated in $^{20}\text{Ne}(^3\text{He},t)^{20}\text{Na}$ and has been variously and incorrectly identified as the mirror of the 3173 or 3488-keV 1^+ states in ^{20}F , and even as the mirror of a supposed 1^- state at 3173 keV in ^{20}F [Des90]. Careful comparison of ^{20}F and ^{20}Na , and available data on reactions leading to both, suggests that the 2646-keV state is the mirror of the 2966-keV 3^+ state in ^{20}F . With this identification, the $(t,^3\text{He})$ and $(^3\text{He},t)$ cross sections are consistent [Cla90] and the Coulomb shift is appropriate. Our suggested analog assignments are shown in Figure 4.1-3.

Resonant capture to the 2646-keV state can proceed via a $1d_{5/2}$ proton coupled to the ground state of ^{19}Ne ($J^\pi = 1/2^+$) or via a $2s_{1/2}$ proton coupled to the 238-keV first-excited state ($J^\pi = 5/2^+$) (in principle, other excited states could become important at

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extremely high temperatures). Proton single-particle widths of $\Gamma_{sp}(p_0) = 9.7$ eV and $\Gamma_{sp}(p_1) = 2.1$ eV were calculated within the framework of scattering from a real Woods-Saxon potential ($r_0 = 1.26$, $a = 0.6$ fm). The $l = 2$ spectroscopic factor for $^{20}\text{F}(2966 \text{ keV})$ has been measured [For72, For74] in the $^{19}\text{F}(d,p)^{20}\text{F}$ reaction to be $S = 0.054$. The corresponding shell-model value is $S = 0.068$. For $^{19}\text{Ne}^* + 2s_{1/2}$, we take the shell-model value of $S = 0.35$. Thus we obtain proton widths of $\Gamma_{p0} = 0.52$ eV and $\Gamma_{p1} = 0.73$ eV. Nothing is known of the γ decays of $^{20}\text{Na}(2646 \text{ keV})$. Its mirror has a mean lifetime [Aiz87] of 60 ± 40 fs, decaying primarily via M1's to the 2^+_{11} , 3^+_{11} and 4^+_{11} levels. The shell-model lifetime for this state is 3.5 fs, more than an order of magnitude shorter than the measured value, but consistent within the experimental uncertainty. One prediction of the current work is that if the $^{20}\text{F}(2966 \text{ keV})$ lifetime were to be better measured, a much smaller value should result. Correcting for the E_γ^3 factor and applying a small N,Z correction in the M1 operator [Bro87], the mean lifetime in ^{20}Na should be 5.5 fs, i.e. $\Gamma_\gamma = 0.12$ eV.

Figure 4.1-3 $A = 20$ Mirror pairs.

Table 4.1-1 Summary of resonance parameters for $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$

E_x^a	E_{cm}	J^π	Γ_p	Γ_γ	$\omega\gamma$	$\omega\gamma$	$\omega\gamma$	
(keV)	(keV)		(eV)	(eV)	(this study) (meV)	[Lam90]	(literature) [Kub89]	[Smi92]
2646	447	3 ⁺	$\Gamma_{p0} = 0.52$ $\Gamma_{p1} = 0.73$	0.12	80 37	11.3	6.23	7
2857	658	3 ⁻	0.02	0.02 ^b	≤ 20	19.2	15.95	20
2986	787	1 ⁺	1.0×10^4	8×10^{-3}	2.2	28.8	51.19	70
3056	857	0 ⁺	2.1×10^4	0.01	7.5	12	7.50	7.5

a) [Smi92].

b) Assumed in order to give an upper limit on $\omega\gamma$.

A similar procedure was used to extract resonance parameters for the other nearby states at 2857 keV ($E_{\text{cm}} = 658$ keV, $J^\pi = 3^-$); 2986 keV ($E_{\text{cm}} = 787$ keV, $J^\pi = 0^+$) and 3056 keV ($E_{\text{cm}} = 857$ keV, $J^\pi = 1^+$). These results are listed in Table 4.1-1. The $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$ reaction rate has been calculated using these resonance strengths and the contribution from non-resonant direct capture [Lan86] and is shown in Figure 4.1-4. For reactions involving ^{19}Ne in its *ground state*, the rate is dominated by the 447-keV resonance ($E_x = 2646$ keV). However, by $T_9 = 1$, ^{19}Ne will be in its first-excited state 15% of the time and in its second-excited state 3% of the time. For $T_9 > 2$, the ground-state population falls below 50% of the total. Consequently, we have estimated the resonance strength for population of the 447-keV resonance from the first-state of ^{19}Ne . The other resonances have strengths which appear to be determined primarily by the exit channel (i.e. $\omega\gamma \approx \omega\Gamma_\gamma$) and as a result, they should not change dramatically with temperature unless the proton width is drastically decreased (in which case they will become even less important). Assuming that these latter strengths are in fact unchanged by thermal excitation in ^{19}Ne , an approximate analytic expression for the reaction rate which includes the effects of thermal excitation to the first-excited state (for population of the 2646-keV state) is

$$N_A \langle \sigma v \rangle = 5.45 \times 10^3 T_9^{-1.227} \exp(-4.378/T_9^{1.082}) \text{ cm}^3 \text{ s}^{-1} \text{ mole}^{-1}.$$

This approximation reproduces a more exact calculation to better than 10% over the temperature range $0.25 \leq T_9 \leq 2.0$, and once again the 2646-keV state is the major

contributor to the total rate. For temperatures below this range, the ground-state rate is appropriate, with the contribution from direct capture. Above $T_9 \approx 2$, the population of higher-lying excited states cannot be ignored, so this approximation may not be accurate.

With our new calculations, the rate of the $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$ reaction is increased by about an order of magnitude over earlier results [Kub89, Lam90, Smi92]. However, this increase is not astrophysically significant because the flow into the rp-process is limited by the rate of the (slower) $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$ reaction [Mag90]. For $T_9 = 0.4 - 2$, the (p,γ) rate is 6.0 - 1.6 orders of magnitude greater than the (α,γ) rate, independent of density. In other words, once material is converted into ^{19}Ne , it will be rapidly passed along to higher masses.

Figure 4.1-4 Thermonuclear reaction rate for $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$ under the assumption that ^{19}Ne is in its ground state. Resonance contributions are labeled according to their energy. The direct-capture rate (DC) is from [Lan86].

Experimental verification of our results for the 2646-keV state are desirable and here the increased resonance strength is significant because it leads directly to a corresponding increase in the expected count rate for the $^1\text{H}(^{19}\text{Ne}, ^{20}\text{Na})\gamma$ reaction. Assuming a beam intensity of 1 pA, the 2646-keV state will be produced at a rate of 3860/hr. In addition, our predictions of $J^\pi = 3^+$ and $\Gamma_\gamma\Gamma = 0.09$ can be examined via indirect nuclear spectroscopy. An article describing this work has been submitted to Phys. Rev. C.

4.1.4 Experimental Investigation of the $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$ Reaction Rate

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For a better understanding of the $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$ reaction one needs to measure the gamma decay width (Γ_γ) of the first excited state above the proton emission threshold in ^{20}Na . There are also some questions about the J^π of this state which need further investigation. Indirect methods, as the $^{20}\text{Ne}(p,n)^{20}\text{Na}$ or the $^{20}\text{Ne}(^3\text{He},t)^{20}\text{Na}$ reaction, can be used to produce ^{20}Na in this excited state.

We have tried to measure Γ_γ with the $^{20}\text{Ne}(p,n\gamma)^{20}\text{Na}$ reaction using a proton beam from the TUNL tandem accelerator. Due to the large Q-value for this reaction (-14.67 MeV) and an excitation energy of 2.646 MeV of the excited state to be investigated, we needed a proton beam energy close to 20 MeV, the maximum energy that the TUNL machine can provide. For the experiment we used a pulsed proton beam from the direct extraction source in combination with a gas cell and the two shielded neutron detectors at the 38° (NTOF) beam leg. We intended to measure coincidences between the neutrons and γ -rays, with NaI detectors, to investigate the decay properties (J^π and $\Gamma_\gamma\Gamma$) of the state at 2.646 MeV. Unfortunately we could not get a stable beam from the tandem at the required energy.

We then proceeded to do this measurement in a similar experiment, $^{20}\text{Ne}(^3\text{He},\gamma)^{20}\text{Na}$, using the WNSL tandem facility at Yale University. After a preliminary run this approach looks promising and further experiments are scheduled for the second half of 1993.

4.1.5 Measurements of the $^{24}\text{Mg}(^3\text{He}, ^6\text{He})^{21}\text{Mg}$ Reaction

M.S. Smith³, A.E. Champagne, J. Görres⁴, R.B. Vogelaar⁵ and M.A. Hofstee

The $^{20}\text{Na}(p,\gamma)^{21}\text{Mg}$ reaction follows the $^{19}\text{Ne}(p,\gamma)$ reaction at the onset of the rp-process. Although a direct measurement of this reaction is not presently possible, in

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principle its cross section can be extracted from the properties of the relevant compound states in ^{21}Mg . Unfortunately, ^{21}Mg is a difficult nucleus to produce with stable beams and targets. The $^{24}\text{Mg}(^3\text{He}, ^6\text{He})^{21}\text{Mg}$ has been measured by Pardo [Par80] and by Kubono *et al.* [Kub92].

Figure 4.1-5 Levels observed in the $(^3\text{He}, ^6\text{He})$ reaction [Par80, Kub92]. Note that the two measurements are in disagreement in the region near the $^{20}\text{Na} + p$ threshold where, based upon the structure of ^{21}F [End90], several states are expected to reside.

However these two studies do not provide consistent information about states near the $^{20}\text{Na} + p$ threshold. This situation is illustrated in Figure 4.1-5 and the differences are significant: Since Pardo [Par80] did not see any evidence for any (p,γ) resonances, an rp -process beginning at ^{19}Ne would be unlikely. On the other hand, Kubono *et al.* [Kub92] predict a rapid $^{20}\text{Na}(p,\gamma)$ reaction. They estimated a rate by making use of the measured lifetimes for states in the analog nucleus ^{21}F and by assuming $\theta_p^2 = 0.1$ for all of the states that they observed. A more reasonable estimate of θ_p^2 can be obtained by comparing measured analog shifts with those calculated using a single-particle model. These calculations are in progress, but obviously require a resolution of the discrepancies among the two ($^3\text{He}, ^6\text{He}$) measurements.

To further examine the states of interest we have begun our own measurements of the $^{24}\text{Mg}(^3\text{He}, ^6\text{He})^{21}\text{Mg}$ reaction. Preliminary data were taken at $E(^3\text{He}) = 70$ MeV using the Princeton AVF cyclotron and QDDD spectrometer. Analysis is underway and further measurements are planned.

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4.1.6 Radioactive Ion Beams for Nuclear Astrophysics

A.E. Champagne for the RIBENS collaboration¹

The present development schedule at Oak Ridge calls for initial experiments with radioactive beams to begin in April 1995. To prepare for this opportunity, the RIBENS

¹ Involving Oak Ridge National Laboratory, Univ. of Notre Dame, Yale Univ., Univ. of Washington, Ohio State Univ., Michigan State Univ. and Princeton Univ.

(Radioactive Ion Beams - Explosive Nucleosynthesis) collaboration has identified several first-priority measurements and has agreed upon a conceptual design for these measurements. In any radioactive-beam measurement, detection efficiency is an important consideration because beam currents are at most on the order of pA. However, because our measurements involve extreme inverse kinematics (heavy-ion beams on targets of H or He), we can take advantage of kinematic focusing and detect recoils with high efficiency. Unfortunately, clean separation of recoils from the beam is complicated by the fact that they have almost identical momenta. Since optical elements which simply disperse in momentum will not provide adequate separation, some form of velocity selection is also required.

The separator that RIBENS plans to build consists of a Wien filter backed by an electrostatic deflector and a dipole magnet. Drift spaces of approximately 1 m in length separate the elements. With this configuration of elements, we expect the beam to be reduced by a factor of 10^{-11} - 10^{-13} of its original intensity. At the focal plane of the separator, the recoils can be detected directly using an ionization chamber or be implanted in a moving tape for measurements of delayed activity. Although we anticipate the possibility of acquiring the major components of this device via surplus, we are preparing an equipment proposal to the DOE.

Our choice of initial measurements is dictated in part by technical considerations, for example, by which beams are available or relatively easy to produce. For this reason, at the outset we will focus on reactions involving F, Si, S, and As beams. In particular, we will begin with the $^1\text{H}(^{17}\text{F}, ^{18}\text{Ne})\gamma$ reaction because it is an important reaction in the hot CNO cycles and because the ^{17}F beam is expected to be quite intense.

4.2 High-Spin Spectroscopy and Superdeformation

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As finite condensed-matter systems with strong short-range interactions, nuclei exhibit a tremendous variety of properties that depend on a number of factors, including nucleon number, angular momentum and excitation energy. One manifestation of the dependence on nucleon number is the existence of spherical and deformed shell gaps in the single-particle energy levels, leading to strong variations in the nuclear shape. Our research program focuses on two major areas: (a) studies of nuclear properties associated with very elongated nuclear shapes (superdeformed states, having major to minor axis

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ratios of $\approx 2:1$), and (b) investigations of the evolution of the nuclear shape as a function of proton and/or neutron as well as a function of angular momentum.

The superdeformation studies are a continuation of a highly successful program based at Argonne. Following calculations by R. Chasman [Cha89], our group found the first evidence for a new region of superdeformed nuclei centered around ^{192}Hg . Over the last four years, considerable effort has been focused on the exploration of this region of nuclei. Work performed at the ATLAS facility has found superdeformed bands in a chain of Hg nuclei with $A = 189-192$, and in ^{193}Tl . More recently, superdeformed bands have been investigated in $^{192,195,196}\text{Pb}$ and in ^{191}Tl .

Figure 4.2-1 γ -ray spectrum of the superdeformed band of ^{196}Pb obtained by summing spectra in coincidence with the 214, 257, and 387 keV transitions.

One of the most interesting features of the superdeformed (SD) bands in this mass region is the behavior of the dynamic moments of inertia ($\mathcal{J}^{(2)} = 4\hbar^2/\Delta E_\gamma$), derived from the energy difference of successive γ -ray transitions. In nearly all cases, the $\mathcal{J}^{(2)}$ values exhibit a smooth increase with increasing rotational frequency ($\hbar\omega \approx E_\gamma/2$). This rising trend could be due to several effects, either individually or in combination, such as changes in deformation (centrifugal stretching), a decrease in pairing strength, or the alignment of single-particle orbitals carrying large amounts of angular momentum. Our lifetime measurements in the SD band in ^{192}Hg [Moo90] proved that centrifugal stretching is not responsible for the rise in $\mathcal{J}^{(2)}$ in this nucleus. Cranked shell-model (CSM) calculations were quite successful in reproducing the measured deformation and the rise in the $\mathcal{J}^{(2)}$ values. These calculations suggest that a gradual reduction in pairing strength and the gradual alignment of quasiparticles in high- j orbitals is responsible for the rise in $\mathcal{J}^{(2)}$. However, the calculations also predict a sharp downturn in the $\mathcal{J}^{(2)}$ values at high rotational frequencies, which is not observed in the data. We are now in the process of carrying out measurements in other SD nuclei in this mass region with the goal of elucidating the properties of the SD moments of inertia.

4.2.1 Detailed Spectroscopy of the Superdeformed band of ^{196}Pb

Of the SD bands in the $A \approx 190$ region, perhaps the most interesting one is in ^{196}Pb . This band extends to the lowest rotational frequency ($\hbar\omega \approx 85$ keV) and, by inference, to the lowest spin ($I = 4\hbar$) in the mass region. The spectrum presented in Figure 4.2-1 is the sum of spectra in coincidence with the cleanest gates in the SD band. This spectrum was obtained from the reaction $^{170}\text{Er}(^{30}\text{Si}, 4n)^{196}\text{Pb}$ at 142 MeV. The ^{30}Si beams were supplied by the ATLAS accelerator at Argonne. Our measurements extend the previously known [Bri90, Wan91] band by one transition at the bottom and two transitions at the top. The two higher-lying transitions are of particular interest in light of the discussion above.

Figure 4.2-2 compares the $\mathcal{J}^{(2)}$ values derived from the present data to those of the SD band in ^{194}Pb [Bri90], as a function of rotational frequency $\hbar\omega$. The band in ^{196}Pb exhibits an upbend in the $\mathcal{J}^{(2)}$ curve at higher $\hbar\omega$, possibly due to a band-crossing, while the $\mathcal{J}^{(2)}$ of ^{194}Pb continues with the gradual rise. We have performed detailed (CSM) calculations in order to better understand the behavior of the $\mathcal{J}^{(2)}$ moment of inertia in these bands. The results of our calculations are plotted as lines in Fig. 2 for ^{196}Pb (solid) and ^{194}Pb (dashed). The calculations reproduce the trends observed in the data rather well, *i.e.* at low frequency $\mathcal{J}^{(2)}$ is lower in ^{196}Pb than in ^{194}Pb , but the respective rises with $\hbar\omega$, are such that at higher frequencies the calculations for the two bands result in very similar $\mathcal{J}^{(2)}$ values, as seen in the data.

We have also performed lifetime measurements in this band using the Doppler shift attenuation method (DSAM). We used the same reaction to populate the SD band, but in this case the recoiling ^{196}Pb nuclei were slowed down and stopped in a thick Pb

foil. The Doppler-shifted γ -ray lineshapes were compared to the results of a Monte-Carlo simulation of the stopping and decay process. Lifetime values for the γ -ray emitting states were derived from this comparison. The results of this analysis are presented in Figure 4.2-3. The data points are the experimentally determined fractions of the full Doppler shift $F(\tau)$, the solid line represents the result of a calculation in which the quadrupole moment Q_0 is taken to have a constant value of 18 eb for the entire band. The dashed lines correspond to the calculated $F(\tau)$ values for the error bars of ± 3 eb on the best-fit Q_0 of 18 eb. The inset to Figure 4.2-3 shows the results of a lineshape analysis carried out for the 546, 508, and 468 keV transitions in the SD band. In this analysis, the lifetimes of the individual transitions are extracted from the fitting process. After correction for internal conversion, the lifetime values were converted into the plotted transition quadrupole moments using the rotational formula.

Figure 4.2-2 Dynamic moment of inertia $J^{(2)} = 4\hbar^2/\Delta E_\gamma$ as a function of rotational frequency $\hbar\omega$, for the superdeformed bands in ^{196}Pb (circles) and ^{194}Pb (diamonds). The calculated $J^{(2)}$ curves for the SD bands in ^{196}Pb and ^{194}Pb are represented by the solid and dashed lines, respectively.

Figure 4.2-3 Measured fraction of the full Doppler shift $F(\tau)$ for transitions in the superdeformed band of ^{196}Pb . The solid line corresponds to the calculated shift for a quadrupole moment (Q_0) value of 18 eb and the dashed lines are for Q_0 values of 15 and 21 eb. Inset: Quadrupole moment values extracted from lineshape fits to the 468, 508, and 546 keV transitions.

Our results are consistent with the Q_0 values expected for the SD band from a large number of theoretical calculations. While the error bars are rather large, our results indicate that the quadrupole moment remains essentially constant within the band, despite the very large change in the $\mathcal{J}^{(2)}$ values over the observed frequency range. This feature was also observed in the SD bands in ^{192}Hg [Moo90] and ^{194}Pb [Wil93]. These observations reinforce the suggestion from CSM calculations that changes in pairing and the gradual alignment of high- j orbitals are responsible for the rising moments of inertia in the SD bands in this mass region. A paper summarizing these results is in preparation to be published in *Physical Review C*.

