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**STUDIES OF NUCLEAR PROCESSES AT THE
TRIANGLE UNIVERSITIES NUCLEAR LABORATORY**

Progress Report

1 September 1994-31 August 1995

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TRIANGLE UNIVERSITIES NUCLEAR LABORATORY

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Introduction

0.0.1 Introduction

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

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

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

Efforts on parity violation (PV) in neutron resonances (the TRIPLE collaboration) have focused on the analysis. The γ -ray background in the neutron beam has been measured and the beam's time structure modeled—these features have been included in the analysis to obtain the PV asymmetries. An analysis method (for the determination of the rms PV matrix element) has been developed which facilitates inclusion of partial spectroscopic information. This enables the analysis of PV data from $I \neq 0$ targets. New measurements in 1995 will emphasize the use of our new gamma-ray detector array which makes possible the study of isotopic samples.

- **Time-reversal invariance tests:**

We have completed the most precise direct test to date of time-reversal invariance in nuclear physics. The measurement uses 6 MeV polarized neutrons transmitted through a cryogenically aligned rotating single-crystal holmium target. The amplitude of the time reversal violating asymmetry was found to be zero to less than one part per million. The measurement sets new limits on the size of the ρ meson-exchange coupling between nucleons.

- **Chaos in the nucleus:**

There has been major progress in obtaining a complete level scheme for ^{30}P . With the new Compton-suppression spectrometer and with excellent beam energy resolution

(~ 200 eV), we have studied approximately 50 resonances in the $^{29}\text{Si}(p, \gamma)^{30}\text{P}$ reaction. The observed γ -branchings and strengths limit the quantum numbers of both initial (resonant) states and final states. Angular distributions will be measured to remove remaining ambiguities. This complete level scheme should provide a definitive study of the statistical properties of eigenvalues and transition matrix elements in light nuclei, as well as clarifying the role of symmetry breaking on these properties.

- **Three-nucleon force effects:**

The effect of three-body forces have been clearly observed in neutron-deuteron scattering data which is providing the most compelling evidence in nucleon scattering of modifications to the basic two-body force due to the nuclear medium.

- **Polarized ^3He :**

We have constructed the world's largest solid polarized ^3He target. The target operated at 13 millikelvin in a 7 Tesla magnetic field. Polarized neutron scattering provides important information on the structure of ^4He and can not be performed without a dense, highly polarized target.

- **Cryogenic Microcalorimeters:**

We have recently observed heat pulses from our prototype cryogenic microcalorimeters. These devices are being developed for measurements of β spectra. The current measurements are not at the required sensitivity, but several improvements are in progress.

- **Astrophysical S-factors:**

We have measured the astrophysical S-factor for the $\text{D}(p, \gamma)^3\text{He}$ reaction with high precision. We find a value which is about 1/2 the size of the presently accepted value. In addition, we are measuring capture to the 2^+ isospin mixed state in ^8Be at 16.69 MeV using a polarized proton beam at 80 keV. This work is closely related to the $^7\text{Be}(p, \gamma)$ reaction which is very important to the solar neutrino problem.

- **The $^{17}\text{O}(p, \alpha)^{14}\text{N}$ reaction and models of internal dynamics of stars:**

Recent significantly improved measurements of the $^{17}\text{O}(p, \alpha)$ reaction at stellar energies allow the observations of ratios of $^{17}\text{O}/^{16}\text{O}$ on the surface of stars to be used as a more sensitive diagnostic tool for probing the mixing of material in the interiors of stars.

- **Low-Energy Beam Facility:**

We have almost completed the upgrade of the low-energy acceleration facility. The range of energies accessible to this system using the polarized ion source, minitandem accelerator and high-voltage chamber is 20-530 keV. This will soon (summer of 1995) be upgraded to 680 keV.

- **Compton backscattering source:**

We have measured the bremsstrahlung background radiation produced when 200-800 MeV electrons are stored in the Duke Free Electron Laser Laboratory (DFELL) ring. Results confirmed that this background will be negligible for a Compton Backscattered source of polarized gamma rays $8 < E_\gamma < 224$ MeV.

- **Nuclear Data Project:**

We have completed the review "Energy Levels of Light Nuclei $A = 18-19$ and submitted the manuscript to Nuclear Physics A for publication in Fall 1995. The journal has already made the document available on the internet through its Nuclear Physics Electronic (NPE) service. In Fall 1994 and Spring 1995 we set up a World Wide Web (WWW) server that provides a comprehensive guide to $A = 3-20$ evaluated nuclear data services. Energy level diagrams are available for online viewing or printing. The full text and tables of the 1993 TUNL $A = 16-17$ review and the recently completed $A = 18-19$ review are provided. These documents can be viewed on line as they would appear on the printed page. The capability of searching on any character or string is provided as well as utilization of imbedded hypertext links for navigating through the documents.

The TUNL research program focuses on the following areas of nuclear physics:

- Parity violation in neutron and charged-particle resonances—the mass and energy dependence of the weak interaction spreading width.
 - Chaotic behavior in ^{30}P from studies of eigenvalue fluctuations in nuclear level schemes.
 - Studies of few-body systems, with specific experiments to address:
 - The D-state structure 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 and charge-independence and charge-symmetry breaking in the ^3P components of the N-N interaction.
 - The charged πNN coupling constant from neutron-proton analyzing-power data.
 - Delineation of the structure of the low-energy ^4He continuum from scattering of polarized neutrons from a polarized ^3He target.
 - The quark structure of nucleons, to be investigated in a collaboration at CEBAF.
- The topics include:
- * Electroproduction of pions in the $\bar{e} + \bar{p}$ reaction.

* Determining electromagnetic form factors of the neutron by $d(\vec{e}, e', \vec{n})p$.

- Nuclear astrophysics. We are using the Low Energy Beam Facility and the refurbished Enge split-pole spectrometer at TUNL, and we are also members of a collaboration at the Holifield Radioactive Ion Beams Facility at the Oak Ridge National Laboratory.
- Nuclear data evaluation for $A = 3-20$, for which TUNL is now the international center.
- High-spin spectroscopy and superdeformation in nuclei, involving collaborations at Argonne National Laboratory.

Developments in technology and instrumentation have been vital to our research and training program. In this progress report we describe:

- A proposed polarized γ -beam facility at the Duke Free Electron Laser Laboratory.
- Cryogenic systems and microcalorimeter development.
- Continuing 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 beginning installation of an on-line Spin Filter Polarimeter (SFP) on the high-voltage frame of the polarized-ion source. We are currently building rapid-cycle cryogenic microcalorimeters (bolometers), which are devices that operate in the milli-Kelvin temperature regime to detect incident radiation with high energy resolution. In the development of polarized targets, we have completed a dynamically polarized proton target in collaboration with the University of Texas and LANL.

The nuclear data evaluation project for nuclei with $A = 3-20$ provides a service to the international nuclear physics community, and benefits the TUNL research program.

The TUNL seminar program continues with characteristic vigor, supplemented by 13 in-house lectures on TUNL instrumentation and safety procedures. A related program, the Triangle Nuclear Theory seminars, is also beneficial to TUNL faculty and students.

The talents and enthusiasm of the 16 faculty members, 11 research staff and postdoctoral associates, and 35 graduate students from the three Triangle universities are responsible for the successes of our research program. We also benefit from collaborations with staff members from Tennessee Technological University, North Georgia College, North Carolina A & T State University, North Carolina Central University, State University of New York-Geneseo, China Institute of Atomic Energy and Tsinghua University (Beijing), and Jagellonian University (Cracow).

The TUNL Advisory Committee—Drs. David Balamuth (University of Pennsylvania), James Friar (Los Alamos National Laboratory), Gerald Garvey (Los Alamos National Laboratory), and Steven Vigdor (University of Indiana) 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 status of a project, please contact the physicist whose name is underlined in the author list.

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0.0.2 Personnel¹

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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—The TRIPLE Collaboration

B. E. Crawford, C. R. Gould, D. G. Haase, L. Y. Lowie, G. E. Mitchell, N. R. Roberson, S. L. Stephenson, and other members of the TRIPLE Collaboration¹

The nucleon-nucleon force consists of the strong parity conserving (PC) interaction and the weak parity nonconserving (PNC) interaction. The PNC interaction has a strength of order 10^{-7} relative to the PC interaction. The weak interaction can be detected by measurement of pseudo-scalar observables of the type $(\vec{\sigma} \cdot \vec{k})$ where $\vec{k}$ is the momentum and $\vec{\sigma}$ is the spin of the nucleon. Resonances formed with polarized low-energy neutrons show strong PNC effects. The weak interaction causes the mixing of nuclear levels of the same spin and opposite parity. Two mechanisms enhance the size of the parity violation: the levels are very close together in energy and very strong (s-wave) resonances are mixed into very weak (p-wave) resonances. In heavy nuclei these combined enhancements magnify the PNC effects (by 10^4 to 10^6) in the helicity dependence of the total neutron cross section.

The TRIPLE collaboration uses the high-flux epithermal neutron beam from LANSCE (Los Alamos Neutron Scattering Center) to study the neutron-nucleus weak interaction. The longitudinal asymmetry $P = (\sigma_p^+ - \sigma_p^-)/(\sigma_p^+ + \sigma_p^-)$, where σ_p is the cross section of p-wave resonances and the + or - indicates the helicity of the neutrons, has been measured for neutron energies up to several hundred eV. In the two-level approximation

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

where $M = \langle s | V^{\text{PNC}} | p \rangle$ 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. In the actual analysis a multi-level expression is used and the effects of many s-wave resonances are included.

Our approach assumes that the compound nuclear (CN) system is chaotic, and treats the PNC matrix elements as random variables. A statistical analysis of our initial results

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yielded root-mean-squared matrix elements with values $M \approx 1$ meV. This agrees well with the expected estimate $M_{\text{Theor}} = M_{\text{sp}}/N^{1/2}$, where the single particle weak matrix element is taken as $M_{\text{sp}} \approx 0.5$ eV and $N \approx 10^6$ is the approximate number of components in the wave function of a typical CN state in a heavy nuclide.

Our first measurements studied transmission of longitudinally polarized neutrons through ^{238}U and ^{232}Th . These early results are summarized in two review articles [Bow93, Fra93]. The ^{232}Th measurement revealed an unexpected correlation in the sign of the longitudinal asymmetries. All attempts to explain the sign effect as a general feature of the weak neutron-nucleus interaction failed.