Figure 4.2-4 γ -ray spectra obtained by summing spectra in coincidence with members of one of the M1 bands in ^{196}Pb . The spectra were measured in Compton suppressed Ge detectors located at angles of 34.5° (top), 90° (middle), and 145.5° (bottom) with respect to the beam direction. The arrows indicate the unshifted γ -ray energies.

4.2.2 Lifetime Measurements in the M1 Bands in ^{196}Pb

Among the more exciting developments in nuclear structure physics over the past year has been the discovery, in neutron deficient Pb nuclei, of very collective rotational bands (non-superdeformed) at high angular momentum connected by strong magnetic dipole (M1) transitions. It is believed that protons in high-j orbitals coupled to moderately deformed oblate shapes are responsible for the large $B(\text{M1})$ values. As a byproduct of our high-statistics measurements for the SD band in ^{196}Pb , we have obtained vast quantities of information on the yrast and near-yrast level structure of this nucleus. Several bands connected by M1 transitions have been observed in the data [Hug93]. Figure 4.2-4 shows a coincidence spectrum of one of the M1 bands obtained in detectors located at angles of 145.5° , 90° , and 34.5° to the beam direction. Clearly, some of the γ -rays in this band exhibit very large Doppler shifts in our backed target data, suggesting fast lifetimes (*i.e.*, large collectivity). A detailed analysis of the Doppler-shifted lineshapes is now in progress with the aim of extracting experimental $B(\text{M1})$ values for comparison with theoretical calculations.

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4.3 The Nuclear Mean Field: Dispersion Relations and Nucleon Scattering

During the last few years Mahaux and collaborators [Mah91] published several important papers in which they developed and justified the dispersive optical model (DOM) in relation to nucleon-nucleus scattering. They demonstrated the significance of applying this model to the scattering regime (positive nucleon energies) and of extending the DOM into the negative energy region for the purpose of studying and describing bound-state properties, such as binding energies, spectroscopic factors or spectral functions, and occupation probabilities. The power of this model is that in a natural way it accounts for the energy dependence of the strength and the radius parameter of the central real potential and that it allows one to use the wealth of nucleon-nucleus scattering data that is available in the literature to characterize the extension of the nuclear mean field into the shell-model region in a consistent manner. It also assists in determining the formulation of the energy dependence of the absorptive potential in relation to the Fermi energy as a reference point.

We write the nuclear mean field with a real and an imaginary part as follows:

$$M(r, E) = V(r, E) + i W(r, E)$$

$$V(r, E) = V_{HF}(r, E) + \Delta V(r, E)$$

$$\Delta V(r, E) = (P / \pi) \int_{-\infty}^{\infty} [W(r, E') / (E' - E)] dE'$$

where $W(r, E)$ is the conventional absorptive potential, which contains surface and volume contributions. The $V_{HF}(r, E)$ is the Hartree-Fock contribution. The dispersion relation (DR) is given by the bottom formula; we note that it produces a contribution $\Delta V(r, E)$ to the real potential that depends on the strength and shape of the imaginary potential at all energies. The P in the DR denotes a principal-value integral. The surface contribution $\Delta V_S(r, E)$ to the real central potential has a strong variation with nucleon energy in the region between $-20 < E < +10$ MeV. Since Mahaux's original work on ^{208}Pb , dispersive optical models for nucleon-nucleus scattering have been investigated for about nine nuclei here at TUNL and for some of the same nuclei and a few others by research groups elsewhere. There have been outstanding successes so far for the closed-shell nuclei ^{40}Ca and ^{208}Pb , two cases where considerable empirical single-particle bound-state information exists. In these two cases the (ground-state) occupational probabilities calculated from the DOM confirm the observations of (e,e'p) reactions that there is a sizable depletion in the single-particle states below the Fermi energy and a 5-8% occupation of the low-lying particle states, which are unoccupied in the independent particle model.

In the following subsections we outline our recent progress in developing the DOM for neutron-nucleus scattering from a wide range of nuclei and for testing its applicability for the 2s-1d shell nuclei for the first time.

4.3.1 Modifications to the Optical-Model Search Code GENOA

G.J. Weisel, J. Vanderkam, R.L. Walter and W. Tornow

For many years the neutron group at TUNL has used our own versions of the global (in energy and atomic number) spherical optical-model code GENOA that originated with F. Perey of ORNL. In a series of stages over the last few years we converted this code into a DOM. We chose to insert the dispersion relation into this particular code because we were familiar with it and because we desired to conduct reasonably exhaustive searches of the global-in-energy type. Our first DOM version used numerical integration to obtain the DR contributions. Although this innovation for global search codes was a great time saver over the old energy-by-energy search, it was nevertheless time consuming and tedious to determine if one had approached an optimum

solution because of the ambiguities in OM parameters. In the next step we made a major improvement by replacing the numerical integration method with closed-form solutions to the dispersion integrals. (This has been done for powers of 2, 4, and 6 for the volume absorption, and 2 and 4 for the surface absorption.) This change allowed the search to proceed about eight times faster, thereby permitting us to be more thorough in our searches. In the next step we followed the concept introduced by Mahaux and Sartor [Mah91] and allowed the absorptive potentials to be unsymmetric about the Fermi energy (see below). These authors also indicated that the absorptive potentials should be zero for a few MeV on both sides of the Fermi energy, and we incorporated this "offset" modification also. (Closed forms for the integrations were derived for these potential forms as well.) Lastly, we inserted relativistic kinematics and relativistic corrections into the Schroedinger wave equation to allow us to compute up to 80 MeV with adequate accuracy.

Unfortunately, in the case for nucleon scattering, the dispersion relation as written in the bottom equation above is only an approximation. The $W(r,E)$ there signifies the usual local-equivalent optical-model absorption potential. According to Mahaux and Sartor one should actually use a non-local absorptive potential in the integrand. They argue that if one introduces non-locality, the volume absorptive potential falls to zero at about -200 MeV and also rises rather rapidly around 60 MeV from the usual plateau. These changes clearly make the integrand unsymmetric about the Fermi energy. This modification was only recently inserted into our DOM search code. The significance on the observables has neither been fully studied nor fully appreciated yet. Its influence (through the dispersive contribution) is felt most strongly in the deeply-bound hole states and in the scattering description (or parametrization) above 50 MeV, a region exceeding that studied by Mahaux and Sartor. [Mah91]

Several presentations on our work have been given during the past year. Invited papers were delivered at the Int. Conf. on the Application of Accelerators in Science and Industry (Denton, TX) and at the International Workshop on Nuclear Data for Fusion Energy (Del Mar, CA) and two contributed papers were given at the APS spring meeting in Washington, D.C. Some of the work is summarized in the Proceedings of the Fast Neutron Physics Conference (Beijing, PRC, 1992).

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4.3.2 Measurements of $A_Y(\theta)$ at 15.5 MeV and $\sigma(\theta)$ at 15.5 MeV and 19 MeV for $^{28}\text{Si}(n,n)$ and the Dispersive OM Analysis

M.A. AlOhalil¹, G.J. Weisel, M.M. Nagadi¹, C.R. Howell, W. Tornow, R.L. Walter

Our new data for $^{28}\text{Si}(n,n)$ for $A_Y(\theta)$ at 15.5 MeV and for $\sigma(\theta)$ at 15.5 and 19 MeV fill important gaps in the previous TUNL data sets. These data have been combined with available published data to form a large data set from 1 - 80 MeV for model analyses. In addition, bound-state information was collected from the literature in order to provide some constraints on the parameters to be derived in the dispersive OM analysis. Our earlier attempts at producing a DOM have been superseded by a new analysis conducted with the automatic search method.

We also investigated sensitivities to the range of parameter values that were found in the TUNL analysis by Nagadi *et al.* for the neighboring nucleus ^{27}Al and in our current work (see below) for the $n + ^{32}\text{S}$ reaction. We have found a satisfactory solution for ^{28}Si that produces reasonable fits to the ^{28}Si scattering data and single-particle bound-state energies. The main problem between the model calculations and the scattering data is the inability to describe the total cross section below 5 MeV, which is a difficulty similar to that experienced by Nagadi *et al.* for ^{27}Al . Nagadi *et al.* illustrated that this discrepancy can be reduced if one allows the radius of the real central potential to decrease as the incident neutron energy decreases; we believe that this would be true for ^{28}Si also, but we did not explore this.

4.3.3 Nuclear Mean Field for the $n + ^{32}\text{S}$ Interaction

M.A. AlOhalil¹, G.J. Weisel, M.M. Nagadi¹, R. Setze, C.R. Howell, W. Tornow, R.L. Walter, J. Lambert²

For $^{32}\text{S}(n,n)$ our new $A_Y(\theta)$ data at 15.5 MeV and $\sigma(\theta)$ data at 15.5 and 19 MeV were added to the earlier TUNL data of Howell *et al.* and published data of several others to create a comprehensive data set from 0.5 to 40 MeV. Total cross-section data are available only up to 32 MeV. In order to confine our OM parameters to physical values, we fabricated σ_T "data" for the energy range from 32 to 80 MeV using the following: the experimental values for σ_T for ^{28}Si , the conventional OM parameters of Howell for ^{28}Si and ^{32}S , and the DOM parameters from our specialized ^{28}Si model above.

A DOM analysis was performed using the parameters from the ^{28}Si DOM as a starting point; eventually we obtained a solution in which some parameters could be constrained to be identical to those for ^{28}Si . In addition, the model parameters were restricted in such a way that an acceptable agreement to known bound-state energies of

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Figure 4.3-1 The $\sigma(\theta)$ data compared to the calculation using the constrained DOM for $n+^{32}\text{S}$. The TUNL data are from 8 - 17 MeV. The dashed lines indicate the shape elastic (SE) contribution and the solid lines indicate the SE plus the compound nucleus contribution.

the $n + {}^{32}\text{S}$ system was also produced. The calculations compared to data for $\sigma(\theta)$ and $A_y(\theta)$ are shown in Figures 4.3-1 and 4.3-2. This is the first time that such a wide energy-range of data for ${}^{32}\text{S}$ has been described by an OM with constant geometry potentials. The calculated σ_T values (see Figure 4.3-3) agree well with the average of the data except in the range from 5 - 12 MeV where the fits are about 15% higher than the data. The Hartree-Fock part of the nuclear mean field V_{HF} is graphed in Figure 4.3-4 alongside the required depths that would give the exact single-particle binding energies of the $n+{}^{32}\text{S}$ particle and hole states; an exponential energy dependence for V_{HF} was found to be satisfactory over the entire energy range from -80 to +80 MeV. Our results for V_{HF} evaluated at the Fermi energy E_F are plotted in Figure 4.3-5 as a function of E_F for ${}^{28}\text{Si}$ and ${}^{32}\text{S}$ as well as for three heavier nuclei. The systematic behavior is quite obvious.

Figure 4.3-2 The TUNL $A_y(\theta)$ data compared to the calculation using the constrained DOM for $n+{}^{32}\text{S}$. Compound-nucleus corrections were applied to the experimental data to obtain this shape elastic $A_y(\theta)$ "data".

Figure 4.3-3 The σ_T data compared to the calculation using the constrained DOM for $n+^{32}\text{S}$. The "data" above 32 MeV have been fabricated from ^{28}Si data (see text).

Figure 4.3-4 The depth of the Hartree-Fock part V_{HF} of the mean field as a function of neutron energy for $n+^{32}\text{S}$.

Figure 4.3-5 The depth of the Hartree-Fock part V_{HF} of the mean field as a function of Fermi energy E_F for five nuclei.

4.3.4 Parameterization of the Nuclear Mean Field for the $n + ^{27}\text{Al}$, $n + ^{28}\text{Si}$ and $n + ^{32}\text{S}$ Interactions

M.A. AlOhalil¹, G.J. Weisel, C.R. Howell, W. Tornow, R.L. Walter

As an additional step along the way to investigating a DOM for the sd-shell, we first obtained a constrained dispersive OM for $^{27}\text{Al}(n,n)$ from bound-state energies up to 80 MeV. New TUNL $\sigma(\theta)$ and $A_Y(\theta)$ data comprised part of the data set. The model, which was based on parameters of the above ^{28}Si DOM, gave quite good fits. The major improvement over the DOM reported in TUNL XXXI is in the description of the σ_T below 15 MeV. Our new calculation for σ_T and data from the literature are shown in Figure 4.3-6. A portion of the $\sigma(\theta)$ calculations and data are shown in Figure 4.3-7.

Having achieved this success with a partially constrained model for ^{27}Al , we then attempted to describe the complete data sets for ^{27}Al , ^{28}Si and ^{32}S with a highly constrained model, a type of global model for this limited mass range. In the first stages of the development we used averages of the parameters for the three DOM's. It was clear from the predicted $\sigma(\theta)$ distributions that the absorption for the ^{27}Al case had to be reduced, whereas for ^{28}Si and ^{32}S it had to be increased; thus, nuclear structure or correlation effects needed to be treated differently for each nuclei. Therefore, we allowed the strengths of the volume and surface absorption to differ for all three nuclei. The total

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chi-square improved by 5% to 23% upon allowing these two parameters to adjust to their optimum value for each nucleus.

In a final step, we applied a correction to V_{HF} for ^{27}Al to account for the isospin interaction (taken from previous global SOM potentials) and a shift to account for the 2.0 MeV difference in E_F for ^{27}Al compared to the average E_F for ^{28}Si and ^{32}S . The absorption strengths were reoptimized for ^{27}Al . The net effect was that the our lowering of V_{HF} by 1.5 MeV caused an increase of 2.2 MeV in the strength of the volume absorption, a move in the direction of being more systematic with the absorption strengths of ^{28}Si and ^{32}S . The result is that we were able to obtain a global model with a real isospin term in which only two parameters differ, the strength parameters for the volume and surface absorption with the energy dependencies having the same functional form. This model gives a good representation of the scattering data for all three nuclei. There is little observable difference between the quality of agreement with our global model fits and the fits with our individual DOM models; the most noticeable is that the σ_T agreement in the 4 to 10 MeV region is a bit worse for ^{27}Al and ^{32}S . No attempt to optimize the single-particle binding energies was considered in developing this global model. When the model was used to predict binding energies, the calculated values were found to be in somewhat poorer agreement than those obtained with the specialized ^{28}Si and ^{32}S models.

Figure 4.3-6 The σ_T data compared to calculations using the constrained DOM for $n+^{27}\text{Al}$.

Figure 4.3-7 The $\sigma(\theta)$ data compared to calculations using the constrained DOM for $n+^{27}\text{Al}$.

4.3.5 Analysis of the $n + ^{93}\text{Nb}$ and $n + ^{120}\text{Sn}$ Interactions from -15 MeV to 80 MeV *R.L. Walter, R.S. Pedroni¹, C.R. Howell, Z.M. Chen², R.W. Finlay³, G.J. Weisel, W. Tornow*

The $^{93}\text{Nb}(n,n)$ spherical OM obtained at TUNL by Pedroni *et al.* [Ped90] was modified to include the dispersion relation. In addition the database now includes the new high-accuracy σ_T data of Finlay *et al.* [Fin91] and unpublished $\sigma(\theta)$ data of Finlay at 20 and 26 MeV. In addition, low energy $\sigma(\theta)$ from ANL and data in the 20-MeV range from others are included. Since no single-particle data for $n + ^{93}\text{Nb}$ exist, we employ knowledge from states in $n + ^{89}\text{Y}$ to constrain the parameterization. We are tuning the DOM using our improved dispersive search code that contains the relativistic corrections

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and the unsymmetric absorptive potentials. Our initial observation is that extremely good fits seem achievable.

For $n + {}^{120}\text{Sn}$, we have combined data from TUNL and the literature to create a large database of $\sigma(\theta)$, $A_y(\theta)$, and σ_T measurements from 2 to 80 MeV. Bound-state binding energies for single-particle states were also collected from the literature. The compound nucleus calculations were performed for $E < 8$ MeV to obtain estimates of the shape-elastic $\sigma(\theta)$ and $A_y(\theta)$. The dispersive OM fits obtained thus far are very encouraging in terms of the ability to describe the complete scattering database and the known single-particle binding energies.

[Ped90] R.S. Pedroni *et al.*, Phys. Rev. C43, 2336 (1991).

[Fin91] R. Finlay *et al.*, Nuclear Data for Basic and Applied Science (1991) Jülich, Germany, Proc. of 1991 Conf., ed. S.M. Qaim, 1992, p. 720.

4.3.6 The Dispersive Optical Model for $n + {}^{208}\text{Pb}$ and $n + {}^{209}\text{Bi}$ G.J. Weisel, W. Tornow, C.R. Howell, R.L. Walter

The DOM formulation [Rob91] derived at TUNL for $n + {}^{208}\text{Pb}$ gives a good description of the data for $\sigma(\theta)$ from 8 - 40 MeV, $A_y(\theta)$ from 10 - 17 MeV, σ_T from 4 - 60 MeV and for the single-particle bound states, that is, neutron particle states in $n + {}^{208}\text{Pb}$ and neutron-hole states in ${}^{208}\text{Pb}$. The model, which looks to be very promising for providing important spectroscopic and mean field information, is deficient in its description of $\sigma(\theta)$ in the 4 - 8 MeV region. Because of the possible significance of this failure, we collected a similar data set for ${}^{209}\text{Bi}(n,n)$ as we used in the ${}^{208}\text{Pb}$ work of Roberts *et al.* [Rob91] and undertook a DOM analysis in order to see if the DOM was capable of explaining this reaction better or if the problem was symptomatic of nuclei in this mass range. To examine the model in more detail, we also included $\sigma(\theta)$ data between 1.5 and 4 MeV. In addition to the ${}^{209}\text{Bi}$ analysis, we conducted a complementary, constrained analysis of the ${}^{208}\text{Pb}(n,n)$ system.

Our ${}^{209}\text{Bi}$ database differed from that in a previous DOM analysis by [Das90] in that we now have available high-accuracy σ_T data ($\Delta\sigma_T \approx 1\%$) up to our maximum energy of interest, 80 MeV, and we also have our new high-accuracy $A_y(\theta)$ data at 6 and 9 MeV that we measured to develop a more constrained database. Furthermore, we conducted new calculations of the compound-nucleus (CN) contribution to the $\sigma(\theta)$ for elastic scattering for ${}^{209}\text{Bi}$ and ${}^{208}\text{Pb}$, as possible errors in the CN calculations were anticipated to be one of the problems associated with the previous failure for the ${}^{208}\text{Pb}$ analysis. In addition, our dispersive OM differed from [Das90] and [Rob91] in three ways: We introduced the offset away from the Fermi energy at which the absorption goes to zero [Mah91], we investigated the unsymmetric form for the volume absorption to

Figure 4.3-8 The DOM fit compared to the $\sigma(\theta)$ data for $n + ^{209}\text{Bi}$ from 5 - 24 MeV.

Figure 4.3-9 The $A_y(\theta)$ data of TUNL for $n + {}^{209}\text{Bi}$ and the DOM fit.

account for non-localities in the OM absorptive potential, and we incorporated relativistic effects.