We have developed improved equipment for this experiment, including a new large-area, high-polarization proton target for polarizing the neutron beam [Pen94], a new ^{10}B -loaded liquid scintillator for transmission experiments with large samples [Yen94], and a large solid angle pure CsI detector for capture experiments with isotopic samples [Fra94]. These three new devices are described in a series of papers in the proceedings of a workshop on time reversal invariance and parity violation held in Dubna.

The polarized proton filter system is based on a 5-Tesla split-coil superconducting magnet operating at 1 K. The microwave dynamic nuclear polarization method is used with electron-beam irradiated solid ammonia. In practice neutron polarizations of $\sim 70\%$ are achieved. The new high count-rate neutron detector is a ^{10}B -loaded liquid scintillator. The scintillator housing is divided into 55 cells, each viewed by a photomultiplier with a high current base. Pulses are summed to produce a 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 gamma-ray detectors are pure CsI, 12" long and approximately 4" $\times$ 4" in cross section. The cross section is a partial wedge, so that 12 detectors form a cylinder around the beam pipe. Two such cylindrical arrays (24 detectors) provide a solid angle of approximately 2.8π . The 24-detector array is also located in the 56-meter counting house.

During the 1993 run cycle we performed transmission measurements on ^{238}U and ^{232}Th (repeating our initial measurements), obtained new transmission data on ^{115}In , natural silver (^{107}Ag and ^{109}Ag), and performed a capture measurement on ^{113}Cd (with a preliminary version of the capture detector). Preliminary analysis yielded five or more resonances with parity violations at the $\geq 2\sigma$ level for ^{238}U , ^{232}Th , ^{115}In , $^{107,109}\text{Ag}$, and ^{113}Cd . The sign correlation in the ^{232}Th longitudinal asymmetries is confirmed — eight of eight statistically significant effects are positive. A region of the ^{232}Th data is shown in Figure 1.3-4. The experimental yield asymmetries $\varepsilon = (N^+ - N_-)/(N^+ + N_-)$ are shown for two different orientations of the longitudinal polarization of the neutron beam. The signs of the large effects reverse as expected. Excluding ^{232}Th , the new data (combined with a few older measurements) yield longitudinal asymmetries which have approximately 20 plus values and 10 negative values. This suggests that the sign correlation observed in ^{232}Th is specific to that nuclide, and is not a general feature of the weak interaction. This new result has led to a

Figure 1.1-1: Transmission yield for ^{232}Th . Resonances with large parity violations are denoted by arrows. In the bottom two curves, the experimental yield asymmetry ϵ is plotted for two different orientations of the neutron polarization.

number of doorway state models.

LANSCCE was not available to perform experiments in 1994. A major experimental run is planned for 1995. We expect to focus more on the capture experiments, which can be performed with smaller samples of separated isotopes. More emphasis will be placed on targets in the mass $A \approx 100$ region in order to complement the data from $A \approx 230$. The motivation is to determine experimentally the mass dependence of the weak neutron-nucleus interaction. Meanwhile we have improved our analysis codes. We have modeled the time structure of the neutron beam and now can simulate the observed asymmetric

line shape which obtains when the beam resolution dominates. We also have performed detailed studies of the background. In addition (see the next section) we have formulated the appropriate probability density functions and likelihood functions when some or all of the spectroscopic parameters are unknown.

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[Yen94] Y.-F. Yen *et al.*, *ibid.*, p. 210, World Scientific, Singapore, 1994.

1.1.2 Analysis of Parity Violation in Neutron Resonances

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The analysis used to determine the rms parity violating matrix element M from the longitudinal asymmetries measured by the TRIPLE Collaboration has been extended to include targets with spin and to situations where only partial spectroscopic information is available. The key experimental goal is the determination of M , the matrix element describing the neutron-nucleus weak interaction. In practice, the precision with which M can be determined is governed by the status of the relevant nuclear spectroscopic information. In favorable cases with all spectroscopic information available, the uncertainty is determined by the sample size. However, in most cases there is incomplete information available for some or all of the relevant spectroscopic parameters. We have considered the methods of analysis appropriate under various circumstances, corresponding to the wide range of spectroscopic knowledge available for different nuclides.

In these experiments the longitudinal asymmetry is measured for p-wave neutron resonances. Since the parity violation in (weak) p-wave resonances is caused by mixing with (strong) s-wave resonances, clearly one needs the spectroscopic parameters for both the s- and p-states, including the total angular momentum J , the resonance energy E_0 , and the neutron width Γ_n . We derived probability density functions when there is complete knowledge, partial knowledge, or no information concerning the spectroscopic parameters. Given the probability density functions, the likelihood method can be used to determine the relevant parameters from the experimental results.

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It is convenient to consider target spin $I = 0$ and $I \neq 0$ separately. The $I = 0$ case is much simpler. For $I = 0$, all s-wave resonances must have $J = 1/2$, the p-wave resonances have $J = 1/2$ or $3/2$, and the corresponding p-wave neutron amplitudes are pure $j = 1/2$ or $3/2$ (where j is the neutron total angular momentum). Usually the s-wave and p-wave neutron widths and resonance energies are known, but the spins (particularly of the much weaker p-wave resonances) often are not known. The TRIPLE collaboration showed that for $I = 0$ target nuclides, knowledge of the resonance energies and neutron widths of the s- and p-wave resonances is sufficient to extract values of M from a set of measured PV asymmetries.

More spectroscopic information is needed to characterize p-wave resonances for targets with $I \neq 0$. The p-wave states with $J = I \pm 1/2$ can be formed with both $p_{1/2}$ and $p_{3/2}$ neutrons, and thus there are two entrance channel neutron amplitudes. The neutron orbital angular momentum and the neutron spin are first coupled to form the projectile spin j , and j is then coupled to the target spin I to form the total spin J of the target-projectile system. For s-wave resonances the projectile spin $j = 1/2$, while for p-wave resonances $j = 1/2$ or $3/2$. Very few projectile-spin neutron decay amplitudes have been measured. In addition, the spins of the resonances often are unknown. For these cases we derived expressions for the probability density function of M by averaging over unknown spectroscopic parameters. We derived the probability density functions appropriate for the various cases and then obtained the appropriate likelihood expressions. We then applied these formulae to experimental data.

Our conclusion is that given the relevant spectroscopic parameters, one can obtain reliable and reasonably precise values for the rms PV matrix element M from the longitudinal asymmetry data. With partial information M can still be obtained, but with increased uncertainty. Measurements to improve the level of spectroscopic information would significantly reduce the uncertainty in M and are strongly encouraged. Our considerations provide a framework for establishing priorities among the various spectroscopic measurements. Two papers have been prepared on this analysis [Bowa, Bowb].

[Bowa] J. D. Bowman *et al.*, submitted to Phys. Rev. C.

[Bowb] J. D. Bowman *et al.*, to be published in the proceedings of the Third International Seminar on Interaction of Neutrons with Nuclei.

1.1.3 Parity-Violation Tests with Charged Particles

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Parity-violation tests with charged particles in light or medium mass nuclei ($A \approx 20-40$) would complement the measurements with neutron resonances in heavy nuclei by the TRIPLE collaboration. In principle several measurements could be performed: either elastic scattering or a reaction could be studied; if a reaction is 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 (only A_z is non-zero for angle-integrated cross sections).

High resolution (p, p) and (p, α) resonance data from TUNL exist for the targets ^{23}Na , ^{27}Al , ^{31}P , ^{35}Cl , and ^{39}K . We considered all of the (134) unnatural parity resonances observed in these data. We adopted the following criteria: calculations were performed for any natural parity state of the same J whose energy differed from that of the unnatural parity state by less than eight times the sum of the two total widths. For each of these resonance pairs, the values of $A_z(\theta)$ and $A_x(\theta)$ were calculated for both the (p, p_0) and (p, α_0) reactions; we also calculated the value of A_z for the (p, α_0) reaction integrated over 4π .

The Hamiltonian was $H = H_0 + H_{PV}$, 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 internal mixing between two states. 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. The longitudinal analyzing power A_z is

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

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 enhancement. We also calculated the analyzing power component A_x .

The results depend dramatically on energy, angle, and the specific resonance parameters. A suitable figure of merit for $A_z(\theta)$ is $\beta_{P_z} = (A_z/V)^2 \frac{d\sigma}{d\Omega}$, since maximizing this "figure-of-merit" minimizes the time to reach a given sensitivity in V (assuming that all other experimental factors remain the same). Sample results are shown in Figure 1.1-2. Results for $A_x(\theta)$ and $A_z(\theta)$ are comparable but fluctuate from resonance to resonance. The A/V values are typically one to two orders of magnitude smaller for the (p, p_0) reaction than for the (p, α_0) reaction. Preliminary results are discussed in two recent papers [Shr94, Mit95].

At present the feasibility of these experiments is under consideration. The proposed experiments require a number of developments, including improvement in the stability of the polarized beam energy, position, and polarization direction. A recently installed stripper bias amplifier has reduced the energy fluctuations due to accelerator voltage fluctuations by a factor of approximately 10. This is equivalent to terminal voltage fluctuations of approximately 30 V. An improved slit feedback steering system is currently being constructed

Figure 1.1-2: Values of A_z/V as a function of laboratory energy and angle for a pair of resonances in ^{32}S (top). Figure-of-merit β_p versus energy and angle for this same pair of resonances (bottom).

to provide the necessary improvements in beam position stability. Preliminary tests of systematic effects using polarized beam will begin soon.

Since the counting rates are a primary concern, a large solid angle detector would be of particular value. However, since in some cases the sign of the parity violation changes with angle, a segmented detector is essential. There are a number of examples where the difference in the net effect for a single detector and a segmented detector is two orders of magnitude. Fortunately the gains from segmenting the detector are very small after the number of segments reaches $N \approx 6$.

In order to confront issues of systematic errors, one needs to know the value of the experimental quantity A_z , not A_z/V . Of course determining V is the goal of the measurement, but one can obtain an estimate for $\langle V \rangle$ by assuming a value for the weak spreading width [$\Gamma_W = 2\pi|V|^2/D(J)$, where $D(J)$ is the local average level spacing for resonances with spin J]. We assume that Γ_W is constant and equal to the value obtained in the TRIPLE measurements for U and Th, and use the experimental values of $D(J)$. This yields an estimate for $\langle V \rangle$ for each resonance pair. The estimates for $\langle V \rangle$ are usually between 50 and 150 meV. The values for A_z range from 10^{-3} to 10^{-7} , with most in the 10^{-4} to 10^{-6} range. Measurements at the 10^{-4} level would be sufficient to provide significant new information – this level of sensitivity is our initial goal.