A consistent, constrained analysis was made of the $n + {}^{209}\text{Bi}$ and $n + {}^{208}\text{Pb}$ reactions, sequentially fixing parameters to be the same for each system. We found a compromise set of geometry parameters for all the terms of the nuclear potentials (volume real, volume and surface imaginary, and spin-orbit) without having much affect on the total χ^2 for the global-in-energy fits. We incorporated a correction for the isovector term of the real potential (which we took from a previous spherical OM global description of neutron scattering) and we were able to obtain a common Hartree-Fock potential V_{HF} for the two systems.

The only differences remaining in the models are the characteristic Fermi energies and slightly different surface absorptions, which we introduced to allow for nuclear structure differences between the doubly-closed shell nucleus in one case and the additional one-valence nucleon in the other case. The fits to the $\sigma(\theta)$ data are reasonable in the energy range from 1.5 - 3.5 and are not shown here. A problem similar to that seen at backward angles in the $\sigma(\theta)$ of our earlier work on ${}^{208}\text{Pb}$ between 4 and 8 MeV exists

for ^{209}Bi as well. The nature of the discrepancy for $5 \leq E \leq 9$ MeV is illustrated in Fig 4.3-8. We have not addressed this discrepancy by way of more calculations. We note that Johnson, Horen, and Mahaux indicated that in this energy range the absorption (mainly surface type) must depend on the orbital angular momentum quantum number, as nodes in the wave function exist at the nuclear surface in some cases.

The new TUNL $A_Y(\theta)$ data for ^{209}Bi and the DOM fits are shown in Figure 4.3-9. The total cross section fits agree to within about 1%. Similar agreement with $\sigma(\theta)$ and $A_Y(\theta)$ exists for our constrained ^{208}Pb model developed here. The ^{208}Pb total cross section is shown in Figure 4.3-10. Considering that our model fits the single-particle bound-state binding energies down to -20 MeV, *this type of agreement with differential data and total cross section data from 1.5 to 80 MeV is powerful testimony to the physical arguments underlying the dispersive optical model for nucleon-nucleus scattering.*

We have calculated the spectroscopic factors and occupation probabilities for $n + ^{208}\text{Pb}$ and compared them to those seen in the DOM work of Mahaux and Sartor [Mah91] and to those seen in $^{208}\text{Pb}(e,e'p)$ measurements, according to the tabulation in [Mah91]. We find that our values also show about 16% depletion of the hole states and about 9% occupancy of the particle states within ± 5 MeV of the Fermi energy. The model can be used further to calculate spectral functions for deeply-bound hole states to predict results that might be obtained at CEBAF in the near future. A status report of the $^{209}\text{Bi} - ^{208}\text{Pb}$ project is given in [Wal93].

Figure 4.3-10 The dispersive OM fit to the $\sigma_T(\theta)$ data for $n + ^{208}\text{Pb}$. Note the offset from zero for the vertical scale.

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4.3.7 The Nucleon-Nucleus Spin-Spin Interaction and Coupled-Channels and DOM Models for $n + {}^{27}\text{Al}$ and $n + {}^{59}\text{Co}$

M.M. Nagadi¹, J.P. Delaroche², C.R. Howell, W. Tornow, R.L. Walter

In order to develop a comprehensive understanding of the neutron-nucleus interaction, we have extended the data base for $n + {}^{27}\text{Al}$ and $n + {}^{59}\text{Co}$ elastic scattering. As stated in TUNL XXXI, we performed high accuracy $\sigma(\theta)$ and $A_y(\theta)$ measurements at 15.5 MeV for both nuclei and $\sigma(\theta)$ measurements for ${}^{59}\text{Co}$ at 10, 12, 14, 17, and 19 MeV. One reason for studying these systems is that spin-spin total cross-section σ_{ss} exist for $n + {}^{27}\text{Al}$ and $n + {}^{59}\text{Co}$, but the energy dependence of these data have not been satisfactorily explained. A major problem is that consistent optical models did not exist for these specific systems for the complete energy range of interest (0.5 - 35 MeV).

We have now developed two potentials for this energy range for each nuclear system, one a DOM and the other a simple coupled-channels model. In both cases we used σ_T data up to 80 MeV to constrain the energy dependence of our potentials at high energies. We assumed a rotational model for the coupled-channels (CC) calculation and took into account only the coupling of the ground state to itself (*i.e.*, the reorientation effect). The quality of the fits to the differential data was good and was similar for all models except in the first diffraction minimum, where the CC model did better. Compared to the DOM, the CC model also gave better agreement with the σ_T data for Al below 5 MeV. For ${}^{59}\text{Co}$ the σ_T could not be described perfectly, particularly between 2 - 4 MeV and 6 - 9 MeV where the fits miss the data by about 10%; however, both models predict σ_T to within about 3% between 12 and 80 MeV.

Using the above potentials, we calculated σ_{ss} using the straightforward method of Gould *et al.* [Gou86]. For ${}^{27}\text{Al}$ both models give a reasonable description of the available data [Gou86, Hee89] except for a single datum at 7.6 MeV. It would be useful to have more ${}^{27}\text{Al}$ σ_{ss} data in the low energy range, although it must be recognized that there is much resonance structure here. For both ${}^{27}\text{Al}$ models, we used a surface spin-spin potential with strengths of $V_{ss} = 0.8$ MeV and $W_{ss} = 0.0$ MeV, and with $r_{ss} = 1.0$ fm and $a_{ss} = 0.654$ fm. For ${}^{59}\text{Co}$ the spin-spin total cross-section calculations using the method of Gould *et al.* from 250 keV to 31 MeV are shown for the two models in Figure 4.3-11 where they are compared to the data of Heeringa *et al.* [Hee76, Hee77] and Fisher

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et al. [Fis72]. The calculations used almost the same spin-spin interaction as given for ^{27}Al .

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Figure 4.3-11 Spin-spin cross-section calculations for ^{59}Co compared to available data.

4.3.8 A Derivative Rule for Predicting the Spin-Spin Cross Section and Estimating the Strength of the Spin-Spin Interaction

J.P. Delaroche, M.M. Nagadi, R.L. Walter

In the process of developing nucleon-nucleus optical models for the purpose of formulating the spin-spin interaction, we discovered a phenomenon similar to the one that relates the vector analyzing power $A_y(\theta)$ to the differential cross section $\sigma(\theta)$ in elastic scattering of nucleons. The spin-orbit interaction has the effect of adding (subtracting) a surface contribution to the real central volume potential when the incident nucleon has its

spin pointing parallel (anti-parallel) to the orbital angular momentum. To first order, this addition (subtraction) amounts to increasing (decreasing) the radius of the real potential. Viewed from a diffraction model, these changes in the scattering radius will cause the location of the diffraction maxima and minima to shift to smaller angles in the one case and to larger angles in the other case. These shifts produce large differences between the scattering cross sections at a given angle for the parallel and antiparallel conditions. Such differences divided by the average cross section define the analyzing power. Where the slope of $\sigma(\theta)$ is large, large $A_Y(\theta)$ values result and where the slope is near zero, the $A_Y(\theta)$ is very small and usually has a zero crossing nearby.

When one views the total cross section as a function of energy $\sigma_T(E)$ over a large energy range, e.g., 0 - 80 MeV, one notices several Ramsauer interference maxima for medium-weight and heavy nuclei. The positions of these maxima change systematically with atomic number and are related to the radius of the nuclei. For neighboring nuclei, one can predict the amount of shift that will occur by considering the fractional increase of the radius of the scattering center. A surface spin-spin interaction has the effect of increasing or decreasing the scattering radius, depending on whether the spin of the incident nucleon is parallel or antiparallel to the spin of the target (which is orientated in measurements of the spin-spin total cross section σ_{ss}). Likewise, if the spin-spin potential has a volume form, it will either deepen or lessen the strength of the real central volume potential, depending on the relative orientation of the nucleon and target spins. Both of the surface and volume shapes for the spin-spin potential will cause similar shifts on the location of the Ramsauer peaks in the total cross section σ_T . Parallel spins will shift the maxima to higher energies and antiparallel to lower energies. Where σ_T is flat, there will be a zero in σ_{ss} .

If one expresses σ_T as a function of the potential parameters and makes a Taylor expansion, one can estimate the change in σ_T for a specific change in V or W . In this way one can test the sensitivity of σ_T to an increase or decrease that would be caused by a V_{ss} or a W_{ss} term in the full nucleon-nucleus potential. We investigated this derivative rule for the three nuclei (^{27}Al , ^{59}Co and ^{93}Nb) for which σ_{ss} data exist. We assumed that the W_{ss} term is zero and that V_{ss} is of a volume form, for convenience. In each case, the calculation represents the systematics of the data quite well. We conclude that for this condition regarding the W_{ss} and the V_{ss} form, the strength of a volume V_{ss} ranges from 0.2 MeV for ^{27}Al to 0.12 MeV for ^{93}Nb . We believe that it would be possible to approximate the strength of a surface σ_{ss} potential from the volume potential through the prescription of equal volume integrals. In Fig 4.3-12 the prediction for σ_{ss} for ^{59}Co based on the derivative of the experimental total cross section is compared to available data. The quality of the agreement is comparable to that calculated from the optical potentials. A manuscript detailing this work is nearly complete.

Figure 4.3-12 Spin-spin cross section for ${}^{59}\text{Co}$ calculated from the derivative of the total cross section compared to available data.

4.4 Configuration Mixing in ${}^{56}\text{Co}$ and ${}^{46}\text{Sc}$ Using (d, α) Reactions

E.R. Crosson, A. Eiro(Lisbon), G. Graw(Munich), S.K. Lemieux, E.J. Ludwig, and F.D. Santos(Lisbon)

Cross-section measurements in (d, α) reactions have frequently been used as a spectroscopic tool to probe neutron-proton correlations within complex nuclei. This reaction involves the transfer of a neutron-proton cluster with spin-1 and hence, for unnatural parity transitions of a unique J transfer, there may be a mixing of transition amplitudes with different orbital angular momentum $L = J \pm 1$. While cross section angular distributions can identify the predominant orbital angular momentum of the transferred clusters, tensor analyzing power measurements (TAP) of these reactions are quite sensitive [San85] to the magnitude and sign of the L -mixing ratio, R where $R = G(L=J+1, J) / G(L=J-1, J)$. The $G(L, J)$ correspond to spectroscopic amplitudes which can be calculated theoretically. For fp -shell nuclei studied as part of the present work, R can now be predicted by shell-model calculations which include a mass-dependent interaction and $1f_{7/2}$, $1f_{5/2}$, $2p_{3/2}$, and $2p_{1/2}$ active orbitals.

The TAP angular distributions in (d, α) reactions are sensitive to the presence of the D -state component of the α particle and hence calculations of these observables should use realistic α -particle wave functions which include S - and D -state deuteron-deuteron overlaps in exact finite-range DWBA calculations. Our study concentrated on relatively strong transitions to states in ${}^{56}\text{Co}$ and ${}^{46}\text{Sc}$ via ${}^{58}\text{Ni}(d, \alpha){}^{56}\text{Co}$ and ${}^{48}\text{Ti}(d, \alpha){}^{46}\text{Sc}$ reactions. Transitions to 7^+ states in each of these residual nuclei, which

are unmixed in L, have been used to test whether the α -particle wave function, target bound-state geometry and optical-model potential parameters were reasonable choices.

Measurements were made at the Munich HVEC-MP tandem accelerator laboratory using 22-MeV vector- and tensor-polarized deuterons. The α particles were detected using a Q3D magnetic spectrograph and an overall spectrum resolution of ~ 25 keV was obtained. The angular distributions $\sigma(\theta)$, $A_y(\theta)$, $A_{yy}(\theta)$, and $A_{xx}(\theta)$ were analyzed using exact finite-range DWBA calculations which included the α -particle wave function and optical-model potential parameters used in previous analyses of reactions for these nuclei [Cro92]. For each transition we used TAP distributions to obtain both the magnitude and sign of the L-mixing ratios by minimizing differences between experimental and theoretical values of A_{yy} and A_{xx} .

Table 4.4-1 Values of R determined from minimizing χ^2 for angular distributions of A_{xx} and A_{yy} for the states studied in ^{56}Co and ^{46}Sc in comparison with theoretical shell-model predictions.

$^{58}\text{Ni}(d,\alpha)^{56}\text{Co}$				
E_{ex} (MeV)	J^π	$R_{A_{yy}}$	$R_{A_{xx}}$	R_{th}
0.158	3^+	0.1	0.1	-0.4
0.576	5^+	-0.2	-0.2	-0.15
1.009	5^+	-0.2	-0.1	0.36
1.930	3^+	-0.3	-0.5	-0.70
$^{48}\text{Ti}(d,\alpha)^{46}\text{Sc}$				
E_{ex} (MeV)	J^π	$R_{A_{yy}}$	$R_{A_{xx}}$	R_{th}
0.228	3^+	0.0	0.0	-0.31
0.774	5^+	0.1	0.1	-0.58
1.643	4^+	-0.1	+0.3	-
1.852	1^+	-1.0	-0.7	-0.33

For all the states where fits were attempted, values of the best-fit value of R compared closely when A_{yy} and A_{xx} were used. These values are shown in Table 4.4-1 along with theoretical predictions provided by Brown [Bro93]. The agreement with theory is not particularly good, which might be expected for early calculations in this shell, since small two-particle admixtures can have a large effect on these predicted ratios. The $A_y(\theta)$ data were found to have less sensitivity to R, while cross section data

Figure 4.4-1 Angular distributions of the cross section ($d\sigma/d\Omega$) in mb/sr, $A_{\pi\pi}$ and $A_{\pi d}$ at $E_d = 22$ MeV for the $^{58}\text{Ni}(d, \alpha)^{56}\text{Co}$ to the 3^+ state of ^{56}Co at $E_x = 0.158$ MeV (a), the 5^+ state of ^{56}Co at $E_x = 0.576$ MeV (b), the 5^+ state of ^{56}Co at $E_x = 1.009$ MeV (c), the 3^+ state of ^{56}Co at $E_x = 1.930$ MeV (d). The full curves are DWBA calculations using realistic $<dd|a>$ form factors generated with the Argonne potential and correspond to the best-fit value for the L-mixing ratio, as described in the text. The DWBA calculation of $d\sigma/d\Omega$ is normalized to the data.

Figure 4.4-2 Angular distributions of the cross section ($d\sigma/d\Omega$) in mb/sr, A_{yy} and A_{xx} at $E_d = 22$ MeV for the $^{48}\text{Ti}(d, \alpha)^{46}\text{Sc}$ to the 3+ state of ^{46}Sc at $E_x = 0.228$ MeV (a), the 5+ state of ^{46}Sc at $E_x = 0.774$ MeV (b), the 4- state of ^{46}Sc at $E_x = 1.643$ MeV (c), the 1+ state of ^{46}Sc at $E_x = 1.852$ MeV (d). The curves are DWBA calculations using realistic $<dd|\alpha>$ form factors generated with the Argonne potential and correspond to the best-fit value for the L-mixing ratio, as described in the text. The DWBA calculation of $d\sigma/d\Omega$ is normalized to the data.

showed sensitivity to the magnitude of R in some cases but much less sensitivity to the sign. The curves shown with the data in Figures 4.4-1 and 4.4-2 were generated with the averaged best-fit value of the L mixing. The data compare quite well with theory, indicating that TAP observables for this reaction provide a useful spectroscopic tool.

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4.5 Radiative Capture Studies

4.5.1 Isovector Giant Quadrupole Resonance in $(\vec{p}, \gamma)$ Reactions

M. A. Godwin, W. R. Dodge, G. Feldman, E. Hayward, L. H. Kramer, H. R. Weller

Giant quadrupole (E2) resonances (GQR) have been investigated via hadron scattering, resulting in a reasonable understanding of the systematics of the isoscalar (collective) mode. However, due to the difficulty of unfolding the E2 intensity from electron scattering cross sections, the isovector component of the E2 resonance (IVGQR) is not well understood.

Polarized proton capture reactions offer several distinct advantages in the search and study of resonant E2 strength. First, real photons are detected, which restricts the contributing multipoles to relatively low order ($\lambda \leq 3$). Second, E1/E2 interference effects can give rise to noticeable signatures in the measured observables, such as cross-section asymmetry and especially the vector analyzing power at 90° .

We have concluded a program of $(\vec{p}, \gamma)$ studies utilizing the polarized proton source of the 88-inch Cyclotron at the Lawrence Berkeley Laboratory in an effort to identify the isovector giant quadrupole resonance and to understand its systematics. This laboratory is capable of delivering polarized proton beams at energies up to $E_p = 50$ MeV, quite sufficient to span the region of excitation of the IVGQR.

Our recent efforts have focused on the $^{89}\text{Y}(\vec{p}, \gamma)^{90}\text{Zr}$ reaction. We have examined the relative cross section and the product of the analyzing power and relative cross section for ground and low lying states of ^{90}Zr with a beam of 22.5-MeV protons. This data has been previously discussed [Wel91].

Shown in Figure 4.5-1 are the energy dependence of $A_y(90^\circ)$ for both the transition to the ground state and to the strong cluster of three states near $E_x \sim 2.3$ MeV, which we refer to as the γ_{123} transition. These states have spin-parity of 0^+ , 5^- and 4^- , are 1.76, 2.32 and 2.73 MeV and possess a spectroscopic factor C^2S of 0.52, 1.13 and 1.11, respectively [Vou69]. The lines are direct-semidirect calculations, discussed below. Notice the large values for the γ_{123} transition analyzing power, which appears to show a

peak at $E_p \approx 23$ MeV, whereas the transition to the ground state demonstrates neither of these properties.

Using the DSD model, calculations of $A_\gamma(90^\circ)$ as a function of energy have been performed. These calculations were made for the ground state as well as each of the first three strong single-particle excited states. Included in these calculations are the giant dipole resonance, isovector and isoscalar electric quadrupole resonances and direct E1, E2 and E3 radiation. Dietrich [Die77] argues that the isospin splitting of the giant dipole resonance is a small effect, so we have included only the $T_<$ component. The isoscalar quadrupole coupling was treated as a real, surfaced-peaked interaction of strength $U_0 = 50$ MeV. The isovector quadrupole interaction is treated as a complex particle-vibration coupling form factor, $V + iW$, where the real volume strength is $V = 70$ MeV and the imaginary surface strength is $W = 110$ MeV. Optical model parameters were obtained from Becchetti and Greenlees [Bac69]. In order to match the binding energies the bound state potential well depth was allowed to vary.

The GDR parameters are $E = 16.7$ MeV, $\Gamma = 4.2$ MeV and $S = 100\%$, and the isoscalar GQR parameters are $E = 14$ MeV, $\Gamma = 7.0$ MeV and $S = 50\%$. With knowledge of all this secure, the resonance parameters for the IVGQR were treated as free parameters in order to best fit the $A_\gamma(90^\circ)$ vs E data gathered for transitions to the first three excited states in ^{90}Zr . These same parameters were used for the γ_0 DSD calculation. In order to account for the three states involved in the γ_{123} transition, DSD calculations were run for each state individually, and the predicted analyzing powers were averaged, weighted by the cross section. In order to establish some reliability for this method, we have run the DSD codes, extracted cross section and cross section times analyzing power data as a function of gamma-ray angle, and plotted these with the experimentally determined values. Figure 4.5-2 shows these results. Although there is not an overwhelming agreement, the general form is reproduced and the data is somewhat consistent.

The best fits are shown in Figure 4.5-1, where the solid line includes all the resonances mentioned above and the dashed line does not include the IVGQR. The IVGQR was determined to be centered at $E_{\text{GQR}} = 29.0$ MeV, with a width of $\Gamma_{\text{GQR}} = 5.5$ MeV, and exhausting $S = 100\%$ of the isovector E2 energy-weighted sum rule, for each of the three states involved. The resonance like structure in the γ_{123} data is reproduced only by including the IVGQR. Without this feature, no peaking structure is seen. Certainly there is a need for enhancement of the collective (semi-direct) E2 strength in this energy regime, establishing the presence of IVGQ radiation. Although the DSD model predicts the same behavior in the γ_0 transition, our data do not show this.

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Figure 4.5-1 Shown above are the analyzing power data over energy along with DSD calculations for both transitions studied. The solid curve includes the IVGQR whereas the dotted curve does not. The fitting procedure employed is explained in the text.

Figure 4.5-2 Depicted above are the angular distribution data for transitions to the ground state as well as the first three excited states. The dashed curves indicate a Legendre fit to the data, and the solid curves show a DSD calculation.

4.5.2 Radiative Capture Mechanisms in the $^{89}\text{Y}(\vec{p}, \gamma)$ Reaction

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We have measured the spectra of gamma rays from approximately 14 MeV to the endpoint in the $^{89}\text{Y}(\vec{p}, \gamma)$ reaction with 19.6-MeV polarized protons from the TUNL tandem accelerator. Gamma spectra were measured with a pair of 25.4 cm x 25.4 cm anticoincidence-shielded NaI detectors at angles of 30, 55, 90, 125, and 150° with respect to the incident beam. The purpose of this experiment was to examine the portion of the gamma spectrum corresponding to radiative capture to both bound and unbound final

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states, and to compare the results to model calculations for direct-semidirect and precompound processes.

The gamma spectra show significant analyzing powers as well as forward peaking of the angular distributions. These features allow discrimination between compound processes, which do not exhibit such effects of interference between compound processes, which do not exhibit such effects of interference between different channels, and direct processes. While multistep-compound processes have been calculated for fast-nucleon radiative capture [Ob190, Hor90], there has as yet been no estimate of multistep-direct gamma production. The observed interference effects indicate that multistep-direct processes are important at energies lower than those for which direct-semidirect capture is the dominant mechanism.

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4.6 High Energy Resolution Resonance Studies at 100-400 keV

G.E. Mitchell, C. Rolfs¹, W.H. Schulte¹, H.W. Becker¹

As a part of a continuing program in nuclear physics and astrophysics, as well as for atomic and condensed matter applications, we have made significant improvements in targetry and in the energy resolution characteristics of the 400-keV Münster accelerator. The German group has now moved to Ruhr Universität Bochum, where there is a Tandem Dynamitron and a small accelerator which will be upgraded to be similar to the Münster accelerator. Results have been published on the experimental techniques, on the spectroscopy of ²²Na, and on atomic effects on α - α scattering to the ground state of ⁸Be (see 1992 TUNL Progress Report). Recent results include significant improvements in high resolution depth profiling and observation of replica resonances which appear to be associated with the compound system.

4.6.1 High Resolution Experimental Techniques

Details of the improved accelerator configuration and performance have been published [Sch92]. Recent improvements include an energy scanning system (over a range of up to 4 keV in steps as small as 0.4 eV) in which a control voltage is applied to the external control of the high voltage power supply. The HV terminal ripple was usually less than 12 V, and under favorable circumstances less than 4 eV. Windowless

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gas targets were employed for many of these experiments; the target thickness could be varied from less than a monolayer of target material to rather thick targets. The temperature of the gas target could be varied from 25 K to room temperature. The short and long term energy stability and reproducibility of the ion beam energy (after a brief warm-up period) were better than 3 eV.

4.6.2 New Doublet in $^{21}\text{Ne}(p,\gamma)^{22}\text{Na}$ Reaction

The resonances at $E_p = 126, 272, \text{ and } 291 \text{ keV}$ were studied and new values for the resonance widths obtained. These results have been published [Bec92]. The values for the widths are (old limits in parentheses): $E = 126 \text{ keV} \rightarrow \Gamma < 12 \text{ eV}$ (old value $\Gamma < 1200 \text{ eV}$); $E = 272 \text{ keV} \rightarrow \Gamma < 3 \text{ eV}$ (old value $\Gamma < 100 \text{ eV}$); $E = 291 \text{ keV} \rightarrow \Gamma < 11 \text{ eV}$ (old value $\Gamma < 200 \text{ eV}$). The improvement of one to two orders of magnitude on the limits shows the advantages of the present system. During the measurement, the background near the 272 keV resonance seemed anomalously high: detailed investigation led to the discovery of a new resonance at 271 keV (888 eV below the previously identified state) with $\Gamma < 5 \text{ eV}$. Since the doublet was not resolved in earlier measurements, this new result cast doubt on the previous spin assignment based on gamma decay properties. We studied γ -ray spectra at the two resonances, which proved to have quite different decay patterns. We made a revised spin-parity assignment of $1^+, 2, 3^+$ for the 272 keV resonance and concluded that the new 271 keV state has $J^\pi = 3^+, 4, 5^+$. This new 271 keV resonance is probably the $T = 1$ analog of the $E_x = 6345 \text{ keV}, 4^+$ state in ^{22}Ne .

4.6.3 Atomic Effects in α - α Scattering Through the Ground State of ^8Be

The resonant α - α scattering to the ground state of ^8Be represents the first step in the triple- α stellar nucleosynthesis process and therefore is of considerable interest to nuclear astrophysics. The parameters of this s-wave resonance were determined in a very difficult, crossed beam measurement by Staub's group [Ben68] in 1968. They measured kinematic coincidences between pairs of detectors at 45° . The resonance at 184 keV was split into two or three structures. The multiple structures were attributed to atomic effects, caused by rearrangement of the three electrons in the entrance channel. Subsequent analyses based on realistic atomic physics models [Fea79] could not fit the data.

We have remeasured α - α scattering in the vicinity of the 184 keV resonance. The keys to the experiment were the very good beam energy resolution (described above) and the utilization of a supersonic gas jet with special pumping and collimation. The net result was an overall energy resolution of about 25 eV, as compared with a value of 95 eV in the previous measurement.

The new results are presented in Wüstenbecker *et al.* [Wüs92]. There are several important experimental results. The size and shape of the two structures for each angle pair are nearly identical, and the signs and shapes of the structures change from one angle pair to the other as predicted. The structures are asymmetrical, with a sharp low-energy edge followed by a high-energy tail. There are only two structures, which are equal in magnitude; this is in disagreement with the previous experimental results. Although the present results are in better agreement with calculations than are the previous data, none of the presently available models reproduce the data in detail.

4.6.4 Energy-Loss Phenomena

The quantized nature of the energy loss of energetic charged particles in matter is manifested in the yield curves of narrow nuclear resonances. There is a peak in the thick target yield curve near the resonance energy, followed by a plateau. This phenomenon is known as the Lewis effect. The physical basis for this effect is that particles lose energy in discrete steps -- some particles with an energy above the resonance will "jump over" the resonance and therefore not contribute to the yield. This effect is only observed with very good energy resolution and with very clean targets. In order to analyze such data one needs to understand the details of the energy loss. For solid targets these effects are obscured by the large Doppler contribution, which cannot be measured independently from the energy loss properties. Since for gas targets the Doppler effect is greatly reduced, we decided to study the Lewis effect and related energy loss phenomena in windowless gas targets. Energy loss spectra were obtained for gas target thicknesses ranging from ultra thin targets to rather thick targets. Data for very thin targets provide information on the atomic excitation mechanism at impact parameter $b = 0$, while thick target studies provide information on the energy loss spectra integrated over all impact parameters.

For thick ^{21}Ne targets a very pronounced Lewis peak was observed [Sch92]. This is the first clear observation of the Lewis effect in gas targets and is thought to be the largest Lewis effect (peak relative to plateau) ever observed. With the measured collision spectra both for $b = 0$ and for all values of b , the thick-target yield curve could be simulated including the magnitude of the Lewis effect and the presence of damped oscillations on the plateau.

With very good energy resolution and thin targets, the effects of atomic excitations must be included. These excitation processes result in echoes or replicas of the resonance at projectile energies above the resonance energy. For the 272 keV resonance in $^{21}\text{Ne}(p,\gamma)^{22}\text{Na}$ a very clear replica resonance is observed above the resonance energy; the energy of this replica resonance corresponds well to the L-shell excitation energy for the compound atom Na, not to the L-shell energy of the target. Similar results were observed for a resonance in $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ -- the energy of the replica resonance corresponds to the excitation energy in the compound atom Mg, not to

the excitation energy in the target. The experimental results are being prepared for publication[Ebb93]; detailed analysis of these unique results will require additional theoretical efforts.

4.6.5 High Resolution Depth Profiling

The very high stopping power dE/dx in the projectile energy range of a few hundred keV make low energy resonances attractive for depth profiling measurements. In order to achieve the full potential, one requires excellent experimental beam energy resolution. The target must be free of surface contaminants, and should be cooled to reduce the Doppler spread. We studied depth profiling with narrow resonances in the $^{18}\text{O}(p,\gamma)^{19}\text{F}$, $^{18}\text{O}(p,\alpha)^{15}\text{N}$, $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$, and $^{29}\text{Si}(p,\gamma)^{30}\text{P}$ reactions. The results are extremely promising. For a resonance at 324 keV in the $^{29}\text{Si}(p,\gamma)^{30}\text{P}$ reaction a nominal surface depth resolution (the ratio ΔE to dE/dx) of order 10 angstroms may be achievable. Results for ^{18}O were positive, including measurements on an ^{18}O - ^{16}O - ^{18}O SiO_2 sandwich.

Effects of surface contaminants were studied with the 309 keV resonance in the $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ reaction obtained from in situ evaporated metallic sodium targets. The magnitude of the Lewis peak was measured for a freshly evaporated sodium target and some 20 minutes later. The magnitude of the Lewis peak in the second measurement was reduced significantly. Estimates are that a contaminant layer corresponding to one atomic layer results in a decrease in intensity of about 10% for the Lewis peak. This suggests that monitoring the intensity of the Lewis peak may be a novel and sensitive method of studying surface layers. We plan to study this effect in a controlled fashion in the near future. Our present results on applications of high resolution resonance spectroscopy to condensed matter studies are presented in a paper by Schulte *et al.*[Sch93].

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4.7 Nuclear Data Evaluation For $A = 3 - 20$ *D.R. Tilley, H.R. Weller*

Nuclear data evaluation activities at TUNL are an outgrowth of the experimental research in few-nucleon systems carried out over a number of years by the radiative capture group. This evaluation work began in 1985 in response to requests by the National Nuclear Data Center for the TUNL group to undertake updates of the $A = 3$, and $A = 4$ systems, reviewed earlier by Fiarman and Hanna [Fia75], and Fiarman and Meyerhof [Fia73]. More recently, TUNL was assigned responsibility for data evaluation in the region $A = 3 - 20$ by the Department of Energy, following the retirement of Professor Fay Ajzenberg-Selove of the University of Pennsylvania, who had carried out data evaluation in this mass region for many years. Current and future TUNL efforts in nuclear data evaluation are summarized as follows:

$A = 3, 4$: New reviews for the $A = 3$ and 4 systems were carried out at TUNL and published respectively as "Energy Levels of Light Nuclei $A = 3$ ", D. R. Tilley, H. R. Weller and H. Hasan, Nuclear Physics A474 (1987) 1, and "Energy Levels of Light Nuclei $A = 4$ ", D. R. Tilley, H. R. Weller, and G. M. Hale, Nuclear Physics A541, (1992) 1. TUNL continues to survey the literature and compile references for $A = 3$ and 4 on a regular basis.

$A = 5 - 20$: TUNL now carries on literature coverage for $A = 3 - 20$ on a continuing basis, compiling bibliographical listing for relevant experimental and theoretical work, utilizing several resources including Monthly Updates from NNDC, Current Contents on Diskette with Abstracts, and Physics Abstracts. TUNL is preparing the Review of $A = 16, 17$. Preliminary versions were issued ($A = 16$ in July 1992 and $A = 17$ in December 1992) and copies were mailed out to solicit corrections and suggestions. Preparation of the final manuscript in ESP-LaTeX format has been completed and was submitted to Nuclear Physics A in early July 1993. Following this, TUNL began to work on $A = 18-20$ and will continue the cycle. TUNL plans also include data entry into the ENSDF files of NNDC.

DOE has recently approved a proposal to fund a post doctoral research associate whose time would be equally divided between few-nucleon radiative capture research and the TUNL $A = 3 - 20$ data evaluation project. It is expected that the additional manpower will enhance the pace of our efforts to carry out data evaluation for $A = 3-20$, to publish reviews for these nuclei on a timely basis, and especially to carry out the entry of $A = 3-20$ data into the NNDC Evaluated Nuclear Structure Data Files (ENDSF) for ready access by the nuclear community.

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5. NUCLEAR INSTRUMENTS AND METHODS

5.1 FN Tandem Accelerator Operation

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

5.1.1 Tandem Operation

The TUNL FN tandem accelerator operated a total of 4200 hours during the period September 1, 1992 through June 31, 1993. The upgraded tandem has operated with a maximum terminal potential during this period of 10.0 MV. Beams accelerated during this period include polarized protons and deuterons, unpolarized protons and deuterons, and ^4He .

The tandem was opened only twice for maintenance. After 10,600 hours of post-upgrade operation, in March 1993, the accelerator was opened after failing to condition to 10 MV. Several failed column resistors were discovered and replaced. The gridded lens also required repairs and modifications to the power supply to better protect it from sparks. The Pelletron chains were inspected and cleaned, no abnormal wear or stretch was detected. The drive belts for the Pelletron were replaced with Goodyear Hi Performance PD belts - in hopes of reducing the dust generated at the chain drive motors. Other modification made inside the tandem included; installing belt guards to contain the belt dust and prevent it from contaminating the column structure, also the alignment of the drive pulleys was corrected and this also should produce less wear and dust from the drive belts.

In May 1993, the new NEC Terminal Potential Stabilizer circuit was installed, replacing the HVEC stabilizer which had been used since 1976. This old circuit was designed in 1968 and many of the components were obsolete and not readily available. The new stabilizer is being used with logarithmic slit current preamplifiers built for us by Yale. These preamplifiers are based on a design by Trainor at Seattle, and has a much wider input current range and bandwidth than the NEC preamplifiers. With the new stabilizer, it is possible to measure terminal voltage fluctuations on the order of volts - whereas the old stabilizer had a noise level of about 1 kV. The measured terminal voltage ripple with the new stabilizer is normally less than about 100 V peak-to-peak. We had some difficulty with the installation as the NEC system requires a high voltage coaxial cable to connect the corona controller to the corona points feedthrough. We had two RG-8 cables fail and finally had to use a now obsolete 80 kV cable to make this connection.

In May 1993, after only 140 hours of operation, the tandem was unable to hold voltage and another tank entry was made. On entering, it was discovered that the control string for the terminal steerer had broken and was laying on top of the tube. In addition, one column resistor had failed due to the sparking and two others were high and had to be replaced.

5.1.2 Spare Accelerator Tubes

Funds have been obtained from the DOE to enable us to purchase two spare accelerator tube sections for the FN tandem. These two tubes will complement the two spare tubes on hand at LLNL-CAMS. A formal agreement will enable both laboratories to draw on these spare tubes in case of a tube failure. The order for these tubes should be let in late June 1993, with delivery expected to be near the first of 1994.

5.1.3 Higher Voltage Operation

A number of experiments are planned which will require the tandem to operate at 10 MV. We have had difficulty in achieving stable operation above 9.5 MV, and so have decided to add up to 10% Sulfur Hexafluoride (SF_6) to the gas mixture. While increasing the SF_6 content of the accelerator pressure vessel, we investigated several means to measure the SF_6 content in-house rather than sending a sample to an outside laboratory for analysis, a process that normally takes two weeks to return a result. A method of measuring the SF_6 content by comparing the optical path length in a sample of Nitrogen/Carbon Dioxide (0% SF_6) with a sample of the tank gas in a Michelson interferometer was developed. This procedure is discussed more fully in Section 5.4. At present, we are restricting the maximum terminal voltage to 9.5 MV until we can adjust the tube spark gaps and perform other adjustments which we believe will help improve the high-voltage operation of the tandem.

5.1.4 Gas Plant Repairs and Modifications

Following the May 1993 tank opening, we had our main gas compressor inspected by the manufacturer, as we were experiencing some problems with its operation. They recommended a complete overhaul and against running the compressor until it was overhauled. Until the overhaul is completed, we have no means for pumping the gas out of the accelerator in order to perform repairs to the tandem. The compressor repairs are expected to be completed by the end of July 1993. In addition, we have made plans to make changes to the gas handling system which will enable us to use the compressor to reclaim SF_6 gas from the high pressure storage tanks. These changes will also simplify loading of new SF_6 into storage.

5.1.5 New Building Chiller

This spring, Duke University replaced the 25-year-old building chiller in the Nuclear Laboratory. A new chiller with dual compressors was installed. This new unit will provide some redundancy in the event of failures and should permit laboratory operations to continue in the event of minor system failures. The replacement project was entirely funded by the University and represents a \$312,750 investment in the future of the laboratory.

5.1.6 New Compressed Air System

A new laboratory air compressor with twice the capacity of the old one, was installed in the mechanical room. This new compressor was needed due to the age and condition of the old compressor, and increased demands for compressed air cooling of gas cell targets. This new compressor can be upgraded to provide three times our previous capacity. A backup compressor will also be relocated from the accelerator bay to the mechanical room - which will greatly simplify maintenance. The old chemical dryer was replaced with a refrigerated dryer - which should not require nearly as much maintenance, and does not consume 10% of the compressed air for regeneration. We are also experimenting with using Vortex coolers for target cooling applications, as they may permit us to further reduce the compressed air consumption for these applications.

5.2 KN Accelerator Operation and Maintenance

C.R. Westerfeldt, E.G. Bilpuch, C.R. Bybee, E.P. Carter, J.M. Drake, G.E. Mitchell, J.F. Shriner, Jr.¹, P.M. Wallace

In winter 1992-1993 the high-performance stainless-steel-electrode accelerator tube was refurbished and reinstalled. The refurbished tube has only been conditioned to 1 MV at this point. This tube was fitted with magnetic suppression for secondary electrons during the rebuild. It is hoped that this modification will significantly reduce the radiation produced around the accelerator. New preamplifier circuits have been constructed for the generating voltmeter and capacitive pickoff signals from the KN accelerator. The homemade corona stabilizer circuit has been modified to interface with these new preamplifiers. The voltage stability which we have measured with the new CPO preamps is about 1 - 2 KV p-p when under corona control.

We are having increasing difficulty with our homemade magnet-field stabilizer for the main analyzing magnet in this laboratory. This circuit was constructed in 1985 and has never worked as well as we would have liked. Field stability is on the order of 1 - 2 Gauss at best and we would prefer it to be at least an order of magnitude better. We are investigating several alternatives to improve or replace this magnet controller.

Our primary development efforts this past year have concentrated on replacement of the failed energy stepping computer, and on the design and construction of the new scattering chamber for the $^{29}\text{Si}(p,\gamma)$ experiments. In addition, a new higher-speed diffusion pump was installed on the accelerator tube extension to replace a failed pump. This new pump has improved the base vacuum from 2×10^{-6} Torr, to better than 9×10^{-7} Torr. A new interlock and control station has also been completed for the electrostatic analyzer pumping system and has been installed.