One can estimate the time required to measure V at some level for a particular pair of resonances from our calculations for the enhancement. Incorporating beam intensity, target thickness, solid angle and detector efficiency into a constant k , then for a figure-of-merit β , the time required to determine V at some level V_0 is $t = k/(\beta V_0^2)$. One can invert this procedure and ask what limit is set on V if one measures for a given time t_0 and no parity violation is observed. For a number of favorable cases, run times of the order of one day should be sufficient to set a limit on V of < 50 meV; in practice this limit would constraint Γ_W to be less than or equal to the value measured in heavy nuclei.

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1.2 Time-Reversal-Invariance Measurements

1.2.1 A Parity-Even Test of Time-Reversal Invariance with MeV Neutrons

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We have performed a new search for parity-conserving, time-reversal noninvariance (PC TRNI). The measurement involves searching for a PC TRNI five-fold correlation (FC) term $\vec{s} \cdot (\vec{I} \times \vec{k}) \vec{I} \cdot \vec{k}$ in the neutron-nucleus forward scattering amplitude. Here, $\vec{s}$ is the spin of the incident neutron with momentum $\vec{k}$, and $\vec{I}$ is the spin of the target. The first measurement was reported by Koster [Kos91]. In the present work, we use the ${}^2\text{H}(\vec{d}, \vec{n}){}^3\text{He}$ source reaction with an improved deuterium gas cell (section 1.2.2) and a higher target alignment to gain a factor of fifty improvement in sensitivity to the FC term.

The FC term is measured via polarized neutron transmission through a rotating, cryogenically aligned ${}^{165}\text{Ho}$ target. The cross section for neutrons polarized parallel/antiparallel (+/-) to the direction $\vec{I} \times \vec{k}$ is given by

$$\sigma_T^\pm = \sigma_0 + \tilde{t}_{20}(I) P_2(\cos \theta) \sigma_2 \pm \tilde{t}_{10}(s) \tilde{t}_{20}(I) A_5 \sigma_0 \sin 2\theta \quad (1.1)$$

where $\tilde{t}_{10}(s)$ is the polarization of the neutron beam, $\tilde{t}_{20}(I)$ is the tensor alignment of the holmium target, σ_0 is the unpolarized cross section, σ_2 is the deformation effect cross section, A_5 is the PC TRNI spin-correlation coefficient, and θ is the angle between the holmium crystal alignment axis and the beam direction. Double modulation (flipping the neutron spin while simultaneously rotating the holmium target) uniquely isolates the $\sin 2\theta$ angular signature of the FC term. A sequence of measurements of the transmission asymmetry

$$\mathcal{E}_5 = \frac{N^+(\theta) - N^-(\theta)}{N^+(\theta) + N^-(\theta)} \quad (1.2)$$

as a function of angle θ , can be fit to the form $\mathcal{C} + \mathcal{D} \sin 2\theta$ ($\mathcal{C}, \mathcal{D}$ constants) to yield

$$A_5 = \frac{\mathcal{D}}{\tilde{t}_{10}(s) \tilde{t}_{20}(I) n \sigma_0}, \quad (1.3)$$

where $n = 0.065$ atoms/b is the target thickness and $\sigma_0 = 5.0$ b at $E_n = 5.9$ MeV.

The holmium target is rotated from -180° to 180° and back to -180° in increments of 22.5° . The neutron spin is flipped every 100 ms. At each angle, 256 eight-step sequences are accumulated, each consisting of neutron spin up (+) or down (-) in the sequence $+ - - + - + + -$. To confirm that the target is aligned, we measure the deformation effect cross section at 9.5 MeV using the unpolarized yields ($N^+(\theta) + N^-(\theta)$). The FC experiment is carried out at a lower energy of 5.9 MeV, where the deformation effect cross section is zero [Kos94].

The normalized asymmetry as a function of run number or angular sequence is shown in Figure 1.2-1. There is no evidence for a $\sin 2\theta$ variation in the asymmetry, and a fit to these data yields a coefficient $\mathcal{D} = (1.12 \pm 1.01) \times 10^{-6}$. The PC TRNI spin correlation coefficient $A_5 = (9.81 \pm 8.85) \times 10^{-6}$ is consistent with time-reversal invariance.

The A_5 value can be converted to a PC TRNI coupling constant using the microscopic folding-model calculations of [Eng94]. We find a 1σ bound on the ratio of T-violating to

Figure 1.2-1: The normalized detector asymmetry as a function of run number. Each run corresponds to approximately four minutes worth of data taken in the angular sequence $-180^\circ \rightarrow 180^\circ \rightarrow -180^\circ$ in 22.5° steps.

T-conserving coupling constants of $\bar{g}_\rho = (2.6 \pm 2.4) \times 10^{-2}$, which implies a bound on the ratio of T-violating to T-conserving nuclear matrix elements of $\alpha_T = (3.2 \pm 2.9) \times 10^{-4}$. These measurements are a factor of four improvement over the previous detailed balance measurements of Richter [Bla83, Hax94] and now constitute the most precise direct test of parity-even, time-reversal invariance in nuclear physics.

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1.2.2 Polarized Neutron Source and Detectors for the Parity-Even Test of Time-Reversal Invariance

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The parity-even, time-reversal measurement presented in Section 1.2.1 involved measuring the polarized neutron transmission through an aligned ^{165}Ho target. We produced 5.9 MeV polarized neutrons using the $^2\text{H}(\vec{d}, \vec{n})^3\text{He}$ reaction. The neutron flux was maximized with a newly designed, cryogenically cooled deuterium gas cell. The large neutron fluxes required the development of two four-detector arrays of plastic scintillator neutron detectors capable of handling MHz counting rates.

A liquid nitrogen cooled deuterium gas cell was developed for use as a neutron production target. The cylindrically shaped cell was 3.81 cm long, 0.851 cm diameter, and filled with 8 atm of deuterium gas. The deuterium beam enters through a 15.2 μm Havar window and stopped by a 0.51 mm gold foil surrounding the gas. The gold is soldered into a copper sleeve and thermally anchored to a 1.91 cm diameter solid copper coldfinger extending 71 cm into a liquid nitrogen bath. A base temperature of 86 K was obtained with 8 atm of gas and no beam. The cell is housed inside a stainless steel vacuum can and pumped on by both the beam line vacuum pumps and activated charcoal surrounding the coldfinger.

Beam currents of up to 2.0 μA were incident upon the cell, contributing up to 12 W of heat. This heat caused large temperature variations, and thus large fluctuations in the density of the gas within the cell. These variations were removed by controlling the temperature of the cell using 6 Ω heater connected to a generic temperature controller. The temperature was stabilized at 168 K and monitored with a 1000 Ω (at 0°) calibrated platinum thermometer. Temperature variations of less than 0.5 K were observed with beam on target.

The neutron flux was detected with two four-detector arrays of plastic scintillator neutron detectors. The 0° transmission detector array consisted of four isolated segments of Pilot-U scintillation material ($6.35 \times 6.35 \times 10$ cm) joined to form a $12.7 \times 12.7 \times 10$ cm thick detector. Each scintillator was connected to a 2" Hamamatsu 1828-01 phototube through a polished lucite light guide. A side view of the detector array is shown in figure 1.2-2(a). The monitor detector array consisted of four segments of Pilot-U scintillation material machined to form a "halo" around the solid angle subtended by the 0° transmission detectors. The scintillators were connected to 1-1/8" Hamamatsu R-1398 phototubes through polished lucite light guides. A front view of the monitor detector array is shown in figure 1.2-2(b).

The phototubes were biased using a LeCroy HV4032A power supply connected to a transistorized voltage divider circuit. The transistorized circuit was designed to maintain gain linearity in the final amplification stages of the photomultiplier tube. The circuit was assembled in-house on a printed circuit board. The 0° transmission detectors were biased to

Figure 1.2-2: The two four-detector arrays of neutron detectors.

–1600 V and the monitors biased to –1100 V to obtain 500 mV pulses with 10 ns widths. With 2 μ A of beam, typical total count rates of 4.4 MHz and 14.1 MHz were observed for the 0° and monitor detector arrays. Measurement of a transmission asymmetry to accuracies better than 10^{-6} were obtained with this system.

1.2.3 Neutron Resonances in ^{165}Ho , and the Five-Fold Correlation Test of Time Reversal

P. R. Huffman, C. M. Frankle¹, C. R. Gould, D. G. Haase, J. A. Harvey², N. R. Roberson, and L. W. Weston²

In 1988, Bunakov proposed the five-fold correlation test of time-reversal violation in the neighborhood of two interfering p-wave resonances [Bun88]. He showed that mixing of the compound-nuclear wave functions enhances the sensitivity to a time reversal violating, parity conserving (TVPC) term in the neutron forward scattering amplitude. A similar enhancement exists if a d-wave resonance interferes with an s-wave resonance, or more specifically, if the d-wave admixture of a predominantly s-wave resonance interferes with the s-wave component of a neighboring resonance with the same spin. Until now, however, no suitable pair of resonances, p-wave or s- and d-wave, has been located in a nucleus which can be aligned.

Even if one pair of resonances is located, there is a problem arising from the stochastic nature of the compound-nuclear wave functions. It is not possible to set a bound on the

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E	$2g\Gamma_n$	Γ_γ	σ_{00} (b)	σ_{02}^{max} (mb)
24.791	0.0144	49.7	43	24
75.078	0.0844	93.4	44	40
119.98	0.7847	104.5	229	122
187.94	0.6317	74.	165	172
210.86	0.3675	78.	81	129
227.87	0.9676	274.	48	61
235.94	0.9926	78.	195	216
248.6	0.5854	78.	110	169
264.98	1.756	146.	165	158

Table 1.2-1: Nine previously unidentified resonances in ^{165}Ho .

strength of the TVPC nucleon-nucleon interaction from just a single null measurement in the resonance regime. The possibility exists that the unknown resonance parameters and TVPC matrix elements will take on values which preclude observation of a TVPC signal independent of the strength of the underlying TVPC interaction. Davis has recently shown that at least three independent resonance measurements are needed to usefully constrain the strength of TVPC interactions [Dav94].

In order to identify multiple pairs of resonances suitable for searching for TVPC effects, we have carried out a high-resolution study of ^{165}Ho resonances below 500 eV. Holmium is a nucleus which is easily aligned by cryogenic techniques. Importantly, spins of many of the strong *s*-wave resonances are known from previous work [Mug84].

The measurements were carried out at ORELA using a room temperature holmium metal target. We found nine new weak resonances in the energy range 1-500 eV, and confirmed the energies and resonance parameters for many of the other resonances. A SAMMY [Lar89] R-matrix fit to the data is shown in Figure 1.2-3.