¹ Tennessee Technological University, Cookeville, TN

5.2.1 Computer Control System

A new computer control system for the electrostatic analyzer was purchased and installed this spring. Previously, the feedback system for the electrostatic analyzer was controlled by a Micro PDP-11 micro-computer. This computer has been replaced by a personal computer with a Intel 486 microprocessor. The software package LabVIEW for Windows and a compatible data acquisition board were purchased from National Instruments to control the feedback system. The AT-MIO-16X data acquisition board is equipped with two 16-bit DAC's, eight ADC's, and eight digital I/O lines. This software package is a very powerful graphical programming language that can be used for many other control systems in the laboratory.

The analyzer control system is relatively straightforward. First, the desired beam energy is entered on our VAXstation 3200, which sends the energy to the PC over an RS-232 line. The PC determines a corresponding programming voltage to send to the analyzer plate power supplies and sends out that signal on the two DAC's. The PC next prompts a Fluke 8502A Digital Multimeter to sample the actual voltage difference across the two plates and then reads this value over a second RS-232 serial connection. Corrections for deviations from the desired value are made with a proportional-integral-differential (PID) control loop. If the actual plate voltage difference is outside an allowed deviation, data is turned off until the voltage returns within range. Energy deviations are graphed so that fluctuations can be easily monitored. The procedure continues to loop through this procedure, correcting the plate voltages and changing them when a new desired energy is sent from the VAX, until the experimenter stops the data acquisition.

5.3 Atomic Beam Polarized Ion Source

5.3.1 Routine Operation and Maintenance

E.R. Crosson, J. Dunham, and T.B. Clegg

The TUNL intense atomic beam polarized source has been used for experiments ~70% of the scheduled accelerator days in the past year. During this time, 113 days have been for experiments in the low energy experimental area, and 117 for experiments with the tandem accelerator. The source has been used during 124 days for polarized D^+ production, 76 days for polarized H^+ , and 30 days for unpolarized beams. Most of our routine effort has been directed toward maintaining the source for this heavy experimental program.

One significant period of difficulty arose when dissociator discharges became unstable for hydrogen operation, even while operating stably with deuterium. After considerable investigation, involving searches for leaks, adjustments of the rf coil exciting the dissociator discharge, and installation of a dissociator tube with a larger diameter region where the discharge is most intense, no significant improvement was achieved. Finally, when the N_2 gas input was moved from the region of the cooled dissociator nozzle to a point where it mixed completely with the H_2 in the dissociator

tube, the discharge stabilized immediately. With these changes, stable operation for at least two weeks has been routinely possible for experiments. There has also been a noticeable reduction after this length of time in the production of white SiO_2 powder deposited in the dissociator tube near the nozzle.

We continue to address problems with low beam polarizations when some rf cavities are used. Many problems were related to the sources constantly having to supply beams for experiments with widely different beam polarization requirements. Frequent changes to accommodate users have made it difficult to achieve optimum operation for anyone. Slowly during the past year, we have improved the reliability of most rf transition hardware, the associated external electronics, and all interconnections. New rf oscillators are being constructed and a new interface for users in the control room will be installed soon. We expect these efforts to remove most day-to-day difficulties. Remaining will be a more fundamental problem with the strong-field, 400 MHz cavity used for the deuterium $3 \leftrightarrow 6$ transition. Although we raised the cavity Q, we have been unable to raise the injected rf power level because of internal discharges between electrodes, probably from multipacting. Thus, it seems we must consider an alternative cavity design to raise the effective rf power at the beam.

5.3.2 Source Description and Documentation

E.R. Crosson, and T.B. Clegg

This year we have documented our entire program of atomic beam polarized source development work. Four manuscripts have been prepared for publication. One manuscript describing the 1992 proof-of-principle test of the spin-filter polarimeter concept has been accepted for publication. Three others describing (1) the overall source design, installation, and performance, (2) the rf transition systems used to polarize the beam, and (3) the ECR and cesium ionizer systems, have recently been submitted for publication. In addition, two conference reports on these activities will be published. Most important for the daily use of the source at TUNL, a complete manual has been written describing operation and routine maintenance procedures for the source.

5.3.3 Spin-Filter-Polarimetry

E.R. Crosson, C.D. Roper, and T.B. Clegg

The proof-of-principle test of the spin-filter cavity from our old Lamb-shift polarized source as an on-line polarimeter was reported in 1992. Since then, we have begun the engineering design to install such a polarimeter permanently on our atomic beam source. A conceptual view of this design is shown in Figure 5.3-1. A positive, polarized ion beam enters the cesium canal where, when needed, charge exchange in cesium vapor occurs to provide polarized negative ions. The spin-filter cavity will be placed immediately after this canal. There, it can be tuned to pass individual hyperfine

state populations of $2S_{1/2}$ metastable atoms emerging from the cesium canal before they become redistributed in changing local B-fields. Our tests have shown that under these conditions the populations reflect those of the original positive ion beam. Placing the cavity close to the cesium canal also maximizes the number of metastable atoms available for polarimetry. It also facilitates using the strong electric fields in the acceleration gap immediately following the cavity to cause the metastable atoms to decay. The Lyman- α decay radiation can then be reflected easily into an ultraviolet-sensitive phototube for detection.

Central to the use of the spin-filter polarimeter is having a B-field uniform to ≤ 0.05 mT over the spin-filter cavity. This uniform field must then be swept between 53 and 61 mT without destroying its uniformity, in order to reveal the desired relative hyperfine state populations. To assure that this will be possible in the installation shown in Figure 5.3-1, we have made computer calculations of the expected B-field, by using the code POISSON from LANL. Our results demonstrate that with the coil configuration shown and with magnetic shielding provided by the low-carbon steel plate placed between the cavity and the cesium canal, obtaining such uniformity will be possible, while lengthening the overall source by only ~ 28 cm to install the spin-filter cavity. The major design concern still being addressed is that of maintaining easy access to the cesium and ionizer regions of the source for routine maintenance.

5.3.4 Improved Polarized Beam Quality and Extraction Efficiency *E.R. Crosson, K. Veal, J. Dunham, and T.B. Clegg*

Recent results obtained during commissioning of the new atomic beam polarized ion source at IUCF have shown that up to $300 \mu\text{A}$ of positive polarized ion beam can be extracted from that source and momentum-analyzed into a Faraday cup. Although the polarization of this beam is yet to be measured (a spare spin-filter system from TUNL is being loaned to IUCF for this purpose), the fact that this large current is associated with the presence of the polarized atomic beam in the ionizer is highly encouraging.

We have recently begun at TUNL a program of geometry changes inside the beam extraction region from our sources ECR ionizer to try to obtain similar performance to that at IUCF. In our initial test we found that gridded apertures in the first two beam extraction electrodes led to some improvement in the output polarized D^+ beam. In our single test $60 \mu\text{A}$ was obtained in Faraday cup 4 m from the source after acceleration to 80 keV and momentum analysis, as compared with a typical 25 to $35 \mu\text{A}$ without gridded apertures. When this higher intensity beam was converted to D^- beam via charge exchange in cesium, the intensity gain was not so significant. The $8 \mu\text{A}$ obtained on the Faraday cup at the entrance to the tandem accelerator matched our best beams obtained before the apertures were gridded. Work is continuing to make further improvements in the beam and to measure accurately its emittance.

Figure 5.3-1 Schematic of arrangement for installing new spin filter polarimeter in line with the present atomic beam polarized source components.

5.3.5 Atomic Beam Transport Calculations

J. Coleman, T.B. Clegg, and W.J. Thompson

With the advent of permanent magnet sextupole systems having pole-tip fields of ~ 1.4 kG, it has been shown that combinations of such sextupoles can be found which perform significantly better than the existing electromagnetic sextupoles in the TUNL atomic beam system. At Heidelberg and Wisconsin, atomic beam fluxes improved by approximately a factor of three over that at TUNL are now routine in systems designed for use with polarized gas storage cell targets.

Following the lead of those developments, we are working on Monte Carlo calculations which model the trajectories of atoms in the beam between the dissociator nozzle and the ionization region. The code developed at Heidelberg and Wisconsin provided for numerical integration of the force on each atom along the trajectory. Though proven by comparison with experiment to be reliable, this underlying calculational technique is inefficient. There are known analytical solutions for the path of an atom as it passes through the central region of a magnetic sextupole, even when this sextupole is tapered along the axis. We have devised a new computer code using these analytical formulas which is several orders of magnitude faster than the previous code. In doing so, we plan to incorporate also the capability to search on dimensions and locations of the component sextupoles in the focusing system to find the optimum solution for any new TUNL system.

At the present time the coding is in progress. When finished in summer 1993, we will apply it to known systems at TUNL and Wisconsin to verify its reliability before using it to settle on a new design for a permanent magnet solution for the TUNL sextupole focusing system.

5.3.6 A Prebuncher for the Atomic Beam Polarized Ion Source at TUNL *C.R. Howell, C.D. Roper, D. Pennock, T.B. Clegg, W. Tornow, and R.L. Walter*

Motivated by the need for a high-efficiency beam pulsing system to perform polarized neutron time-of-flight measurements using beam from the TUNL atomic beam polarized ion source (ABPIS), in 1991 we started development of a prebuncher to compress the beam from the ABPIS into the 100-ns phase acceptance of the TUNL double-drift buncher system [Wen80]. We have demonstrated [How92] that the beam from the ABPIS can be compressed in time by modulating the voltage on the plasma limiting bars surrounding the electron-cyclotron-resonance (ECR) ionizer. In addition to proving the concept, we found that as the peak-peak amplitude of the applied sawtooth signal was increased towards the optimum voltage to form a time focus on target, the extraction efficiency of the seven-lens system on the ABPIS decreases. At the optimum ramping voltage of 180 V peak-to-peak, the beam intensity on the low-energy (LE) cup, located at the base of the tandem, was reduced by a factor of two from the non-ramped value.

Over the last year issues relevant to making the prebuncher a practical laboratory device were addressed. The sawtooth generator circuit was modified to improve its reliability, to increase its maximum output voltage capability, and to decrease the flyback time of the output signal. The main improvement was a result of adding a second EIMAC 4CX350A tetrode in parallel with the one in the output stage of the circuit. A time profile of the prebunched beam produced using the modified circuit is shown in Figure 5.3-2. The modifications to the circuit reduced the full-width at half maximum of the beam bursts from 44 ns to 24 ns and increased the efficiency into the 100-ns window

of the double-drift buncher system from 68% to 78%. Development work is continuing on the sawtooth generator circuit to improve the flyback time.

In November 1992 a series of measurements was made to gain insight about the cause of the beam intensity loss with increasing amplitude of the applied sawtooth signal. Beam intensity measurements were made on the LE cup for two solutions of the lens-1 voltage (VL1) setting, -4.8 kV and -1.0 kV, as a function of d.c. bias voltage on the ionizer cavity. The results for positive biasing voltages are summarized in Figure 5.3-3. For both VL1 settings the voltage applied to the other lenses were adjusted for optimal beam transmission to the LE cup with the ionizer cavity grounded. With the VL1 = -4.8 kV setting and all other lens voltages set as described above, we found that as little as -20 V d.c. biasing on the ionizer cavity almost extinguished the plasma. It is unclear why such a small negative bias severely affects the stability of the plasma, while a positive biasing voltage as high as 200 V seems to have little or no influence on the intensity of the plasma. We found that with the -20 V bias on the ionizer, the beam intensity loss on the LE cup could be regained with a slight increase of the rf power to the ionizer and minor adjustments to the voltages of the first three lenses. Modifications are being made to the first three electrostatic lenses and to the ECR ionizer plasma confinement cavity to improve the extraction efficiency of the ABPIS. The changes include installation of 98% transmission grids in the first three lenses. Measurements to determine the impact of these modifications on the prebuncher are planned.

Because the amplitude of the sawtooth signal applied to the ionizer needed to form an optimum time focus is mainly determined by the flight time of the particles through the extraction channel of the ABPIS, voltage adjustments to any of the seven electrostatic lenses in the extraction channel during running would require a compensational change in the sawtooth amplitude. At present the optimum time focus is found by performing a scattering experiment with the extracted beam after acceleration through the tandem [Wen80]. A high-frequency beam stop has been developed to make optimization of the sawtooth amplitude more convenient. This special beam stop enables a direct measurement of the time structure of the beam on the low energy end of the tandem.

[Wen80] S.A. Wender *et al.*, Nucl. Instr. and Meth. **174**, 341 (1980).

[How92] C.R. Howell *et al.*, TUNL Progress Report XXXI (1991-1992) p. 160.

Figure 5.3-2 Time profile of the energy-modulated beam. This spectrum was accumulated by elastically scattering deuterons from a gold foil in the 52° beam-line chamber. The amplitude of the applied sawtooth was 180 V peak-to-peak, and the lens-1 voltage setting was -2.5 kV.

Figure 5.3-3 Plot of beam current on the low-energy cup as a function of applied d.c. biasing voltage to the ECR ionizer cavity for two settings of the lens-1 voltage. See text for details.

5.4 Development of Techniques for Determining the Concentration of SF₆ in the Accelerator Insulating Gas Mixture

R. S. Hoffenberg, S. Mioduszewski, and W. S. Wilburn

For the past year, SF₆ has been added to the insulating gas mixture of the FN tandem accelerator to allow operation at terminal voltages approaching 10 MV. The nominal concentration of SF₆ is thought to be 10%, with the balance being a mixture of N₂ and CO₂. It is therefore important to have an accurate, reliable, and readily available means of determining the SF₆ concentration. Toward this end, we have been investigating two techniques. The first, an optical method for measuring the index of refraction of the gas, has been shown to work well. The second, an acoustical method for measuring the velocity of sound in the gas, is still under investigation.

The optical method for measuring the SF₆ concentration relies on the large difference in index of refraction between SF₆ and the other two gases. A gas cell is placed in one arm of a Michelson interferometer and is filled to 1 atm with a mixture of N₂ and CO₂ in the same ratio as the accelerator gas. This standard gas mixture is then replaced by a sample of the accelerator gas which is bled into the cell. The shift in optical interference pattern due to the change in index of refraction between the two gasses is observed. This shift can be measured to a precision of 1/4 fringe, corresponding to a SF₆ concentration of approximately $\pm 0.3\%$ absolute. The technique has been tried on standard mixtures having SF₆ concentrations of 3, 6, and 10%. The results agree with these values within the precision of the measurement.

The acoustical method for measuring the concentration of SF₆ relies on the large difference in sound speed (approximately a factor of 1/3) between SF₆ and the other two gases. A resonant tube is filled with the N₂-CO₂ mixture at a pressure of 1 atm and is driven at one end by a speaker connected to a signal generator. Accelerator gas is bled into the tube and the change in resonant frequency observed. A test apparatus has been constructed and its sensitivity is presently being investigated.

5.5 Production of Beams and Targets

5.5.1 Measurement of the ${}^7\text{Li}(\bar{p}, \bar{n}){}^7\text{Be}$ Polarization Transfer Coefficient at 0°

C.D. Keith, W.S. Wilburn, C.R. Gould, D.G. Haase, W. Tornow, N.R. Roberson

The ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction has been used for over fifty years as a source of low energy, monoenergetic neutrons from threshold (1.881 MeV) to the ${}^7\text{Li}(p,n){}^7\text{Be}^*$ threshold at 2.373 MeV [Lis75]. We have made preliminary measurements of the transverse polarization transfer coefficient $K_y^{y'}(0^\circ)$ to determine whether this reaction can serve as a source of low energy polarized neutrons. Previous measurements [Rob69] have been made at much higher energies, $E_p=30$ and 50 MeV, and were found to be consistent with $K_y^{y'}(0^\circ) = 0$. At these energies neutrons are also produced via the

${}^7\text{Li}(p,n){}^7\text{Be}^*$ reaction. Since the two neutron groups were not discriminated in this experiment, it was concluded that the competing groups may have averaged to produce no observed polarization transfer. The TUNL measurements were made at proton energies between 2.6 and 5.0 MeV, where the ${}^7\text{Li}(p,n){}^7\text{Be}^*$ reaction is negligible.

The polarization of neutrons from the ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction is well documented [Roh73]. However, the polarization is non-zero only for angles greater than 0° . Furthermore, the reversal of the neutron spin requires the added complication of a spin-precession solenoid. At TUNL the ${}^3\text{H}(\bar{p},\bar{n}){}^3\text{He}$ and ${}^2\text{H}(\bar{d},\bar{n}){}^3\text{He}$ reactions are used to produce polarized neutrons at zero degrees from approximately 2 - 20 MeV. It is hoped, following more intensive measurements of $K_y^{y'}(0^\circ)$, that the ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction can be used to extend polarized neutron experiments in this and similar laboratories to 100 keV or lower.

The polarization of the neutrons was determined by measuring the left-right scattering asymmetry from a ${}^4\text{He}$ gas cell. This technique has also been used to measure $K_y^{y'}(0^\circ)$ for the ${}^3\text{H}(\bar{p},\bar{n}){}^3\text{He}$ reaction. Preliminary results are shown in Table 5.5-1. Only errors arising from statistics are included.

Table 5.5-1 Measured polarization transfer coefficients for the ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction.

E_p (MeV)	E_n (MeV)	$K_y^{y'}(0^\circ)$
5.00	3.33	0.22 ± 0.07
3.60	1.92	-0.09 ± 0.05
3.00	1.31	0.00 ± 0.07
2.60	0.89	0.32 ± 0.06

[Lis75] H. Liskien and A. Paulsen, Atomic Data and Nuclear Data Tables **15** (1975) 57.

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[Roh73] U. Rohrer and L. Brown, Nucl. Phys. **A217** (1973) 525.

5.5.2 Measurements of the ${}^3\text{H}(\bar{p},\bar{n}){}^3\text{He}$ Polarization Transfer Coefficient at 0°

C. R. Gould, D. G. Haase, P. R. Huffman, C. D. Keith, N. R. Roberson, W. Tornow, and W. S. Wilburn

The polarization transfer reaction ${}^3\text{H}(\bar{p},\bar{n}){}^3\text{He}$ is commonly used to produce polarized neutron beams at energies of a few MeV, both at TUNL and at other nuclear physics facilities. The polarization transfer coefficient, $K_y^{y'}$, for this reaction at 0° was measured at the LANL in 1972 [Hai72]. At TUNL we have recently repeated this

measurement at three energies of particular importance to our research. The results of our measurement are in good agreement with the earlier values.

In order to determine $K_y^{y'}$, the polarization of both the incoming proton beam and the outgoing neutron beam must be determined. The proton beam polarization is measured by the inelastic scattering of protons from a 5 μg thick carbon foil. As the analyzing power is known for this reaction, the polarization can be determined by observing the asymmetry in count rate between two detectors placed symmetrically about 0° . In our case, two silicon charged-particle detectors are placed at $\pm 40^\circ$. The pulse-height signals for each detector are read into an ADC and stored in one-dimensional spectra as number of counts versus energy. The elastic scattering peak is easily distinguished from other peaks and there is little background.

Measuring the neutron beam polarization is more difficult, as the neutron energy must be determined by time-of-flight and there is much more background. The neutron polarimeter consists of a ^4He gas cell at a pressure of 100 atm with a small amount of added xenon. Two pair of liquid scintillator-photomultiplier tube detectors placed symmetrically about the beam direction detect the scattered neutrons. The gas cell acts as an active target, scintillating from the recoiling α -particles. Photomultiplier tubes on the top and bottom of the gas cell detect the light of scintillation. Neutron time-of-flight is determined by measuring the time between the α -recoil signal and the neutron detector

Figure 5.5-1 The polarization transfer coefficient $K_y^{y'}$ for the reaction $^3\text{H}(\bar{p}, \bar{n})^3\text{He}$. The TUNL data are shown with crosses, while the LANL data are shown with squares.

The new TUNL data are plotted in Figure 5.5-1 along with the previous LANL data. As can be seen from the figure, the two sets of measurements are in agreement.

[Hai72] R. C. Haight, J. E. Simmons, and T. R. Donoghue, *Phys. Rev. C* **5**, 1826 (1972).

5.5.3 Calculations of Neutron Beam Depolarization in Magnetic Fields W. S. Wilburn

A beam of polarized particles passing through a magnetic field will have the spin directions of the particles rotated about the field direction. If the magnetic field is not homogeneous, different parts of the beam will experience different spin rotations, resulting in a net depolarization of the beam. This effect is particularly important with brute-force type polarized targets such as those used at TUNL, as a polarized neutron beam must pass through a very strong magnetic field up to 7 T in the target. Calculating the effective depolarization of the neutron beam is therefore very important.

The computer code NEUTRONS has been written at TUNL to calculate the depolarization of neutron beams in magnetic fields by performing a Monte Carlo simulation. The code selects random trajectories and calculates the rotation of the spin direction along each trajectory. The spin rotation is obtained by constructing an initial spin state and applying a rotation operator for each step along the trajectory. The steps are made small enough so that the individual rotations can be approximated as infinitesimal rotations. After all trajectories are calculated, spin projections are computed for the final spinors and averaged over all particles. From the average spin projection along the polarization axis, the effective depolarization can be calculated.

In order to calculate the spin rotations, the magnetic field along the beam path must be known precisely. In the case of the TUNL polarized proton target, the magnetic field is due to a superconducting split-coil solenoid with a maximum field of 7 T. The field of the magnet has been calculated on a grid with 1 mm spacing in the region which the neutron beam traverses. The field due to each winding was calculated analytically and the sum of field due to each winding computed. Calculations show that for this target the neutron beam depolarization for energies above 2 MeV is less than 1%. This is the minimum energy at which experiments have been performed with this target. Future experiments, however, plan to go to lower energies or use different geometries where the effect will be larger. It will be possible to use this code to calculate corrections to the neutron beam polarization for these cases.

5.5.4 A Solid, Polarized ^3He Target for Polarized Neutron Scattering

C.D. Keith, C.R. Gould, D.G. Haase, P.R. Huffman, N.R. Roberson, W. Tornow, W. S. Wilburn

In April 1993, the sample container for the solid, polarized ^3He target was installed in the TUNL spin-spin cryostat. As detailed in the 1991 - 1992 TUNL Progress Report, the coin silver container has a sample volume of 13.4 cm^3 . A ^3He - ^4He dilution refrigerator will be used to cool the target to approximately 10 mK inside a 7 Tesla external magnetic field produced by a NbTi superconducting magnet. The polarization of solid ^3He in a 7 Tesla field varies between 25% at 20 mK and 40% at 10 mK.

For the preliminary measurements, the sample volume has been filled with silver powder (300 - 600 micron diameter) at a 29% packing fraction. The powder will provide excellent thermal contact between the coin silver container and the solid ^3He . Therefore the polarization of the ^3He can be determined by measuring the temperature of the sample container. Three independent means of thermometry will be used for this purpose: RuO₂ resistors [Li86]], ^{60}Co nuclear orientation thermometry [Mar83], and ^3He melting curve thermometry [Kei92].

We will also investigate a novel method to determine the target polarization by nuclear means. The polarization of *liquid* ^3He is well determined, and is essentially temperature independent below 50 mK. While the polarization is small (approximately 5%), it may be possible to measure the spin-dependent scattering of polarized neutrons from a polarized liquid ^3He target. This measurement could then be used to calibrate the polarization of the *solid* ^3He target.

In order to solidify ^3He , liquid ^3He must be pressurized to a minimum of 29.3 bar, and the density of the solid is pressure dependent. With this in mind, a pressure-sensitive capacitive strain gauge, incorporated in the design of the target, will be used to determine the density of the solid ^3He . A high precision, 0 - 70 bar, Bourdon tube will be used to calibrate the strain gauge at 4K. A room temperature gas handling system has been constructed and filled with the 21 liters of ^3He necessary to operate the target. Initial attempts to cool and solidify the target were hampered by a small leak in the sample cell. Effort is being made to locate and repair the leak.

[Li86] Q. Li *et al.*, Cryogenics 26 (1986) 497.

[Mar83] H. Marshak, J. Res. Nat. Bur. Stand. 88 (1983) 175.

[Kei92] C.D. Keith *et al.*, Hyperfine Interactions 75 (1992) 525.

5.5.5 Techniques for Tests of Fundamental Symmetries in Compound-Nucleus Scattering with Epithermal Polarized Neutron Beams

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A paper with the above title was published in Nuclear Instruments and Methods in Physics Research. The abstract of the paper follows:

The epithermal polarized-neutron beam facility used for tests of fundamental symmetries is described. The initial unpolarized beam is obtained from the spallation source at the Los Alamos Neutron Scattering Center. Characteristics of the polarized and unpolarized beams are described, as well as design and performance of a fast-spin reversal system, neutron flux monitor and target cooler. Experimental results for polarized-neutron transmission experiments are given to illustrate the overall quality of the system.

This paper brings together and discusses in one report the various components that have been used by the TRIPLE collaboration for parity violation tests with polarized epithermal neutrons. Several items, such as the dynamically polarized proton target used to polarize the neutron beam, the spin-flipper and the ³He ion chamber used as a beam monitor, have been described in other publications.

This paper discussed in detail the 8-step spin sequencing (the order in which the spins are flipped during a measurement), how it minimizes the effects of time-dependent gain drift in the detectors and how it removes the effects of the spin flipper magnetic fields on the detectors. Brief descriptions are also given of the performance of the target cooler and the data acquisition system. Also of major interest is the discussion of the flux measurements for the LANSCE neutron beam.

5.5.6 A Portable 17.3 MeV Gamma-Ray Source

R. M. Chasteler and H. R. Weller

The use of large NaI(Tl), HPGe and organic scintillators for detection of high energy gamma rays, ≥ 8 MeV, has always suffered from the lack of a calibration standard near these energies. Extrapolation using Alpha/Beryllium sources has been the normal

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technique used which requires extrapolating from 2.2- and 4.4-MeV gamma rays, and in the case of NaI(Tl) detectors the 6.8-MeV thermal neutron capture on Iodine gamma-ray. When the actual measurements of ≥ 20 MeV gamma rays are needed, this extrapolation can produce large errors. Also, the determination of a detector's resolution for gamma-ray energies in the vicinity of 15 MeV has required the use of reactions like $^{12}\text{C}(p,\gamma)$ at accelerator energies.

The $^7\text{Li}(p,\gamma)^8\text{Be}$ reaction is a good candidate for a high-energy gamma-ray source due to its high Q-value, 17.3 MeV, and large cross section at low beam energies. Yields of $(7.4 \pm 0.2) \times 10^4$, $(8.0 \pm 0.2) \times 10^4$, and $(9.2 \pm 0.2) \times 10^4$ γ -rays/Coul./Sr. were measured for lab angles of 0° , 45° , and 90° , respectively, at a proton energy of 80 to 0 keV. On the basis of previous measurements of the energy dependence of the cross section, we calculate that these numbers would increase by a factor of ~ 3.2 [Cec92,Rol86] by using protons at 100 keV. If a 100 μA source of 100 keV protons were available, this translates into ~ 1800 of 17.3-MeV γ -rays/sr/min.. Also, the 14.3-MeV gamma ray going to the first excited state in ^8Be will have count rates that are ~ 3.4 times larger.

A device that uses the above reaction to produce a high energy gamma-ray flux could possibly be constructed using a modified Zetatron Neutron Tube [Wei91]. The Zetatron neutron tube is a neutron generator system, in a compact (1.5" diameter by 5.0" long cylinder inside a 6" by 9" insulating cover) accelerator/target tube with an external power supply system. Such a system is extremely convenient and portable. The device produces neutrons by accelerating deuterium and tritium at a deuterium/tritium loaded target. This device should be able to be easily modified to have protons in its reservoir and a ^7Li target. The main advantage of modifying a Zetatron tube would be cost. Devices of this sort presently cost on the order of \$50,000-\$60,000.

The acceleration section of a Zetatron tube runs in a pulsed mode at varying rates of 1 Hz to 10 kHz but with an average tube current of ~ 100 μA . The device listed in [Wei91] uses a power supply of 0-85 kV. Using the yield number above at 80 keV and assuming 100 μA of beam, the device would yield 550 17.3-MeV γ -rays/Sr./min. and 2540 14.3-MeV γ -rays/Sr./min.. If this device could be modified to handle a 100 kV power supply, these numbers would be increased by a factor of ~ 3.2 . Of course, even higher voltages would result in larger yields. Note that although the 14.3 MeV line will have an intrinsic width of 1.5 MeV [Ajz88], the 17.3 MeV line should have an intrinsic width determined by the beam energy loss in the target which, since 99% of the yield is created in the first 50% of the beam energy loss, is substantially less than 50 keV when a 100 kV power supply is used.

This work has been submitted for publication in *Nuclear Instruments and Methods*.

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- [Wei91] J. H. Weinlein, M. L. O'Neal and F. M. Bacon, Nucl. Instr. and Meth. B56/57, 904 (1991).
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5.6 Detector Systems

5.6.1 Installation of the Enge Split-Pole Magnetic Spectrometer

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The TUNL split-pole spectrometer obtained from Michigan State University has been installed and upgraded in two stages with funds provided by the DOE. Construction has been finished, except for the installation of the sliding-seal target chamber, which is nearing completion in the Duke instrument shop. Once the interface to the magnet power supply is finished, all vacuum and control systems will be operational.

During the summer of 1993 we will perform final calibrations and several commissioning tests: 1) Beam will be run to the target chamber to test the optics and alignment of the beamline. 2) Spectrometer performance will be measured with the aid of an alpha source in the target position, followed by tests with beam. Baring unforeseen problems, we expect the spectrometer to be ready for initial experiments in late summer 1993.

Once the split-pole spectrometer is operational, we plan to develop two new focal-plane detectors to complement the 18 cm-long Si PSD telescopes that we already have on hand. The first will be a telescope of single-wire proportional counters backed by a plastic scintillator. This type of detector is simple to use and is immune from radiation damage, but possesses only modest position resolution. The second detector will be a multi-wire proportional counter which will offer better position resolution than either of the other detectors and will also measure angle of entry. This latter feature will allow us to measure and correct for spectrometer aberrations, permitting us to operate at larger solid angles.

5.6.2 Compton-Suppressed γ -Ray Spectrometer

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The Compton-Suppressed Spectrometer (CSS) consists of two 60% efficient High Purity Germanium (HPGe) detectors and a Bismuth Germanate (BGO) anti-coincidence suppression shield. One of the HPGe detectors will insert transversely into the BGO shield. In the High Resolution Laboratory (HRL) the previous γ -ray scattering chamber

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was not equipped to handle these new detectors. Therefore a completely new chamber and detector carriage system was designed.

Requirements for the scattering chamber included a multiple-position target ladder, a high-voltage connection to the target rod for the homogenizer correction signal, and a charged particle detector inside the chamber. The new chamber can hold 6 different targets simultaneously, uses a BNC connector for the homogenizer feedback signal, and has a surface-barrier detector at 165° with respect to beam direction and slightly out of plane for improved detector view of the target.

The detector carriages also had to meet a number of requirements. The carriages had to accommodate both of the HPGe detectors (with their large liquid nitrogen dewars) and the BGO detector. The detector mounts had to allow one HPGe detector to be inserted into the BGO shield and to move with the shield. Both the BGO suppression shield, along with its HPGe detector, and the unsuppressed HPGe detector must pivot independently about the center of the chamber. The suppressed detector carriage required a secondary pivot to allow the BGO and suppressed HPGe detectors to move together as one unit while the HPGe detector remains perpendicular to the incoming γ -rays. These detectors must have the capability to move radially outward from the chamber, in order to allow for changes in the subtended solid angle and for ease of installation.

Another requirement was as large as possible a detector angular range. The angular range achieved for the suppressed detector was from 55° to 125° with respect to the beam direction. In order to achieve this angular range, the BGO detector must be flipped over, and the HPGe detector inserted from the other side. Thus, the detector carriages had to be designed to be compatible with each detector orientation. It was also desirable for the unsuppressed HPGe detector to cover as large an angular range as possible without greatly decreasing the solid angle by increasing the detector-target distance. A design which meets all of these goals was developed; a top view of the arrangement is shown in Figure 5.6-1.

Another major requirement of the system was a semi-circular table top to support lead shielding for the unsuppressed HPGe detector and a NaI detector that will be used for comparison with previous data. The previous γ -ray scattering chamber had a complete circular table that allowed several NaI detectors to be placed upon it for the measurement of angular distributions. We wanted to retain the possibility of using this same type of detector configuration. Our design allows this configuration if the BGO suppression shield and its suppressed HPGe detector are removed; another semi-circular table top can then be attached to make a complete circular table top, which will once again permit several NaI detectors to be used.

The entire detector system is supported from a 2-m-diameter steel plate. This plate has the central pivot which will be aligned with the center of the scattering chamber, as well as angle indications on the edge which will enable the detector carriages to be set at a particular angle. The detector carriages roll along the top of this plate as they pivot about the central axis. The semi-circular table top is supported from this plate as are other beamline supports. A Faraday cup is supported from the floor at the end of the

beamline, which is located just past the edge of the plate. The Faraday cup system includes a table for lead shielding and beamline support.

The design phase is complete. The HPGe detector mounts have been fabricated and are currently being installed. We are awaiting arrival of the BGO crystal so that some final measurements can be obtained before submitting the last few pieces of its support system to the instrument shop for fabrication.

Development of an appropriate data acquisition system has also been underway. The system must be able to collect, display, and perform preliminary analysis online for the two HPGe detectors, both singly and in coincidence, as well as for the surface-barrier detector, and one or more NaI detectors. In addition, we wish to maintain compatibility with our previous HRL data acquisition software whenever possible.

All software employed in the data acquisition uses the XSYS data acquisition and analysis package. The coincidence circuitry is standard, using a TAC module started and stopped by the two HPGe detectors to determine time coincidences. At this point we have incorporated the capability of sorting online on both the TAC prompt peak and on either of two γ -ray peaks (the number of γ -ray peaks can easily be increased if desired) in each HPGe spectrum. We chose Tennelec TC245 amplifiers to process the HPGe signals, primarily because of their ability to perform automatically ballistic deficit correction; this feature is especially desirable for shorter shaping times on large HPGe detectors. Both the HPGe signals and the TAC signal are processed through an Ortec AD413 CAMAC ADC; software determines whether an event is singles or coincidence and sorts accordingly. Coincident events can be recorded in event mode.

The spectra from the surface barrier detector and NaI detector(s) are processed by multiplexing them through a CAMAC buffered memory module (as we have done for many years). However, we have redesigned and rebuilt much of the associated circuitry to improve flexibility and reliability. These hardware changes necessitated corresponding changes in software as well.

The HRL VAXstation 3200 has an 8 mm tape drive. This drive allows recording spectra at much higher density than the 9-track reel-to-reel drive previously used, but its speed is drastically slower. Thus, for situations where excitation functions are being measured at a rate of 2 or 3 points per minute, recording of spectra directly to the tape drive is no longer practical. We have changed all of our data acquisition software to write to disk instead of tape; we have also created a program, to be run in batch mode, which will write available spectra from disk to tape and then delete the disk file. This batch job will be started when one logs on and does all the data area creation and setup; it will continue to run until all files are written to tape and the experimenter has logged off, indicating that further files are not forthcoming.

Extensive testing of the data acquisition system has been performed. We believe that all of the software is working properly and that optimal settings of the electronics modules have been found. The only remaining task of this nature is to set up the veto circuitry for signals from the BGO shield, which awaits arrival of the shield. As part of

Figure 5.6-1 A top view of the spectrometer showing one possible position of the various detectors. In this orientation, one HPGe detector is at 20° relative to the beam, while the other (inserted into the BGO shield) is at 90° .

the testing, we have performed several tests and calibrations with the HPGe detectors and our NIM electronics. In particular, we have measured the energy and timing resolution and the energy calibration and relative efficiencies of these detectors. The results of our tests and measurements are described below.

We have tested the energy resolution (full-width at half maximum) using the high-energy line (1.33 MeV) in ^{60}Co . Tennelec TC245 spectroscopy amplifiers were used with triangular shaping at 8 μs peaking time and with ballistic deficit correction circuitry selected. FWHM values of 1.77 and 1.78 keV were obtained for the two detectors, consistent with the manufacturer's specifications.

The timing resolution of the HPGe detectors was measured using standard fast-timing electronics. The timing tests were carried out using the two γ -ray lines from a ^{60}Co source and using a NaI detector as the reference. With an energy threshold of about 100 keV in the HPGe electronics, FWHM values of about 10 ns were obtained for each HPGe detector. The timing FWHM for HPGe-HPGe coincidence tests was about 20 ns.

Essential to any high quality γ -ray measurement is the ability to obtain both the energy and efficiency calibrations for the detectors. For low-energy γ -ray spectroscopy ($E_\gamma < 2$ MeV), commercially available sources such as ^{152}Eu are typically used. However, it is difficult to extrapolate the energy and efficiency calibrations from the highest energy lines in such a source (~ 1.4 MeV) up to the maximum energies of interest in our measurements (~ 8 MeV for proton capture on ^{29}Si). Therefore, we produced a ^{66}Ga calibration source which contains several γ -ray lines ranging in energy from about 800 keV up to 4.8 MeV.

The disadvantage of this source is that its half-life is only 9.5 hours. Following the procedure of [Ald93], we produced a ^{66}Ga source using the reaction $^{63}\text{Cu}(\alpha, n)^{66}\text{Ga}$ at $E_\alpha = 18$ MeV. Our targets were 1.0 mm thick, natural Cu foils. Alpha beam currents of about 1 μA on target were supplied by the TUNL tandem accelerator. We found that irradiation times of 20-30 minutes are sufficient to produce sources of reasonable strength. In order to reduce the intensity of γ -rays from the decay of ^{68}Ga ($T_{1/2} = 68$ min.) produced by $^{65}\text{Cu}(\alpha, n)$, one should let the source decay for at least 8 hours before using.

Figure 5.6-2 shows the spectrum obtained in one of our HPGe detectors accumulated from the combination of ^{152}Eu and ^{66}Ga sources. This spectrum was obtained in about 5 hours. In order to extract efficiency curves and energy calibrations, the γ -ray intensities and centroids were fitted to Gaussian shapes using the analysis code GELIFT. The experimental centroids and intensities were then compared to the known energies and intensities of the γ -rays emitted by the sources. The codes ENCAL and EFFIT were then used to obtain the energy and efficiency calibrations, respectively. The energy calibration consists of a linear fit of energy vs channel number, and the differences between the fit and true energy values were generally within 0.2 keV.