If holmium is cryogenically aligned, then the deformation effect can be used to locate *d*-wave admixtures in predominantly *s*-wave resonances. Based on standard angular momentum penetrabilities, we estimated the size of the deformation effect for these weak resonances and found it to be accessible to measurement. We further considered these same weak resonances as candidates for TVPC five fold correlation measurements. In favorable circumstances, we estimate that a bound on α_T of order 2×10^{-5} could be achieved, a factor of five to ten better than the present best limits from MeV measurements and atomic and neutron edm measurements.

The parameters of the nine new resonances, and our estimates of the maximum deformation effect cross sections σ_{02} are given in Table 1.2-1.

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Figure 1.2-3: Transmission spectra of ^{165}Ho and the accompanying fit.

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1.3 Quantum Chaos in Nuclei

1.3.1 Distribution of Shell Model Transition Strengths in ^{22}Na

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Because of the need for extremely high quality data to perform effective eigenvalue fluctuation analyses, an alternative signature for quantum chaos which could be applied to nuclear data is desired. One approach we have examined is using the Fourier transform (discussed in Section 1.3.3). Another possibility is to study the distribution of reduced transition strengths. Several analyses [Alh92, Mer93] suggest that such strengths obey a $\chi^2(\nu=1)$ distribution for chaotic systems and a $\chi^2(\nu < 1)$ distribution for regular systems.

As a starting point we are studying B(M1) and B(E2) values calculated for ^{22}Na using the OXBASH shell model code. A total of $\approx 75,000$ strengths have been calculated. Preliminary analysis shows a distribution with $\nu \approx 1$, suggesting that the system is chaotic. We have examined the data for dependence on spin, excitation energy, multipolarity, or isospin character; no dependence of these types has been observed.

Recent work by Zelevinski *et al.* [Zel95] examined shell model eigenvectors for signatures of chaos. They argue that "level statistics alone are not sufficient to describe the process of stochastization" and use the information entropy to characterize the eigenvectors. In light of their arguments, it becomes important that our analysis gives the best possible characterization of reduced transition strengths.

Our work in the past year has focussed on more robust methods of analysis. In particular, we are attempting to determine a better estimate of the uncertainty in ν . Previously, we had been analyzing the data by histogramming it into fixed bins of equal width. Following the method described by Eadie [Ead71], we are now histogramming the data into bins of equal probability. Since the bins now depend explicitly on the value of ν , an iterative procedure must be followed. Development of this procedure is underway; application to experimental data from ^{26}Al will follow.

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1.3.2 A Complete Level Scheme for ^{30}P

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In order to study chaos and isospin breaking in ^{30}P , we are measuring the $^{29}\text{Si}(p, \gamma)$ reaction with the goal of establishing a complete level scheme in ^{30}P . Excitation functions for $^{29}\text{Si}(p, \gamma)$ in the energy range $E_p = 2.0\text{--}3.3$ MeV were measured by Frankle [Fra92], and several new levels were identified. A Compton-suppressed spectrometer [Shr95] has been designed, built, and installed to allow γ -ray detection with both high resolution and high efficiency.

In the past year we have completed a measurement of excitation functions in the range $E_p = 1.0\text{--}2.0$ MeV to search for any previously unknown levels in that region. Reinecke *et al.* [Rei85] have previously studied this reaction in the range $E_p = 0.3\text{--}2.3$ MeV, but the energy resolution of our proton beam is sufficiently better and the need for complete data so great that additional measurements seemed warranted. We have identified three new ^{30}P levels at $E_p = 1.0380$, 1.4333 , and 1.5787 MeV. These levels were identified as belonging to ^{30}P by the observation of γ -rays from ^{30}P while on-resonance and verifying that those same γ -rays were not present off-resonance. The excitation functions in the neighborhood of the $E_p = 1.0380$ MeV resonance are shown in Figure 1.3-1.

For each of the 47 resonances in the energy range $E_p \approx 1.0\text{--}2.5$ MeV, we have measured spectra with our new detector system for an extended period of time. At present identification of the γ -rays in these spectra has been made for ten of the resonances. The resulting decay scheme for one of these resonances is shown in Figure 1.3-2.

In the most recent compilation of $A = 30$ [End91], this level was listed as $E_x = 7762$ keV, $J^\pi = (3 - 5)^+$, $T = (1)$. Our measurements yield $E_x = 7752.7$ keV, $J^\pi = 3^+$ (most of the energy discrepancy is due to a recent revision in the value of S_p for ^{30}P); the isospin remains unknown.

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Figure 1.3-1: $^{29}\text{Si}(p, \gamma)$ in the neighborhood of the newly identified $E_p = 1.4333$ and 1.5787 MeV resonances.

Figure 1.3-2: γ -ray decay scheme for the $E_x = 7752.7$ keV level in ^{30}P . The width of each arrow is proportional to the γ -ray intensity.

Figure 1.3-3: Allowed region in a_2a_4 space for a $3^- \rightarrow 2^-$ transition in $^{29}\text{Si}(p, \gamma)$.

For those levels for which measurement of the electromagnetic decay strengths does not give a unique assignment for $J^\pi; T$, angular distributions are often helpful. We have calculated the appropriate expressions for all reasonable cases. Since there may be either channel spin mixing or ℓ -mixing in the proton channel, the analysis is more complicated than in many previous analyses of capture angular distributions. Thus far, we have focussed on establishing the allowed values of a_2 and a_4 , the coefficients of the angular distribution, for each initial and final state. Because in many cases both protons and γ -rays have associated mixing ratios, one often finds a region of allowed values in a_2 - a_4 space. An example is given in Figure 1.3-3, where we show the allowed region for a $3^- \rightarrow 2^-$ transition in $^{29}\text{Si}(p, \gamma)$. Detailed angular distributions have been measured thus far for five resonances; analysis is in progress.

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1.3.3 Fourier Transform as Test for Chaos

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The standard tests used to evaluate eigenvalue sequences (the nearest neighbor spacing distribution and the Dyson-Mehta Δ_3 statistic) work extremely well in that they distinguish between Poisson and Gaussian Orthogonal Ensemble (GOE) predictions even for rather small sample sizes. The difficulty is that these tests require extremely high quality data – for example missing 10% of the levels from a GOE spectrum can double the value of Δ_3 (a 10% mistake leads to a 100% effect). Since obtaining data which are essentially perfect is difficult, alternative measures that are less sensitive to the purity or completeness of the sequence would be quite valuable. We have considered the Fourier Transform of the eigenvalue spectrum as a test for chaos (i.e., for GOE behavior). The Fourier Transform method has been successfully applied to molecular data sets [Sit94], but has not been applied to nuclear spectra.

We have modeled the behavior of the Fourier Transform of the eigenvalues for GOE and Poisson distributions. We calculate the power spectrum $|S|^2$ for ensembles of eigenvalue spectra; it is convenient to use the variable q/ρ (q is the variable reciprocal to the fundamental variable E and ρ is the level density). A striking difference emerges between GOE and Poisson statistics, for the GOE case there is a dramatic drop for small values of q/ρ which is not present for Poisson statistics. This so-called “correlation hole” persists even when the data are impure or incomplete. We quantified the behavior by considering the area of the correlation hole: the region enclosed by (a) the horizontal line $|S|^2 = \beta$ (where β is the value of the background), (b) the vertical line $q = \lambda$, where λ is the q/ρ value of the first point in the sequence of $|S|^2$ values with $|S|^2 \leq \beta$ (this removes the unwanted spike at the origin), and (3) the $|S|^2$ curve itself. This is the area shaded in Figure 1.3-4.

We calculated 500 GOE and Poisson spectra and averaged the results over the ensemble. In particular we focused on the behavior of the area of the correlation hole. In Figure 1.3-5 the value of the area A is plotted for a variety of cases: as a function of the number of states N , the level spacing D , the sampling parameter Δ , and with the product ND fixed. In all

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Figure 1.3-4: An ensemble-averaged power spectrum with the correlation hole region shaded.

cases the area is constant—in normalized units $A \approx 0.45$. We also considered the impact of missing levels or of incorrectly assigning spins. Even for 50% missing levels, the value of A is only reduced by $\sim 10\%$; for spurious levels the area is reduced approximately linearly with the fraction of spurious levels. Therefore, the area of the correlation hole is superior to the conventional measures. These calculations provide a more quantitative and systematic verification of results obtained previously.

However, the difficulty with the Fourier Transform approach becomes apparent when one applies the method to a single spectrum, rather than ensemble-averaged spectra. For samples on the order of several hundred, the method still works very well (most of the molecular cases involved sample sizes ~ 1000), but for smaller sequences such as $N \approx 50$ the method is inconclusive. After detailed consideration of proton data (from TUNL) and of neutron data (from Columbia) considered to be essentially pure and complete, we conclude that even sample sizes $N \approx 100$ are marginal for a clear distinction between Poisson and GOE.

[Sit94] G. Sitja and J. P. Pique, Phys. Rev. Lett., **73**, 232 (1994).

Figure 1.3-5: Variation of A for ensemble-averaged spectra. First panel: variation of A with N ($D = 0.3$, $\Delta = 0.01$). Second panel: variation of A with D ($N = 100$, $\Delta = 0.01$). Third panel: variation of A with Δ ($N = 100$, $D = 0.3$). Fourth panel: variation of A with N and D ($(N-1)D = 20$, $\Delta = 0.01$).

2 Internucleon Reactions

2.1 Neutron-Proton Interaction

2.1.1 The Low-Energy n-p Analyzing Power and the Charged π NN Coupling Constant

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The π NN coupling constant is the most important coupling constant in nuclear physics. For example, its strength governs the properties of the deuteron and only a few percent difference in its value has dramatic consequences for the quantitative understanding of hadron physics. Therefore, the accurate determination of the π NN coupling constant is of crucial importance.

Machleidt and Li [Mac93] have recently shown that the new value for the charged π NN coupling constant of $g_{\pi\pm}^2/4\pi = 13.54 \pm 0.05$ obtained by the Nijmegen group [Sto93] makes it impossible to reproduce accurately the quadrupole moment Q_d of the deuteron with existing realistic meson-exchange based NN potential models, unless new tensor force generating mechanisms are introduced. The Nijmegen group has repeatedly pointed out that there exists no single NN observable that can be used to determine $g_{\pi\pm}^2/4\pi$: it is the bulk of the NN data that makes an accurate determination of the coupling constant possible. Nevertheless, in measurements at TUNL we focused on a single observable: the analyzing power $A_y(\theta)$ in n-p scattering. At sufficiently low energies only s- and p-waves contribute to this observable. Since the p-waves are peripheral waves, they mainly probe the long-range part of the NN interaction, which is primarily governed by OPE. As is well known, $A_y(\theta)$ for n-p scattering at low energies is determined almost completely by the 3P_J NN interactions; therefore, $A_y(\theta)$ is expected to be sensitive to $g_{\pi\pm}^2/4\pi$. Recent studies performed by Machleidt and Li [Mac93] support this intuitive picture.

We have measured the n-p $A_y(\theta)$ at incident neutron energies of 7.6 and 12.0 MeV to a statistical accuracy of ± 0.0005 . Our preliminary results at $E_n = 12$ MeV are presented in Figure 2.1-1 and compared to the Nijmegen phase-shift analysis [Sto93] and to NN potential models [Mac93] based on different values for $g_{\pi\pm}^2/4\pi$. The absolute normalization uncertainty (not included in Figure 2.1-1) of our data is 1.5-2%. The new data definitely rule out the proposed charge splitting [Mac93] of the π NN coupling constants (see dashed-dotted curve), i.e., the new value $g_{\pi^0}^2/4\pi = 13.47 \pm 0.11$ and the old value $g_{\pi\pm}^2/4\pi = 14.4$, a combination that reproduces both Q_d and p-p scattering data [Mac93].

In the angular range $\theta_{cm} > 60^\circ$ our data are in agreement with Model I (solid curve)

Figure 2.1-1: Preliminary results for the n-p analyzing power $A_y(\theta)$ at $E_n = 12$ MeV in comparison to the NI93 n-p phase-shift analysis prediction [Sto93] and to model studies of Machleidt and Li [Mac93] based on different values for the π NN coupling constants. Details are given in the text.

which is based on $g_{\pi^0}^2/4\pi = g_{\pi^\pm}^2/4\pi = 14.4$. Model II (dotted curve) uses $g_{\pi^0}^2/4\pi = g_{\pi^\pm}^2/4\pi = 13.5$ and predicts $A_y(\theta)$ values which are slightly larger than the present data for $\theta_{\text{cm}} > 60^\circ$. The model dependence of the study of Machleidt and Li [Mac93] can be inferred from the comparison of the dotted curve (Model II) with the long-dashed curve, which was calculated from the Nijmegen n-p phase-shift analysis NI93 [Sto93]. Our data are still subject to small corrections associated with the polarization-dependent efficiency of our neutron detectors. The n- ^{12}C $A_y(\theta)$ data needed for these corrections will be taken in the near future at TUNL. However, it can be stated already at the present time that our final data will not be in agreement with the NI93 prediction. Work on our 7.6 MeV data is in progress.

Our analysis supports the very recent work of Ericson *et al.* [Eri95] who extracted the π NN coupling constant from n-p differential cross-section data at $E_n = 162$ MeV by extrapolating the data in a model-independent way to the pion pole (Chew extrapolation [Che58]). Their result is $g_{\pi^\pm}^2/4\pi = 14.6 \pm 0.3$. However, using a similar Chew extrapolation Arndt *et al.* [Arn95] investigated 55 data sets up to 1 GeV and obtained a result for $g_{\pi^\pm}^2/4\pi$ that is in agreement with the Nijmegen analysis. The absolute normalization of the cross-section data plays a crucial role in this type of analysis.

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2.2 Nucleon-Deuteron Elastic Scattering

2.2.1 Proton-Deuteron Elastic Scattering at Very Low Energy

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A number of workers have emphasized the importance of accurately measuring the proton-deuteron elastic scattering cross section at energies below 400 keV [Che89, Kar93, Fri94]. The primary aim of these measurements is to resolve the discrepancy between the calculated values of the p-d S-wave scattering lengths [Fri83, Che89, Fri90, Che91, Kie94, Kar93] and the phenomenological S-wave scattering lengths extracted from phase shift analyses of the experimental data [Arv74, Hut83]. The p-d differential cross sections have been measured at 315 keV and ~ 240 keV. Analysis of the 315 keV data has been completed and is being used in a phase shift analysis presently being conducted in collaboration with A. Kievsky, M. Viviani and S. Rosati of the INFN in Pisa, Italy. The 315 keV p-d cross section data are shown in Figure 2.2-1. For the purposes of comparison, the 315 keV cross section calculated using the phenomenological phase shifts of [Hut83] (solid line) is also shown, along with the cross section calculated with the S-wave doublet and quartet phase shifts of [Hut83] replaced by those of [Che89] (dashed line). The S-wave doublet effective range function of [Che89] has a pole at $E \sim -25$ keV.

The data point at $\theta_{cm} \sim 130^\circ$ is believed to be an anomaly resulting from a shift in the detection angle. Efforts are underway to ascertain if this is the case and to rectify this point if possible. The analysis of the data at 240 keV continues and should be completed very soon.

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Figure 2.2-1: Proton-deuteron differential cross section at 315 keV compared to p-d cross section calculated using phenomenological phase shifts of [Hut83] (solid line) and the same set of phase shifts with the S-waves replaced by those of [Che89] (dashed line).

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2.2.2 Phase-Shift Analysis of n-d Data and the $A_y(\theta)$ Puzzle

*W. Tornow, H. Witala*¹

Since its discovery [Wit89] the discrepancy between data for the elastic scattering n-d analyzing power $A_y(\theta)$ and results of rigorous three-nucleon (3N) calculations has stimulated interesting theoretical and experimental activities. Sensitivity calculations have shown that this so-called $A_y(\theta)$ puzzle is related to the nucleon-nucleon (NN) 3P_J interactions [Wit91]. More recent calculations [Wit94] indicate that three-nucleon force effects are not responsible for the up to 30% difference found at the maximum of the $A_y(\theta)$ angular distribution between rigorous 3N calculations using two-nucleon (2N) interactions only and experimental data in the incident neutron energy range between 3 and 14 MeV. This observation supports speculations that the problem must be related to the on-shell properties of the 3P_0 , 3P_1 , and 3P_2 NN interactions used in the calculations and not to off-shell effects. Already in 1991 Witala and Glöckle [Wit91] pointed out that a set of 3P_J NN interaction exists that describes both the 2N data and the n-d $A_y(\theta)$. However, these 3P_J interactions exhibit a large breaking of charge independence. In addition the sign of the charge-independence breaking effect contradicts theoretical expectations. Therefore, this solution has not been widely accepted as a viable explanation of the $A_y(\theta)$ puzzle.

Very recently, a strong correlation between the NN 3P_0 , 3P_1 and 3P_2 phase shifts and the n-d $^4P_{1/2}$, $^4P_{3/2}$ and $^4P_{5/2}$ phase shifts was found by Hüber *et al.* [Hüb95], i. e., the n-d $A_y(\theta)$ is very sensitive to the n-d 4P_J phase shifts. This observation led us to perform a n-d phase-shift analysis at $E_n = 3$ MeV. At such a low energy, the phase shifts are real (n-d breakup threshold corresponds to $E_n = 3.33$ MeV) and the six accurate A_y data points measured by the Wisconsin group [McA94] can be used to search for the three real $^4P_{1/2}$, $^4P_{3/2}$ and $^4P_{5/2}$ n-d phase shifts. We modified a code written by Knutson [Knu95] and used as starting parameters in the phase-shifts search the n-d phase shifts (maximum 3N total angular momentum $J_{\max} = 13/2$) obtained from a rigorous 3N calculation using the Bonn B NN potential (with maximum 2N total angular momentum $j_{\max} = 3$). In the search procedure only the $^4P_{1/2}$, $^4P_{3/2}$ and $^4P_{5/2}$ n-d phase shifts were allowed to vary while all other phase shifts and mixing parameters were kept at their values determined by the Bonn B potential. In our phase-shift search we included 12 selected differential cross-section "data points" to make sure that we do not spoil the description of the cross-section. The cross-section "data points" were calculated using the Bonn B NN potential. Figure 2.2-2 displays the n-d $A_y(\theta)$ data at $E_n = 3$ MeV in comparison to both a rigorous 3N calculation using the Bonn B NN potential (dashed curve) and our phase-shift solution (solid curve). Contrary to the Bonn B prediction, the $A_y(\theta)$ data are described very well by our phase shift approach. The associated 4P_J phase shifts are presented in Table 1 in comparison with the n-d phase shifts obtained from Bonn B and the ones found in [Wit91]. Table 1 shows that

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Figure 2.2-2: Neutron-deuteron $A_y(\theta)$ at $E_n = 3$ MeV in comparison to a rigorous 3N calculation (using the Bonn B NN interaction) and the present n-d phase shift fit.

	original Bonn B	modified Bonn B [Wit91]	present work
$^4P_{1/2}$	24.3	23.7	23.1
$^4P_{3/2}$	25.9	25.7	27.0
$^4P_{5/2}$	26.1	26.2	26.5

Table 2.2-1: Neutron-deuteron 4P_J phase shift values in degrees at $E_n = 3$ MeV.

our present results are different from the ones found in [Wit91]. Next we will investigate the stability of our solution by using different starting phase shifts obtained from rigorous 3N calculations performed with the recent NN potential models NI93 [Sto94], AV18 [Wir95] and Bonn B 95 [Mac95]. Afterwards one has to find out how the NN 3P_J interactions in potential models have to be modified in order to reproduce our "experimental" n-d 4P_J phase shifts. Only then it will be possible to see whether the associated NN 3P_J phase shifts describe the 2N data and whether our solution also requires relatively large (and of opposite sign) breaking of charge independence as was found in [Wit91].

Work is in progress to extend the present investigations to energies above the n-d breakup threshold. Here, six n-d $A_y(\theta)$ data sets are available from TUNL that should allow for a good determination of the complex phase shifts $^4P_{1/2}$, $^4P_{3/2}$ and $^4P_{5/2}$ up to $E_n = 14.1$ MeV. We expect this work to contribute significantly to our understanding of the underlying physics associated with the present $A_y(\theta)$ puzzle in n-d elastic scattering.

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2.3 Neutron-Deuteron Breakup Reactions

2.3.1 Neutron-Induced Deuteron Breakup Cross-Section Measurements at 13.0 MeV

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The analysis of the 13-MeV neutron-deuteron (n-d) breakup data for the space and coplanar stars and the collinear configurations are completed. In the star configurations the momentum vectors of the three emitted nucleons in the c.m. lie in the same plane, have equal magnitude and are separated by 120°. The plane defined by the momentum vectors can be oriented arbitrarily in space. The space and coplanar stars are two extreme orientations of the plane. In the space star the plane is perpendicular to the incident beam axis, and in the coplanar star it is horizontal. In the collinear configurations one nucleon is at rest in the c.m. and the momentum vectors of the other two nucleons have equal magnitude

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and are in opposite directions. Our results for two star and two collinear configurations are discussed below.