The lower part of Figure 5.6-2 shows a plot of the measured data points for the relative efficiency; the solid line corresponds to the fitted efficiency curve. The fitting

CSS System

TopView

Scale 1":1'

Figure 5.6-2 The upper two curves show a spectrum for ^{66}Ga and ^{152}Eu sources for one of the HP/Ge detectors. The lower curve shows the relative efficiency measurements and the resulting fit.

function consists of a 7-parameter product of exponential functions. The presence of data points out to energies of 4.8 MeV allows a more reliable extrapolation of the relative efficiency to the highest-energy range of interest to the present experiments. We plan to augment the source calibrations with in-beam measurements of resonances that produce very high-energy γ -rays and have known branching ratios. This procedure will allow us to have a full calibration coverage of the γ -ray energy range for our $^{29}\text{Si}(p,\gamma)$ experiments.

[Ald93] C. Alderliesten *et al.*, private communication and to be published.

5.6.3 New Möller Polarimeter for Hall B at CEBAF

R. M. Chasteler and H. R. Weller

With the promise of higher energy electron beams, 6 GeV, at CEBAF than the originally promised 4 GeV, re-evaluation of the original Möller Polarimeter design [Cha92] for Hall B was undertaken. The previous single-quadrupole design would not work for 6 GeV in the 7 m space allotted for this device. Since the quadrupole being used in the previous design is one of a dozen salvaged devices from SLAC, the possibility of using more than one quadrupole for this device was investigated. It was found that using two of these quadrupoles that a single targeted design can be constructed in the space allotted. An overhead graphic of this design is shown in Figure 5.6-3. This new design has quite a few advantages over the single quadrupole model: 1) it operates over a much larger electron energy range from 400 MeV to 6 GeV, 2) it uses only one target which is important since the target is a polarized electron target that requires external field coils to induce the polarization and pickup coils to measure this polarization, and 3) produces similar center of mass angular distributions at the detectors independent of energy making detector design and coincident electron detection easier. The main drawback of the two quadrupole design compared with the single quadrupole design is the cost for an extra power supply for the second quadrupole. In the two quadrupole design, Quad-1 is focusing in the horizontal plane at beam energies less than 2 GeV and then defocusing at energies above, while Quad-2 is defocusing in the horizontal plane at all beam energies.

Solid-angle calculations for this design have been done and count rates determined for the following criteria: 1) 1/2 mil Vanadium-Permendur target foil with it's plane at 20° wrt. the beam, 2) 10 nA of 50% longitudinal polarized electrons, and 3) 8% of the target electrons polarized. With these rates and the definitions of Möller electron scattering cross-sections and asymmetries [Ols68], the beam polarization will be able to be measured to within 3% statistical accuracy in 60 sec at 1 GeV, 155 sec at 2 GeV, 366 sec at 4 GeV, and 615 sec at 6 GeV. Increases in beam intensity or polarization or target thickness will decrease the measurement time linearly. Varying the statistical uncertainties will vary the measurement time as a ratio of the squares of the uncertainties.

- [Cha92] R. M. Chasteler and H.R. Weller, TUNL Progress Report XXXI 1991-1992, A Quadrupole Möller Polarimeter for Hall B at CEBAF.
- [Ols68] H. Olsen, *Springer Tracts in Mod. Phys.* 44 (1968) 83.

Figure 5.6-3 New Double Quadrupole Möller Polarimeter design for Hall B at CEBAF.

5.6.4 Data Acquisition and Analysis for Hall A at CEBAF

C.R. Howell, J.M. Finn¹, R. Gilman², G. Kumbartzki², P. Ulmer³

As part of our instrumentation obligation to the Hall-A collaboration, we are developing the data analysis and instrumentation controls systems for experimental hall A at CEBAF. An overview of the proposed system was given by Howell *et al.* [How92]. The major design concepts were approved in an external review in December 1992. The main two recommendations were: 1) to collaborate closely with halls B and C to avoid duplication of common components and for consistency between experimental halls, and 2) to use remote procedure calls (RPC) instead of shared memory for process communication when possible, since RPC's are more portable across operating systems and enable communication over networks. The schedule for the project is shown in fig. 1. A functional system with documentation must be available by September 1994 when the detectors start arriving at CEBAF for installation on the two high-resolution magnetic spectrometers in Hall A. The following system components are being developed during the summer 1993 and should be ready by September 1993: 1) X-window histogram display/interface; 2) X-window scalar display/interface; 3) Drawings for major system controls to be used in the graphical interface for instrumentation monitoring and control; 4) event unpacker for CAMAC and FASTBUS; and 5) event driver for intelligent scanning ADCs with built-in alarm lines -- these ADCS will form the foundation of instrumentation monitoring in Hall A. For compatibility with the CERN software library

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Fig. 1. Schedule for development of the CEBAF Hall-A data acquisition/analysis and instrumentation control/monitoring systems.

the histograms will be booked and filled using HBOOK calls. A slightly modified version of the Hall-C test package will be used. The Hall-C parameter interface will be used unmodified.

- [How92] C.R. Howell *et al.*, AIP Conf. Proc. No. 269, eds. F. Gross and R. Holt, The CEBAF 1992 Summer Workshop, Newport News, VA (June 1992)p. 512.; C.R. Howell *et al.*, TUNL Progress Report XXXI (1991-1992) p. 138.

5.6.5 Bolometers and Compact Dilution Refrigerator

D. Junkin, T. P. Murphy, A. E. Champagne, D. G. Haase

The optimum operating temperature for cryogenic bolometers is the 50 - 100 mK range where the specific heat of most materials is at a minimum and one can take

advantage of low thermal noise. Testing of bolometer designs also require a refrigerator that can be cycled from room temperature to 100 mK and back within a few hours. We have built and are completing testing of such a refrigerator, which is a modification of a design by G. Frossatti [Fro 92]. The design was chosen because it is simple to construct and requires fewer solder joints than traditional refrigerators. The Frossatti refrigerator also should be capable of lower temperatures and higher cooling powers because it uses teflon heat exchangers, which have a lower thermal resistance. Unfortunately, the original Frossatti refrigerator is constructed mainly from PVC tubing and requires plastic to metal seals which can be troublesome on repeated use. We have reworked the design to employ more dependable construction materials such as stainless steel and brass, and reliable indium O-ring seals.

We have constructed a complete dilution refrigerator cryostat and gas handling system, along with associated temperature measurement and control electronics. The refrigerator was designed to reach less than 50 mK at a ^3He flow rate of 100 micro-moles per second and a cooling power of about 40 microwatts at 100 mK. In initial tests the refrigerator has cooled to 250 mK, probably limited by ^3He phase instabilities in the condenser or still. New flow impedances are being installed to correct the problem. The refrigerator is very reliable, has developed few leaks, and can be cooled from room temperature to mK temperatures in a few hours. The refrigerator system is now ready for initial tests of bolometric detectors.

[Fro 92] G. Frossatti, *J. Low Temp. Phys.* **87**, 595 (1992).

5.6.6 Development of cryogenic microcalorimeters

D. Junkin, T. Murphy, D.G. Haase, A.E. Champagne,

By virtue of their small size and low heat capacity, microcalorimeters operated at cryogenic temperatures exhibit very high energy resolution combined with low threshold energy. If these devices are to operate optimally, they must have a steep response to temperature change and proper thermal conductance. Since our detectors are based upon thermistor readout (as opposed to e.g. a superconducting transition edge), we require a large dR/dT . Thermal conductance is a compromise between signal size (low conductance) and temperature relaxation (high conductance).

Thermistors were produced via standard techniques at the North Carolina State University Microelectronics Center. Boron-doped silicon wafers (4-6 ohm/cm) were labeled, cleaned and coated with silicon-dioxide. The silicon-dioxide layer was then patterned into 8000 different resistors (having 25 different configurations) through photolithography. The wafers were implanted with phosphorus at the Microelectronics Center of North Carolina. A modeling program was used to predict the implantation energy and dosage needed to produce a doped region at the metal-insulator transition (i.e. at a density of $3.78 \times 10^{18} \text{ P/cm}^3$). Titanium and aluminum contact pads were placed at

both ends of the resistive implanted regions. The resistors were checked at room temperature and found to have the desired resistivity with good contact between the contact pads and the implanted region and were then diced into 1 mm x 1 mm squares. The electrical and thermal contact to the chips were made by wedge bonding gold wire to the aluminum contact pads and a gold plated standard chip carrier. Unfortunately, the room-temperature resistivity is not at all indicative of resistance at low temperatures. Therefore, we have also performed a test at 77 K and are preparing a further measurement in our new dilution refrigerator.

5.7 Updating of TeX, Psprint, and Associated Programs on the VAX Cluster **B. W. Raichle, S.E. Edwards, P.R. Huffman, and W. S. Wilburn**

Several problems were realized with TUNL's electronic typesetting capabilities on the VAX. These include: 1) outdated versions of source code; 2) the inability to print graphics on the VAX; 3) lack of documentation; 4) the inability to easily update. To address these concerns, it was decided to completely reinstall TeX and LaTeX, and to replace psdvi with dvips, in effect, start from scratch. Development was initially done on a VAX workstation (VS09) not on the cluster. Once debugged, the package was moved to the TUNL machine.

Startup information was placed in `tex_startup.com` in the system startup directory. On-line VAX help files were updated. All files are found in the directory `sys$common:[tex]`. Files for this project were obtained through anonymous ftp from various sites including `labrea.stanford.edu` (TeX), `ymir.claremont.edu` (misc. VAX files), and `niord.shsu.edu` (LaTeX). Documentation can be found in three-ring binders in the computer room. In summary, we have updated our electronic typesetting capability with the most recent versions of software we could find. In the process, we have gained the ability to print graphics, created a convenient way to produce quality documents, including submission ready journal articles, and gained much insight into the workings of TeX.

6. EDUCATIONAL ACTIVITIES

6.1 Nuclear Physics Summer School

(C.R. Gould, D.G. Haase, N.R. Roberson, W.J. Thompson)

TUNL and local nuclear theorists have organized and will host the Sixth Annual Summer School on Nuclear Physics Research, which will be held on the campus of North Carolina State University, July 11-25, 1993. About 55 advanced graduate students or recent Ph.D.'s will attend the program. The attendees come from over 15 universities in the US, and from South America and Europe. The Summer School is being supported by a National Science Foundation grant to Oregon State University and a Department of Energy Contract with the Institute for Nuclear Theory at the University of Washington.

The Scientific Chairman of the Summer School are Berndt Müller of Duke University and Russell Roberson of Duke and TUNL. The local organizing committee includes C. Gould, D.G. Haase, and C.R. Ji of NCSU; B. Müller, N.R. Roberson, and R.P. Springer of Duke; and W.J. Thompson of UNC. The speakers for the school and their topics are:

- High Spin States and Superdeformed Nuclei - Jerzy Dudek, Strasbourg
- Nuclear Few-Body Systems - James Friar, Los Alamos National Laboratory
- Relativistic Nuclear Collisions - Johanna Stachel, SUNY - Stony Brook
- Electron Scattering - Dirk Walecka, College of William and Mary
- Weak Interactions in Nuclear Physics - John Wilkerson, Los Alamos Nuclear Laboratory.

Professors R.P. Springer of Duke, and C.R. Ji of NCSU will give shorter presentations on Effective Models for the Nuclear Interaction and Nuclear Physics on the Light Cone, respectively.

The format of the courses will include lecture and discussion sessions each morning and afternoon. Each night the lecturers will hold office hours for discussions with students and students have been invited to give short presentations on their own research programs.

I Graduate Degrees Awarded

Ph.D. Degrees

1. Susan K. Lemieux, "A Spin-Filter Polarimeter and an Alpha Particle D-State Study," Ph.D. degree, UNC. *Supervisor* - T.B. Clegg
2. Kurtis A. Fletcher, "Tensor Analyzing Power Measurements for $D(d,p)^3H$ and $D(d,n)^3He$ at Very Low Energies", Ph.D. degree, UNC. *Supervisor*- E.J. Ludwig
3. W. Scott Wilburn, "Measurements of the Transverse Spin-Dependent Total Cross Section Difference $\Delta\sigma_T$ for the Scattering of Polarized Neutrons from Polarized Protons," Ph.D. degree, Duke. *Supervisor* - N.R. Roberson
4. Mohammad Al-Ohali, "Neutron Scattering Cross Section and Analyzing Power Measurements for ^{28}Si and ^{32}S and Nuclear Mean Field from -80 to +80 MeV," Ph.D. degree, Duke. *Supervisor* - R.L. Walter

Master's Degrees

1. Tim Murphy, "Construction and Testing of a Novel Dilution Refrigerator," M.S. degree, North Carolina State University. *Supervisor* - D.G. Haase
2. Dinko Gonzalez Trotter, "Determination of a_{nn} in a neutron-deuteron Breakup Experiment at $E_m = 13.0$ MeV," M.S. degree, Duke. *Supervisor* - W. Tornow
3. Frank Salinas, "Use of the Neutron-Proton Scattering Length as a Probe of the Three-Nucleon Force," M.S. degree, Duke. *Supervisor* - C.R. Howell
4. David Junkin, "Bolometric Detectors," M.S. degree, University of North Carolina. *Supervisor* - A.E. Champagne
5. Chris Roper, "Analyzing Power Measurement for $^{12}C(\vec{n},n)^{12}C$ from 4 to 7 MeV, and at 15.5 MeV," M.S. degree, Duke University. *Supervisor* - R.L. Walter

II. Publications

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- Penttilä, H. Postma, N.R. Roberson, S.J. Seestrom, S.H. Yoo, and V.W. Yuan, *Phys. Rev.* **B46**, 11290 (1992).
5. Atomic Effects on α - α Scattering to the ^8Be Ground State, S. Wüstenbecker, H.W. Becker, H. Ebbing, W.H. Shulte, M. Berheide, M. Buschmann, C. Rolfs, G.E. Mitchell, and J.S. Schweitzer, *Z. Phys. A - Hadrons and Nuclei* **344**, 205 (1992).
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8. Energy Dependence of Possible Charge-Independence- and Charge-Symmetry-Breaking Effects in NN 3PJ Interactions from Three-Nucleon Continuum Studies, H. Witala, W. Tornow, W. Glöckle, *Few-Body Systems* **13**, 189 (1992).
9. Neutron-Proton Analyzing Power Data Between 7.6 and 18.5 MeV, G. Weisel, W. Tornow, C.R. Howell, P.D. Felsher, M. AlOuali, Z.P. Chen, R.L. Walter, J.M. Lambert, P.A. Treado, I. Slaus, *Phys. Rev.* **C46**, 1599 (1992).
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2. A Very Low Energy Tandem Accelerator, T.C. Black, B.E. Hendrix, E.R. Crosson, K.A. Fletcher, H.J. Karwowski and E.J. Ludwig, to be published in *Nucl. Inst. and Meth., Physics Research*.
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13. Discrete and Integral Fourier Transforms: Analytical Examples, W.J. Thompson and J.R. Macdonald, to be published in Proc. Nat. Acad. Sci. (USA).
14. Spin Substate Mixing by Off-Axis Magnetic Fields, W.J. Thompson, to be published in Nucl. Instrum. Methods.
15. The $^2\text{H}(d,\gamma)^4\text{He}$ Polarization Observables at 20, 30 and 50 MeV, R.M. Whitton, H.R. Weller, E. Hayward, W.R. Dodge, S.E. Kuhn, to be published in Phys. Rev. C.
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17. Fluctuation Properties of Nuclear States: Experimental Status, G.E. Mitchell and J.F. Shriner, Jr., to be published in proceedings of the symposium From Spectroscopy to Chaos.
18. Tests of Time Reversal Invariance and Parity with Charged Particles, G.E. Mitchell, E.G. Bilpuch, C.R. Bybee, J.M. Drake, and J.F. Shriner, Jr., to be published in proceedings of the International Conference on Time Reversal Invariance and Parity Violation in Neutron Reactions
19. A Spin Filter Polarimeter for Low-Energy Hydrogen and Deuterium Ion Beams, S.K. Lemieux, T. B. Clegg, H.J. Karwowski, and W.J. Thompson, accepted for publication in Nuclear Instrum. and Methods A.
20. Nuclear Astrophysics with Radioactive Beams: Prototypical Experiments", A.E. Champagne, Proc. of the Workshop on the Production and Use of Intense Radioactive Beams at the IsoSpin Laboratory, Oak Ridge (1992).
21. P and T Invariance Tests in Neutron Reactions at Los Alamos, P. P. J. Delheij, D. Alde, J. D. Bowman, B. E. Crawford, C. M. Frankle, C. R. Gould, D. G. Haase, J. N. Knudson, A. Masaike, Y. Masuda, Y. Matsuda, G. E. Mitchell, S. S. Patterson, S. Penttila, Yu.P. Popov, H. Postma, N. R. Roberson, S. J. Seestrom, E. Sharapov, H. Shimizu, Y. F. Yen, S. H. Yoo and V. W. Yuan, to be published in proceedings of the Nagoya conference
22. Energy Levels of Light Nuclei $A = 16, 17$, D.R. Tilley, H.R. Weller and C.M. Cheves, to be published in Nuclear Physics A.

Articles Submitted

1. Recent Advances in Low-Energy Few-Nucleon Physics, R. Machleidt, W. Glöckle, I. Slaus, W. Tornow, and H. Witala, submitted to Few-Body Systems.