Our cross-section data (solid circles) for the two collinear configurations are shown in Figure 2.3-1 in comparison to previous n-d data [Str89] (open squares); p-d data [Rau91] (open circles) and rigorous n-d calculations. The normalization uncertainty in the present data is $\pm 5\%$ and is due to the combined uncertainties in the absolute neutron detection efficiency and the normalization factor determined from n-d elastic scattering yields. No attempt was made to extract point-geometry cross sections from the present data. The calculations are made using only two-nucleon forces (Bonn B NN potential). The solid curves are n-d calculations smeared over the finite geometry of our experimental setup. The dashed curves are point-geometry calculations. As can be inferred from the comparison of the solid and dashed curves in Figure 2.3-1, the energy and angle averaging effects in our experiment were negligible except near the maximum of the cross-section enhancements. The locations of the collinear points along the kinematic locus of E_{n1} versus E_{n2} , the S curve, are indicated by the arrows. The present n-d data for the collinear configuration in the top of Figure 2.3-1 ($\theta_1 = 50.5^\circ$, $\theta_2 = 62.5^\circ$ and $\phi_{12} = 180^\circ$) are in good agreement with the p-d data of Rauprich *et al.* [Rau91]. The angles θ_1 and θ_2 are the polar lab angles of the two neutrons (protons in the case of p-d breakup). The angle ϕ_{12} is the difference in the lab azimuthal angles of the two neutrons (protons in the case of p-d breakup). Taking into account the statistical and normalization uncertainties in both n-d data sets and the finite-geometry smearing in the present results, the two n-d measurements are consistent for $S \sim 7$ MeV. The inflection in the data of Strate *et al.* [Str89] around $S = 6.5$ MeV is not seen in the present data, nor is it evident in the p-d data [Rau91]. The calculations are in agreement with the data except at the peak of the NN final-state enhancement around $S = 10$ MeV. The two n-d data sets are in agreement for the second collinear configuration ($\theta_1 = 39.0^\circ$, $\theta_2 = 75.5^\circ$ and $\phi_{12} = 180^\circ$) except around the collinear point ($S = 5$ MeV). The calculations are in good agreement with the present data and do not show the anomalous enhancement reported by Strate *et al.* [Str89]. Based on our findings, we conclude that three-nucleon forces are not needed to describe the cross-section data around the collinear point in these two configurations. However, the situation with the star configurations are quite different.

Our results for the coplanar ($\theta_1 = 17.0^\circ$, $\theta_2 = 50.5^\circ$ and $\phi_{12} = 180^\circ$) and space ($\theta_1 = 50.5^\circ$, $\theta_2 = 50.5^\circ$ and $\phi_{12} = 120^\circ$) star configurations are shown in Figure 2.3-2. The data and calculations are as described above. The present data for the coplanar star are about 25% lower than the cross sections reported by Strate *et al.* [Str89]. Taking into consideration the $\pm 5\%$ uncertainty in the normalization in the present data, they are in good agreement with the calculations. Since the finite-geometry effects in our data are small, as indicated by the difference in the solid and dashed curves, the discrepancy between the present data and that of Strate *et al.* can not be due to finite-geometry effects in our data.

Our data for the space-star configuration are in excellent agreement with the n-d data

Figure 2.3-1: Cross sections for two collinear configurations in n-d breakup at 13.0 MeV. The solid circles are the results of the present work. The other n-d (open squares) and the p-d data (open circles) are from References [Str89] and [Rau91], respectively. The dashed and solid curves are rigorous n-d calculations for point geometry and smeared over the finite geometry of the TUNL experiment, respectively. All calculations are made using the Bonn B potential.

Figure 2.3-2: Cross sections for the space-star (top) and coplanar-star (bottom) configurations for n-d breakup at 13.0 MeV. The data and curves are as described in Figure 2.3-2.

of Strate *et al.* and are roughly 30% higher than the p-d data of Rauprich *et al.* [Rau91]. We suspect the difference between the n-d and p-d data to be due to Coulomb force effects. Even taking into account the $\pm 5\%$ normalization uncertainty in the n-d data sets, the data and calculations differ by more than three standard deviations. The difference between the data and calculations is unlikely to be due to on-shell or off-shell two-nucleon force effects since n-d calculations using a variety of realistic NN potentials (Bonn B, Paris, AV14, Nijmegen) predict the same cross section for the space star within 2%. Also, because over 95% of the space-star cross section is due to the S-wave part of the NN force, and because these force components are determined to high accuracy from two-nucleon scattering data, adjustments to the NN forces within the tolerance allowed by two-nucleon scattering data are insufficient to describe the space-star cross-section data. By process of elimination, we claim that the discrepancy between the space-star cross-section data and calculations can only be due to three-nucleon forces, and the space-star data must be considered in the design of three-nucleon force models.

[Rau91] G. Rauprich *et al.*, Nucl. Phys., A535, 313 (1991).

[Str89] J. Strate *et al.*, Nucl. Phys., A501, 51 (1989).

2.3.2 The TUNL Neutron-Neutron Scattering Length Experiment¹

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This ongoing experiment seeks to measure the absolute cross section of the neutron-neutron final-state interaction (nn FSI) from the kinematically complete analysis of the $^2\text{H}(n, n_1n_2p)$ breakup reaction ($E_n = 13.0$ MeV). It is our objective to achieve a statistical accuracy of 4% or better for 4 detector configurations at nn production angles of 20.5° , 28.0° , 35.5° and 43.0° [Wit95]. For this purpose a goal of 2000 hours of net data accumulation was set. So far 1500 hours have been completed over a period of about one year. The experiment's conclusion is expected by the end of 1995. The experimental setup is shown in Figure 2.3-3.

Small changes were made early this year. In addition to electronic pulser signals introduced at the beginning of the experiment, LED pulsers are now attached to detectors 9, 12, 20 and the center detector. These allow tracking of signals used for time-of-flight and pulse-shape discrimination, permitting distinction between dead time losses in double and triple events. To increase the detection rate for the 43.0° configuration, a ring detector was put in place of transmission detector #1 on the left side of the beam axis.

¹For experimental setup and other aspects refer to TUNL Progress Report XXXIII 1993-94, p. 29.

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Figure 2.3-3: nn FSI detector arrangement.

Figure 2.3-4: Monte-Carlo simulation of TUNL experimental nn FSI configuration using different values for a_{nn} .

The nn FSI cross-section peak height depends strongly on the neutron-neutron scattering length a_{nn} [Tor93]. The extraction of a_{nn} becomes possible by direct comparison of cross sections calculated from Monte-Carlo simulations of the experiment and cross sections obtained experimentally. Simulated and experimental data are treated on equal footing [Sal95]. Monte-Carlo codes and corresponding cross-section libraries are being developed for the configurations of interest. These libraries are created from rigorous three-nucleon calculations based on a modified Bonn B potential model for values of a_{nn} ranging from -15.0 fm up to -19.0 fm. The Monte-Carlo code used for the nd breakup experiment employs these libraries to generate simulated events. Results from simulations for various values of a_{nn} are shown on Figure 2.3-4.

A preliminary analysis has been done of the first batch of experimental data. An example of the cross sections obtained is shown on Figure 2.3-5, where the solid curve corresponds to a point geometry calculation with $a_{nn} = -17.67$ fm.

[Sal95] F. Salinas *et al.*, TUNL Progress Report XXXIV, 1995.

Figure 2.3-5: Cross section for 20.5° configuration from preliminary analysis of the first 261 hours of data taking.

[Tor93] W. Tornow, H. Witała, and D. E. González Trotter, TUNL Progress Report XXXII, 1993.

[Wit95] H. Witała *et al.*, TUNL Progress Report XXXIV, 1995.

2.3.3 Status Report on the TUNL Neutron-Proton Scattering Length Experiment

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We have continued the measurement of the 1S_0 neutron-proton (n-p) scattering length a_{np} in a kinematically complete $n + d \rightarrow n + n + p$ breakup experiment at $E_n = 13.0$ MeV. To extract a_{np} from this reaction we measure the absolute cross section of the neutron-proton final-state-interaction (n-p FSI) peak at four production angles and compare our experimental results to theoretical calculations which are based on different values of a_{np} (see [Pro94]). This experiment takes place simultaneously with the TUNL a_{nn} experiment.

Figure 2.3-6: Experimental Setup

The experimental setup is shown in Figure 2.3-6. It is the same setup as used for the a_{nn} measurements, with detectors D9 through D12 added to detect the second neutron in the n-p FSI configuration. The angles of the four detected neutron pairs in the a_{np} determination are: ($\Theta_{n1} = +20.5^\circ$, $\Theta_{n2} = -100.5^\circ$), ($\Theta_{n1} = +28.0^\circ$, $\Theta_{n2} = -83.5^\circ$), ($\Theta_{n1} = +35.5^\circ$, $\Theta_{n2} = -69.9^\circ$), and ($\Theta_{n1} = +43.0^\circ$, $\Theta_{n2} = -55.7^\circ$). The neutron that forms the final-state interaction (FSI) with the proton is labeled as n1. The positive (negative) sign indicates that the detector is positioned on the right (left) side of the beam axis.

About 260 hours of data have been analyzed using the methods described in the previous progress report. In addition, for each event, we obtain the energies of all the three particles produced, i.e. the energy of the two neutrons (E_{n1} and E_{n2}), and the energy of the proton (E_p). The redundancy in the measured kinematic quantities is used to reduce the accidental

Figure 2.3-7: Two dimensional plot of E_{n1} vs. E_{n2} for n-d breakup at an incident neutron energy of 13.0 MeV. The neutrons were detected at $\Theta_{n1} = +43.0^\circ$ and $\Theta_{n1} = -55.7^\circ$. Cuts on $E_{n1} - E_p$ and $E_{n2} - E_p$ projected spectra have been applied. The curve is a point-geometry kinematic locus. The open circles are the points on the locus to which the data will be projected, see Figure 2.3-8. The circles are separated by 0.5 MeV along the kinematic curve. The parameter S is the path length along the kinematic locus. The curve starts at $S = 0$, where $E_{n2} = 0$, and the value of S increases in the direction of the arrow.

background. Each event is projected onto the E_{n1} vs. E_p plane and is required to fall within a 1.25 MeV wide two-dimensional gate around the projection of the point-geometry kinematic locus on that plane. The same procedure is used for the E_{n2} vs. E_p plane. A histogram of E_{n1} vs. E_{n2} for $\Theta_{n1} = +43.0^\circ$ and $\Theta_{n1} = -55.7^\circ$ is shown in Figure 2.3-7, for all events that pass the E_{n1} vs. E_p and the E_{n2} vs. E_p cuts described above. The curve is the point-geometry locus. The open circles represent the locus points to which the data will be projected. These points are 0.5 MeV apart. Our preliminary results are in good agreement with point-geometry calculations as shown in Figure 2.3-8, for $\Theta_{n1} = +35.5^\circ$ and $\Theta_{n2} = -69.9^\circ$. The data are not corrected yet for the energy smearing due to the finite geometry of the experimental setup and the energy resolution of the detectors.

Our goal is to measure a_{np} to an accuracy of ± 0.5 fm. This requires a measurement of the n-p FSI cross section to a statistical accuracy of about $\pm 3.5\%$. Based on our accumulated yields, we estimate a total of 1750 hours of beam time needed to obtain the required statistical accuracy. We have run 1260 hours to date.

Figure 2.3-8: Plot of the cross section of the n-p FSI along the point geometry kinematic locus. The neutrons were detected at $\Theta_{n1} = +35.5^\circ$ and $\Theta_{rmn2} = -69.9^\circ$. After projection onto the point referred to in Figure 2.3-7, the yields were normalized using neutron-deuteron elastic scattering data. Corrections for the neutron detector efficiencies and attenuation effects in the target were also applied. The curve is a point geometry rigorous 3N calculation using the Bonn B NN potential with $a_{np} = -23.7$ fm.

[Pro94] F. Salinas *et al.*, TUNL Progress Report XXXIII, 1993-1994.

2.3.4 Neutron-Neutron and Neutron-Proton Scattering Length and Three-Nucleon Force Effects

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A crucial problem in the theoretical analysis of the 1S_0 neutron-neutron (n-n) and neutron-proton (n-p) final-state interaction (FSI) cross section obtained from kinematically complete $n + d \rightarrow n + n + p$ breakup experiments deals with possible three-nucleon force (3NF) effects which could invalidate the value obtained for the n-n scattering length a_{nn} and n-p scattering length a_{np} under the assumption that only 2N forces are involved. In order to investigate this issue we performed calculations for the TUNL a_{nn} and a_{np} ex-

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Figure 2.3-9: Calculated peak cross section for the n-n FSI configuration as a function of the production angle of the n-n pair produced in the n-d breakup reaction at $E_n = 13$ MeV. The solid curve is based on 2N forces only (Bonn B NN interaction). The dashed curve uses the Tucson-Melbourne three-nucleon force in addition to the Bonn B potential. Data are being taken at TUNL at n-n production angles of 20.5°, 28.0°, 35.5° and 43.0°. Bottom: Same for n-p FSI configuration.

perimental setup at $E_n = 13$ MeV that include in addition to the Bonn B NN interaction [Mac89] (properly modified for the n-n 1S_0 phase shift) also the Tucson-Melbourne (TM) 3NF [Coo79, Coo81] with a cut off parameter $\Lambda_\pi = 5.8m_\pi$ ($m_\pi = 139.6$ MeV). For details of our calculation see [Hüb93]. Both the 2N- and 3N-forces were allowed to act in all $j \leq 2$ partial-wave states.

Figure 2.3-9 shows the cross section for the n-n (top) and n-p (bottom) FSI condition as a function of the production angle θ_1 of the n-n and n-p pairs in the laboratory system. The arrows indicate the angles where data are being taken at TUNL. As can be seen, the TM 3NF raises the cross section between 0 and 10%, depending on the production angle. At $\theta_1 = 43^\circ$, the cross section is insensitive to the 3NF used in the present work. This feature is very important: There exists a production angle at which the peak height of the n-n and n-p FSI cross section is independent not only of the choice of the specific NN force [Wit95] but also of the presence of a 3NF. A physical interpretation of this phenomenon is presently not available. The angle of $\theta_1 = 43^\circ$ changes with incident neutron energy. It should also be noted that the magnitude of the 3NF effects shown in Figure 2.3-9 depends on the cut-off parameter Λ_π : the 3NF influence decreases with decreasing values of Λ_π [Hüb93].

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2.3.5 Determination of a_{nn} from Kinematically Incomplete Neutron-Deuteron Breakup Data and NN Potential Model Sensitivity

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We calculated proton energy spectra for the $^2\text{H}(n, p)nn$ reaction using a large set of realistic NN interactions. These studies covered the incident neutron energy range from 8 to 63 MeV. The charge-independence breaking in the 1S_0 state was taken into account exactly by considering the total isospin $T = 3/2$ admixture. Figure 2.3-10 represents calculated proton energy spectra at $E_n = 13.0$ MeV and $\theta_p = 3^\circ$. First, we notice in the top panel of Figure 2.3-10 that the FSI peak cross section predicted by the Paris [Lac80], AV14 [Wir84] and Nijmegen [Nag78] potential is between 2% and 4% larger than the one

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obtained with Bonn B [Mac89]. Second (see bottom panel of Figure 2.3-10), the spectra calculated with the recent potentials Nijm93 [Sto94], Nijm I [Sto94] and Nijm II [Sto94] practically overlap and the predicted FSI peak cross section is about 1% lower than the Bonn B value. Finally, the FSI cross section calculated with AV18 [Wir95] is about 3% smaller than the Bonn B result. In Table 2.3-1 we present the values for the 1S_0 nn and np scattering lengths associated with the potential models studied in the present work. Some of the differences observed in Figure 2.3-10 are directly related to differences in a_{nn} .

We start our discussion with the AV18 potential. Clearly, its low FSI cross section is due to its relatively small value for a_{nn} . The AV18 potential contains electromagnetic effects which were turned off in the present calculation in order to compare to other potential models. Therefore, the "nuclear" version of AV18 used here does not describe the deuteron binding energy correctly and this causes also the energy shift of 18 keV observed in Figure 2.3-10 between the AV18 proton energy spectrum and those of the other potential models. Furthermore, the low values shown in Table 2.3-1 for both a_{nn} and a_{np} are the result of neglecting the electromagnetic contributions.

In agreement with the values for a_{nn} listed in Table 2.3-1, the FSI peak cross section obtained in Figure 2.3-10 for Bonn B is slightly larger than those calculated for Nijm93, Nijm I and Nijm II. The latter set of potentials is practically phase-shift equivalent. Since the associated proton energy spectra are almost identical, we conclude that any inherent off-shell differences between NN potential models have probably only a small influence on the proton energy spectra discussed in the present work. In fact, here the observed small differences in the FSI cross section can be explained by the corresponding differences in a_{nn} .

On the other hand, the larger FSI peak cross section noticed in Figure 2.3-10 for the Paris, AV14 and Nijmegen potential compared to the Bonn B result cannot be explained by their different values for a_{nn} . For example, the Paris potential value for a_{nn} of -17.48 fm would imply a smaller FSI cross section than the Bonn B ($a_{nn} = -17.67$ fm) result. However, according to Figure 2.3-10, exactly the opposite is found. Therefore, the differences are most

Potential Model	$a_{nn}(\text{fm})$	$a_{np}(\text{fm})$
AV14	-17.67	-23.73
AV18	-17.16	-23.08
Bonn B	-17.67	-23.76
Nijmegen	-17.82	-23.76
Nijm93	-17.58	-23.75
Nijm I	-17.54	-23.74
Nijm II	-17.40	-23.75
Paris	-17.48	-23.76

Table 2.3-1: Neutron-neutron (a_{nn}) and neutron-proton (a_{np}) scattering lengths of various NN potential models.

Figure 2.3-10: High energy part of the calculated proton energy spectrum for the reaction $^2\text{H}(n, p)^4\text{He}$ at $E_n = 13.0$ MeV and $\theta_p = 3^\circ$ using the Bonn B potential in comparison to the Nijmegen and AV14 NN potentials (top panel) and the Nijm 93, Nijm I, Nijm II and AV18 NN potentials (bottom panel).

likely the result of on-shell differences between the potentials, provided that the replacement of individual NN interaction components in the state 1S_0 by the corresponding components of other NN potentials does not mask or destroy the subtle effects under investigation. Since higher angular momentum NN interactions practically do not contribute to the FSI cross section in this energy range, the on-shell differences must have their origin in the 1S_0 and $^3S_1 - ^3D_1$ NN force components only.

Using the sensitivity of the FSI cross section displayed in Figure 2.3-10 we are confronted with the observation that values for a_{nn} extracted by means of rigorous 3N calculations from kinematically incomplete nd breakup data are subject to a theoretical uncertainty caused by differences between realistic NN potential models. This theoretical uncertainty increases with incident neutron energy. However, below 20 MeV the uncertainty is only about 0.4 fm at the most.

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2.3.6 Observation of Large Discrepancies between Data and Calculations for the Kinematically Incomplete Neutron-Deuteron Breakup Reaction

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In Reference [Tor93] the results of rigorous three-nucleon (3N) Faddeev calculations performed for the kinematically incomplete neutron-deuteron (n-d) breakup reaction were compared to experimental proton energy spectra obtained at a nominal proton emission angle of $\theta_p = 0^\circ$. At $E_n = 14$ MeV it turned out to be necessary to normalize the data of Shirato *et al.* [Shi73] and Haight *et al.* [Hai77] by about 20% in order to achieve agreement between data and calculations in the proton energy range below about 9.5 MeV. Figures 2.3-11 show the unnormalized data of Shirato *et al.* at $E_n = 14.1$ MeV and $\theta_p = 4.0^\circ$ and Haight *et al.* at $E_n = 13.98$ MeV and $\theta_p = 1.6^\circ$ in comparison to rigorous 3N Faddeev

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calculations where the finite geometry of the experimental setup was taken into account using Monte-Carlo techniques. Here, θ_p refers to the mean proton emission angle. The calculations employed the Bonn B [Mac89] nucleon-nucleon (NN) potential in a charge-dependent version. It was shown in Reference [Tor93] that the cross section $d^2\sigma/(d\Omega dE_p)$ in the energy region below 9.5 MeV is insensitive to the value of the neutron-neutron (n-n) scattering length a_{nn} used in the calculation, in contrast to the n-n final-state-interaction (FSI) peak around $E_p = 11.8$ MeV. Furthermore, the normalization factors are nearly independent of the NN potential used in the 3N calculations. Another important feature is the fact that in the energy range below about 9 MeV the theoretical, point-geometry calculations can be compared directly with the experimental data without any averaging over the experimental angular and energy spread.