2. Neutron Resonance Spectroscopy of ^{113}In and ^{115}In , C.M. Frankle, J.D. Bowman, B.E. Crawford, P.P.J. Delheij, C.R. Gould, D.G. Haase, J.N. Knudson, G.E. Mitchell, S.S. Patterson, S. Penttila, Yu.P. Popov, N.R. Roberson, S.J. Seestrom, E.I. Sharapov, Y.F. Yen, S.H. Yoo, V.W. Yuan and X. Zhu, to be submitted to Phys. Rev. C.
3. Dipole and Spin-Dipole Resonances in Charge-Exchange Reactions on ^{12}C , X. Yang, L. Wang, J. Rapaport, G.D. Goodman, C. Foster, Y. Wang, W. Unkelbach, E. Sugarbaker, D. Marchlinski, S. de Lucia, B. Luther, J.L. Ullmann, A.L. Ling, B.K. Park, D.s. Sorneson, L. Rybarcyk, T.N. Taddeucci, C.R. Howell and W. Tornow, submitted to Phys. Rev. C.
4. A Novel Probe of Charge-Symmetry Breaking: Deuteron-induced Deuteron Breakup, C.R. Howell, P.D. Felsher, W. Tornow, M.L. Roberts, J.M. Hanly, G.J. Weisel, M. AlOhal, R.L. Walter, I. Slaus, J.M. Lambert, P.A. Treado, and G. Mertens, submitted to Phys. Rev. C.
5. Resolution of Discrepancy Between Back-Angle Cross-Section Data for n-d Elastic Scattering, C.R. Howell, W. Tornow, H.R. Setze, R.T. Braun, D.E. Gonzales, C.D. Roper, R.S. Pedroni, S.M. Grimes, C.E. Brient, N. Al-Niemi, G. Mertens, submitted to Few-Body Systems.
6. Test of Rigorous Non-Relativistic n-d Elastic Scattering Calculations at Incident Neutron Energies above 70 MeV, C.R. Howell, X. Aslanoglou, F.P. Brady, J.R. Drummond, R.W. Finlay, R.C. Haight, N.S.P. King, A. Ling, P.W. Lisowski, C.L. Morris, B.K. Park, J. Rapaport, J.L. Romero, D.S. Sorensen, W. Tornow, J.L. Ullmann, B. Vlahovic, submitted to Phys. Lett.
7. Nature of the ^{20}Na 2646 keV Level and the Stellar Reaction Rate for $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$, B.A. Brown, A.E. Champagne, H.T. Fortune and R. Sherr, submitted to Phys. Rev.
8. β^+ Decay and Cosmic-Ray Halflives of ^{143}Pm and ^{144}Pm , M.M. Hindi, B. Sur, A.E. Champagne, M.T.F. da Cruz, R.-M. Larimer, K.T. Lesko and E.B. Norman, submitted to Phys. Rev.
9. Response-Function Measurement of an NE213 Scintillator Using the $^2\text{H}(d,n)^3\text{He}$ Reaction, A. Aksoy, A. Coban, A.A. Naqvi, F.Z. Khiari, J.M. Hanly, C.R. Howell, W. Tornow, P.D. Felsher, M.A. Al-Ohal, R.L. Walter, submitted to Nucl. Instrum. Methods.
10. Recent Advances in the Study of Parity Violation in the Compound Nucleus, J. D. Bowman, G. T. Garvey, Mikkel B. Johnson, and G. E. Mitchell, submitted to Annual Reviews of Nuclear and Particle Science.
11. A New Atomic Beam Polarized Ion Source for the Triangle Universities Nuclear Laboratory: Overview, Operating Experience, and Performance, T.B. Clegg, H.J. Karwowski, S.K. Lemieux, R.W. Sayer, E.R. Crosson, W.M. Hooke, C.R. Howell, H.W. Lewis, A.W. Lovette, H.J. Pfutzner, K.A. Sweeton, and W.S. Wilburn, submitted to Nuclear Instrum. and Methods A.
12. RF Transition Systems for the Triangle Universities Nuclear Laboratory Atomic Beam Polarized Ion Source, D.C. Dinger, T.B. Clegg, E.R. Crosson, and H.W. Lewis, submitted to Nuclear Instrum. and Methods A.
13. ECR and Cesium Ionizer Systems for the Triangle Universities Nuclear Laboratory Atomic Beam Polarized Ion Source, T.B. Clegg, W.M. Hooke, E.R. Crosson, A.W. Lovette, H. Middleton, H.G. Pfutzner, and K.A. Sweeton, submitted to Nuclear Instrum. and Methods A.

14. Configuration Mixing in ^{56}Co and ^{46}Sc Using (d, α) Reactions, E.R. Crosson, E.J. Ludwig, M. Bisenberger, R. Hertenberger, D. Hofer, H. Kader, P. Schiemenz, G. Graw, A.M. Eiro, F.D. Santos and B.A. Brown, submitted to Phys. Rev. C.
15. Determination of the Neutron-Neutron Scattering Length from Incomplete Neutron-Deuteron Breakup Experiments, W. Tornow, R.T. Braun and H. Witala, submitted to Phys. Lett B.
18. Radiative Capture of Polarized Deuterons by ^6Li and the D-state of ^8Be , J.Z. Williams, G. Feldman, H.R. Weller and D.R. Tilley, submitted to Phys. Rev. C.
19. A Portable 17.3 MeV Gamma-Ray Source, R.M. Chasteler and H.R. Weller, submitted to Nuclear Instruments and Methods.
20. Angular Distribution Coefficients for (γ, x) Reactions with Circularly Polarized Photons and Polarized Targets and a Correction to Previous Tables, H.R. Weller, R.M. Chasteler, B.S. Marks, R.G. Seyler and D.R. Lehman, submitted to Atomic Data and Nuclear Data Table.
21. Complete Set of Deuteron Analyzing Powers in dp Elastic Scattering: Measurement and Realistic Potential Predictions, H. Witala, L.E. Antonuk, J. Arvieux, D. Bachelier, B. Bonin, A. Boudard, J.M. Cameron, H.W. Fielding, M. Garçon, W. Glöckle, F. Jourdan, C. Lapointe, W.J. McDonald, J. Pasos, G. Roy, I. The, J. Tinslay, W. Tornow, J. Yonnet, W. Ziegler, submitted to Few-Body Systems.

III. Conference Reports

1. Determination of the D-to-S-state ratio of ^3H from the sub-Coulomb $^{119}\text{Sn}(d, t)$ ^{118}Sn reaction, B. Kozłowska, Z. Ayer, T.C. Black, R.K. Das, D.C. Dingle, K.A. Fletcher, H.J. Karwowski and E.J. Ludwig, Bull. Am. Phys. Soc. **37**, 1257 (1992).
2. A Determination of the asymptotic D-state to S-state ratio for ^3He via the $^{93}\text{Nb}(d, ^3\text{He})$ ^{92}Zr and $^{121}\text{Sb}(d, ^3\text{He})$ ^{120}Sn reactions at $E_d = 12$ MeV, Ayer, T.C. Black, J.C. Blackmon, T.B. Clegg, E.R. Crosson, R.K. Das, D.C. Dingle, K.A. Fletcher, B.E. Hendrix, H.J. Karwowski, B. Kozłowska and E.J. Ludwig, Bull. Am. Phys. Soc. **37**, 1263 (1992).
3. A Minitandem Accelerator, E.J. Ludwig, 12th International Conference on the Application of Accelerators in Research and Industry, Denton, TX (1992) 145.
4. Configuration Mixing in ^{56}Co and ^{46}So Using (d, α) Reactions, E.R. Crosson, E.J. Ludwig, M. Bisenberger, R. Hertenberger, D. Hofer, H. Kader, P. Schiemenz, G. Graw, A.M. Eiro and F.D. Santos, Bull. Am. Phys. Soc. **38**, 1064 (1993).
5. β^+ Decay and Cosmic-Ray Halflives of ^{143}Pm and ^{144}Pm , M.M. Hindi, B. Sur, A.E. Champagne, M.T.F. da Cruz, R.-M. Larimer, K.T. Lesko and E.B. Norman, to appear in Proc. 23rd International Cosmic Ray Conference, Calgary (1993).
6. Level Structure of ^4He and the Spin Dependence of the n - ^3He Total Cross Section, C.D. Keith, C.R. Gould, D.G. Haase, P.R. Huffman, N.R. Roberson, W. Tornow, W.S. Wilburn, H. Postma, Bull. Am. Phys. Soc. **37**, 1257 (1992).
7. Electromagnetic Excitation of the 2-Photon Giant Dipole Resonance in ^{136}Xe , E.F. Moore, Bull. Am. Phys. Soc. **37**, 1284 (1992).

8. Backward Angle n-p Differential Cross Sections for $60 < E_n < 250$ MeV, A.E. Feldman, J. Rapaport, G. Fink, X. Yang, F.P. Brady, D. Sorenson, C.R. Howell, W. Tornow, B.K. Park, J.L. Ullman, A. Ling, Bull. Am. Phys. Soc. **37**, 1299 (1992).
9. A Lamb-Shift Polarimeter for Low Energy H and D Ion Beams, S.K. Lemieux, T.B. Clegg, E.R. Crosson, and H.J. Karwowski, Bull. Am. Phys. Soc. **37**, 1305 (1992).
10. Radiative Capture of Tensor Polarized Deuterons on Lithium-7, G.J. Schmid, R.M. Chasteler, H.R. Weller, D.R. Tilley, Bull. Am. Phys. Soc. **37**, 1319 (1992).
11. Possible Charged Particle Studies of Parity Violation in Compound Nuclear Resonances, J.F. Shriner, G.E. Mitchell, E.G. Bilpuch, Bull. Am. Phys. Soc. **38**, 913 (1993).
12. Backward Angle n-p Differential Cross Sections for $65 \leq E_n \leq 250$ MeV, A.E. Feldman, J. Rapaport, Ch. Elster, B. Barmore, F.P. Brady, G. Fink, C.R. Howell, A. Ling, B.K. Park, J.L. Romero, D. Sorenson, W. Tornow, J.L. Ullmann, X. Yang, Bull. Am. Phys. Soc. **38**, 1062 (1993).
13. Measurement of $\Delta\sigma_T$ in Polarized Neutron/Polarized Proton Scattering, W.S. Wilburn, P.R. Huffman, N.R. Roberson, W. Tornow, C.R. Gould, D.G. Haase, C.D. Keith, T.P. Murphy, B.W. Raichle, Bull. Am. Phys. Soc. **38**, 1063 (1993).
14. Neutron-Neutron Scattering Length from Reanalysis of Incomplete n-d Breakup Experiments Using Realistic NN Potentials, R.T. Braun, W. Tornow, H. Witala, W. Glöckle, Bull. Am. Phys. Soc. **38**, 1063 (1993).
15. Spin-Spin Interaction between Polarized Neutrons and Polarized ^{27}Al and ^{59}Co from Coupled-Channel Analyses, J.P. Delaroche, M.M. Nagadi, R.L. Walter, Bull. Am. Phys. Soc. **38**, 1063 (1993).
16. Configuration Mixing in ^{56}Co and ^{46}Sc using (d, α) Reactions, E.R. Crosson, E.J. Ludwig, M. Bisenberger, R. Hertenberger, D. Hofer, H. Kader, P. Schiemenz, G. Graw, A.M. Eiro, F.D. Santos, Bull. Am. Phys. Soc. **38**, 1064 (1993).
17. Consistent Dispersive Optical-Model Analyses for $n+^{209}\text{Bi}$ and $n+^{208}\text{Pb}$ from -20 to +80 MeV, G.J. Weisel, W. Tornow, C.R. Howell, R.K. Das, and R.L. Walter, Bull. Am. Phys. Soc. **38**, 1064 (1993).
18. High Resolution Depth Profiling in Near Surface Regions of Solids by Narrow Nuclear Reaction Resonances below 0.5 MeV with Low Energy Spread Proton Beams, W.H. Schulte, H. Ebbing, W. Becker, M. Berheide, M. Buschmann, C. Angulo, C. Rolfs, G. Amsel, I. Trimaille, G. Battistig, G.E. Mitchell, and J.S. Schweitzer, Conference on Technology and Applications of Ion Beams, Loughborough, Great Britain, 1992.
19. A Detailed Balance Study of Time Reversal Invariance with Interfering Resonances, J.M. Drake, C.R. Bybee, G.E. Mitchell, J.F. Shriner, Jr., and E.G. Bilpuch, Bull. Am. Phys. Soc. **37**, 1676 (1992).
20. Application of Fourier Transform Techniques to QUantum Chaos Studies in Nucler Physics, C. R. Bybee, G.E. Mitchell, J.F. Shriner, Jr., and e.G. Bilpuch, Bull. Am. Phys. Soc. **37**, 1676 (1992).
21. First Tests of a Lamb-Shift Spin-Filter Polarimeter for H and D Beams from a Polarized Ion Source, S.K. Lemieux, E.R. Crosson, H.J. Karwowski, and T.B. Clegg, to be published in Proceedings of the 35th Yamada Conference on High Energy Spin Physics, Nagoya, 9-14 November, 1992, ed. N. Horikawa.

22. On-Line, Efficient, Low-Energy Proton and Deuteron Polarimetry, E. R. Crosson, C. D. Roper, and T. B. Clegg, Proceedings of Workshop on Polarized Ion Sources and Polarized Gas Targets, Madison, May 23-27, 1993, eds. W. Anderson and W. Haeberli, to be published in Am. Inst. of Physics Conference Proceedings.
23. Roundtable Discussion Summary: Atomic Beam Polarized Ion Sources, T. B. Clegg, Proceedings of Workshop on Polarized Ion Sources and Polarized Gas Targets, Madison, May 23-27, 1993, eds. W. Anderson and W. Haeberli, to be published in Am. Inst. of Physics Conference Proceedings.

IV. **Invited Talks**

1. Reaction Rates in the MgAl Cycle, A.E. Champagne, Invited talk given at the Workshop on Galactic Chemical and Dynamical Evolution, Clemson (1992)
2. Reactions Involving ^8Li and Primordial Nucleosynthesis, A.E. Champagne, Proc. of the First Symposium on Nuclear Physics in the Universe, M.R. Strayer, ed., (Institute of Physics 1992).
3. Nuclear Astrophysics with Radioactive Beams: Prototypical Experiments, A.E. Champagne, to appear in Proc. of the Workshop on the Production and Use of Intense Radioactive Beams at the IsoSpin Laboratory, Oak Ridge (1992).
4. Status of the Dispersive Optical Model, R.L. Walter, Int. Workshop for Nuclear Data for Fusion Reactor Technology, San Diego, CA (1993).
5. Dispersive Optical Model Studies at TUNL, R.L. Walter, Int. Conf. on the Application of Accelerators in Research and Industry, Denton, TX (1992).
6. Nuclear Few-Body Systems at Low Energies: A Laboratory for Testing Two- and Three-Nucleon Forces, W. Tornow, Workshop "Neutrons--Their Use in Nuclear Reactions and Fundamental Symmetry Studies," associated with the DNP Fall Meeting, Santa Fe, 1992.
7. Demonstrating Quantum Mechanics: Coulomb Scattering of Carbon from Carbon, W. Tornow, Workshop "Teaching Nuclear, Atomic, and Surface Physics with Accelerators," associated with the Twelfth International Conference on the Application of Accelerators in Research and Industry, Denton, TX.
8. Detailed Balance Study of Time Reversal Invariance with Interfering Resonances, G.E. Mitchell, conference on the Application of Accelerators in Research and Industry, Denton, TX, 1992.
9. Experiments on Parity Nonconservation in Neutron Resonances, G.E. Mitchell, program on Nuclear Physics in Atoms and Molecules, Institute for Nuclear Theory, Seattle, 1993.
10. Atomic and Solid State Effects in Nuclear Resonances at Low Energies, G.E. Mitchell, program on Nuclear Physics in Atoms and Molecules, Institute for Nuclear Theory, Seattle, 1993.
11. Fluctuation Properties of Nuclear States: Experimental Status, G.E. Mitchell, symposium From Spectroscopy to Chaos, Rochester, 1993.
12. Tests of Time Reversal Invariance and Parity with Charged Particles, G.E. Mitchell, International Workshop on Time Reversal Invariance and Parity Violation in Neutron Reactions, Joint Institute for Nuclear Research, Dubna, 1993.

13. High Performance Atomic Beam Polarized Ion Sources, T.B. Clegg, to be published in the Lecture Notes for the RCNP Kikuchi School on Spin Physics at Intermediate Energies, Osaka, 16-19 November, 1992, ed. M. Fujiwara.
14. A Minitandem Accelerator, E.J. Ludwig, 12th International Conference on the Application of Accelerators in Research and Industry, Denton, TX, 1992.

V. Seminars at TUNL (1992-93)

1. Wolfgang Kretschmer, University of Erlangen (8/13/92)
Information of the NN-Interaction from Polarization Transfer and Analyzing Power Measurements in Low-Energy p-p and p-d Scattering
2. Walter Glöckle, University of Bochum, Germany (9/17/92)
Recent Progress in 4-Nucleon Systems
3. Walter Glöckle, University of Bochum, Germany (9/18/92)
Exclusive Electron Scattering from ^3He with Complete Inclusion of the Final State Interaction
4. Harmut Hofmann, University of Erlangen, Germany (10/1/92)
Clusters in Light Nuclei
5. Michael Smith, Oak Ridge National Laboratory (10/22/92)
Big Bang Nucleosynthesis
6. Dirk Walecka, College of William & Mary (11/5/92)
Overview of the CEBAF Scientific Program
7. Richard Madey, Kent State University (11/24/92)
Bates E85-05: The Electric Form Factor of the Neutron from the $^2\text{H}(\bar{\nu}, e' \pi^+)p$ Reaction
8. Nikola Cindro, Rudjer Boskovic Institute, Zagreb, Croatia (12/4/92)
Measuring the Very Large and the Very Small; Determination of the Reaction Zone in Nuclei by Astrophysical Methods (The Hanbury-Brown-Twiss Effect)
9. Akira Msaïke, Kyoto University, Japan (1/14/93)
Tests on Time Reversal Invariance at KEK-Kyoto
10. Mark Lucas, University of Illinois, Urbana-Champaign (1/28/93)
Photon Scattering from the Deuteron at 50 and 70 MeV.
11. Cathleen Jones, Argonne National Laboratory (2/11/93)
A Laser Driven Polarized ^3He Target.
12. Edward Hungerford, University of Houston (2/18/93)
What is so New about Hypernuclear Physics?
13. Scott Price, University of Wisconsin (2/25/93)
Polarization Monitors for Internal Polarized Gas Targets
14. John Cameron, Indiana University Cyclotron Facility (3/18/93)
Some Themes in Hadron Physics: From IUCF to LSS
15. Charles M. Laymon, Los Alamos National Laboratory, P17 (3/25/93)
Investigation of the Isovector Giant Resonance at the Los Alamos Spallation Neutron Source.
16. Mike Lowry, Princeton University (4/1/93)
Weak Interaction Studies with Cryogenic Micro-Calorimeters

17. Willy Haeberli, University of Madison (4/21/93)
Spin-Up Spin-Down
HENRY W. NEWSON MEMORIAL LECTURE
18. Henryk Witala, Jagellonian University, Cracow, Poland and Ruhr-Universitat, Bochum, Germany (5/13/93)
Three-Nucleon Force Effects in the Three-Nucleon Continuum
19. William Parke, George Washington University (5/27/93)
Alpha-Deuteron Radiative Capture
20. Conrad Knight, Radiation Safety Officer, Duke University
Radiation Safety--Biological Effects
21. David Jorgensen, Asst. Radiation Safety Officer, Duke University
Radiation Safety--Instrumentation
22. Paul Carter, Tandem Accelerator Supervisor, TUNL
Safety and Emergency Procedures at TUNL
23. Jim Sewick, Safety Office, Duke University
Fire Safety
24. Todd Woerner, Environmental Safety Office, Duke University
Safe Handling of Chemicals in the Laboratory
25. Donald Lehman, George Washington University (6/17/93)
Radiative Capture of Polarized Deuterons on Hydrogen
26. Tom Clegg, University of North Carolina (6/17/93)
The Physics of the TUNL Polarized Ion Source and Beam Polarimetry
27. Eric Crosson, Duke University, and John Dunham, TUNL Accelerator Technician (6/17/93)
Upgrades to and Maintenance of the TUNL Polarized Ion Source
28. Alton Lovette, Shop Supervisor, Duke University (6/22/93)
The Instrumentation Shop for Nuclear Physics
29. Sidney Edwards, TUNL Electronics Shop and Computer Systems Manager (6/22/93)
Overview of the TUNL Electronics Shop and Computer System
30. Richard Braun and Mark Godwin, Duke University (6/23/93)
Tim Black, University of North Carolina
Experimental Technique for (1) Low-Energy Neutron, (2) Gammag-ray, and (3) Charged-particle Detection
31. Ross Setze, Duke University (6/23/93)
Data Acquisition System at TUNL
32. Mark Mikolajewski, Raleigh Valve and Fitting Co. (6/24/93)
Tube and Pipe Connections
33. Paul Carter, TUNL Accelerator Supervisor, and Chris Westerfeldt, Duke University (6/24/93)
Vacuum Systems in an Accelerator Laboratory and Principles of Accelerator Control Circuits

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