The large data normalization factors found in Reference [Tor93] are of special concern since these two data sets were considered to be the most accurate data of its kind in the n-n FSI region. If confirmed, this finding will have far reaching consequences with respect to our understanding of the low-energy NN interaction and/or the importance of three-nucleon forces in the 3N system. At 14 MeV only the 1S_0 and 3S_1 - 3D_1 NN force components contribute to the calculated proton energy spectrum. Therefore, the observed discrepancy is even more astonishing.

In view of this finding it is important to carefully scrutinize the available experimental information not only around $\theta_p = 0^\circ$, as was done in Reference [Tor93], but also at larger proton emission angles where the n-n FSI is not the dominant feature in the observed proton energy spectrum.

As an example of our studies Figure 2.3-12 shows proton energy spectra obtained by Koori [Koo72] for mean proton emission angles between $\theta_p = 4.0^\circ$ and $\theta_p = 60^\circ$ in comparison to rigorous 3N calculations using the Bonn B NN potential. As can clearly be seen, the calculations disagree with the data at small proton emission angles, as was found already earlier for the data of Shirato *et al.* and Haight *et al.* However, with increasing proton emission angle, the agreement between data and calculations improves significantly and almost perfect agreement is observed beyond $\theta_p = 20^\circ$. The quoted normalization uncertainty of the data of Koori is 3.3%. It should be noted that the experimental database is not entirely consistent, and that some of the data are about 30 years old.

In summary, we confirmed the observation of Reference [Tor93] that rigorous 3N calculations for the kinematically incomplete n-d breakup cross section at small proton emission angles are in serious disagreement with experimental information. The calculated cross section is 20-25% smaller than the measured data. However, the present work showed that the discrepancy diminishes with increasing proton emission angles and disappears almost completely for $\theta_p > 20^\circ$.

We conclude that it is worthwhile to remeasure the cross section for the kinematically incomplete n-d breakup reaction at $E_n = 14$ MeV for proton emission angles $\theta_p < 60^\circ$ using modern experimental techniques. Only with new and accurate data can the present

Figure 2.3-11: Experimental proton energy spectra (dots with error bars) for the $^2\text{H}(n, p)nn$ reaction at incident neutron energy E_n and mean proton emission angle θ_p in comparison to Monte-Carlo simulations of the associated experimental setups using rigorous 3N calculations employing the Bonn B NN potential. (a) $E_n = 14.1 \text{ MeV}$, $\theta_p = 4^\circ$, experimental data taken from Reference [Shi73], (b) $E_n = 13.98 \text{ MeV}$, $\theta_p = 1.6^\circ$, experimental data taken from Reference [Hai77].

Figure 2.3-12: Experimental proton energy spectra of Koori [Koo72] for the reaction ${}^2\text{H}(n, p)nn$ at $E_n = 14.1$ MeV in comparison to rigorous point-geometry 3N calculations using the Bonn B NN potential.

observation of large discrepancies between data and rigorous calculations be explored in a constructive way.

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2.3.7 Preparation for a_{nn} Measurement from a Kinematically Incomplete n-d Breakup Experiment

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The neutron-neutron (nn) scattering length a_{nn} is a parameter that represents the strength of the nn interaction at low energies. It can be compared with the proton-proton (pp) scattering length a_{pp} to investigate the charge-symmetry breaking in nuclear forces. The difference $a_{pp} - a_{nn}$ is primarily a measure of the up-quark and down-quark mass difference and therefore is of fundamental interest. Experiments to determine a_{nn} use mainly one of two deuteron reactions: $\pi^- - d$ capture or n-d breakup. In $\pi^- - d$ capture only the two neutrons interact strongly in the exit channel. Whereas, in n-d breakup reaction, the interaction between the two neutrons in the final-state takes place in the presence of the proton. For both of these reactions, a_{nn} is extracted by analysis of the cross-section data. However, the experimental values of a_{nn} from the two reactions disagree. What is more confusing than this discrepancy is that significantly different values for a_{nn} are reported from similar $^2\text{H}(n, p)nn$ experiments.

A new analysis was done by Tornow *et al.* [Tor93] on proton energy spectra from two previous $^2\text{H}(n, p)nn$ experiments performed close to 14 MeV [Hai77, Shi73]. In this work the 3N continuum Faddeev equations were solved rigorously using the meson-exchange based Bonn B NN potential. It gives a_{nn} of -22.08 ± 1.47 fm from the experiment of Haight *et al.* and -16.00 ± 0.59 fm from the experiment of Shirato *et al.* The a_{nn} values are significantly different from each other, and they are not in agreement with the $\pi^- - d$ capture results of -18.5 ± 0.3 fm [Mac89].

A new $^2\text{H}(n, p)nn$ experiment at an incident neutron energy of 14 MeV is being developed to clarify the inconsistent experimental situation in this energy range. The proton

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energy spectrum from this reaction near $\theta_p = 0^\circ$ must be accurately measured to extract an accurate value of a_{nn} using a realistic NN potential in rigorous 3N Faddeev calculations. The proton energy spectrum from the reaction will be measured using the TUNL Enge split-pole magnetic spectrometer. A vertical drift chamber (VDC) will be developed to provide particle detection in the focal plane. The VDC will be used also to measure the angle of the particle's trajectory, and therefore permit use of a large solid angle in the accumulation of data.

Preliminary tests are underway to study systematic effects which affect the measurement of the proton energy spectrum from the $^2\text{H}(n, p)nn$ reaction and to determine what constraints may be necessary to achieve the desired accuracy of the experiment.

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2.4 Pion-Deuteron Capture

2.4.1 Measurement of the $^1\text{S}_0$ Neutron-Neutron Scattering Length Using the $^2\text{H}(\pi^-, nn\gamma)$ Reaction: LAMPF E1286

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The nucleon-nucleon(NN) scattering lengths are measures of the NN forces at zero energy. Their relative magnitudes are constrained by charge symmetry and charge independence of the strong nuclear force. Charge dependence is well understood in terms of the meson-exchange model of the NN force. The additional exchange of charged mesons makes the n-p force stronger than the NN and p-p forces. The differences in the NN and p-p nuclear forces have been attributed to the mass difference of the up and down quarks [Hen69]. The

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p-p and n-p scattering lengths, a_{pp} and a_{np} , respectively, can be determined to an accuracy of ± 0.3 fm from free two-nucleon scattering data. However, measuring the neutron-neutron scattering length a_{nn} to the accuracy needed to address charge-symmetry issues is difficult. The standard technique for determining a_{nn} is to use a reaction that emits two neutrons with low relative momentum and to measure the cross section for the final-state interaction enhancement. We summarize the current status of the value for the 1S_0 a_{nn} below.

A suggested average value of a_{nn} from the $^2\text{H}(n, nn)p$ reaction is -16.8 ± 0.4 fm [Sch87], but values from different measurements range from about -16 fm to -23 fm. Other reactions, such as $^3\text{H}(d, 2n)^3\text{He}$ and $^3\text{H}(t, 2n)^4\text{He}$, yield results ranging from -16 to -17 fm [Sch87]. Measurements of a_{nn} using the $^2\text{H}(\pi^-, nn\gamma)$ have also been published. An average value of -18.5 ± 0.3 fm [Gab79, Sch87] was obtained in recent measurements. An earlier study had obtained a value of -16.7 ± 1.3 fm [Sal75].

We have made new measurements of neutron-gamma coincidence spectra for stopped pions in a liquid deuterium target. The measurements were conducted in the LEP cave at LAMPF during the summer of 1993. The liquid deuterium target was a right cylinder of dimensions 6 cm diameter $\times$ 6 cm high. A 4.5 cm thick beryllium slab was used to bring the 50-MeV pion beam to rest in the middle of the target. Neutrons were detected by an array of 24 liquid scintillators, and one arm of the neutral meson spectrometer (NMS) was used to detect the associated gamma rays. The large solid angle, high efficiency, and high x-y position resolution of the NMS was a critical ingredient in the design of E1286. The neutron detectors were cylindrical cells of dimensions 12 cm dia. $\times$ 5 cm thick. The use of liquid scintillators enabled gamma-ray rejection by pulse-shape discrimination techniques. The gamma-ray suppression was about 1:20 with our neutron-energy threshold setting of about 1 MeV. The experimental setup is shown in Figure 2.4-1. Data were accumulated over a period of two weeks, with liquid hydrogen and empty target runs included.

Data analysis is underway. Values for a_{nn} will be extracted from two classes of events: those involving only one neutron and a gamma (kinematically complete), and those involving two neutrons and a gamma (kinematically over determined). The first pass analysis is complete. A total of 44 runs have been analyzed. All calibrations, pedestal corrections and time offsets have been applied to the raw data, and the event size has been reduced to 16 parameters. The data sets created by the first-pass analysis are about one-tenth the size of the raw data. A spectrum of yields vs. $\pi - \Theta$ is shown in Figure 2.4-2 for about one-tenth of our accumulated data. The angle Θ is between the emitted γ -ray and the detected neutron in the $n - \gamma$ coincidence measurements. The dashed curve is a calculation by Gibson [Gib95]. The predictions do not include the enhancements in the neutron energy spectrum due to quasifree $\pi^- - p$ capture. In the second pass analysis neutron time-of-flight (TOF) spectra will be sorted from 0.1-radian wide cuts on Θ . In the triple coincidence data ($n_1 - n_2 - \gamma$) conservation of energy and momentum will be used to reduce the accidental background. The value for a_{nn} will be extracted by fitting the NN FSI peak in the neutron TOF spectra. Monte-Carlo simulations will be used to smear the theory over the finite

Figure 2.4-1: Experimental setup for LAMPF E1286: nn scattering length determination using the ${}^2\text{H}(\pi^-, nn\gamma)$ reaction.

Figure 2.4-2: Neutron yields for the ${}^2\text{H}(\pi^-, n\gamma)$ reaction as a function of the angle θ between the momentum vectors of the detected neutron and gamma ray. The solid curve is experimental data and the dashed curve is a prediction by Gibson [Gib95].

geometry of our experiment for direct comparison. The development of the Monte-Carlo code is on schedule. The neutron detector efficiency measurements are being carried out at TUNL and at the Los Alamos Ion Beam facility. They cover the neutron energy range between 0.7 and 14 MeV. These data will be used to correct the neutron TOF spectra for the energy dependence of the neutron detector efficiency.

In the next several months more detector efficiency data will be taken and tabulated for incorporation into the analysis code. The Monte-Carlo code will be completed and used to generate geometric acceptances for our experimental setup. The first comparison between theoretical predictions and experimental neutron energy spectra will be presented at the Division of Nuclear Physics meeting in Bloomington, IN.

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2.4.2 Neutron Detector Efficiency Calibration for a_{nn} Measurements at LAMPF

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A measurement to determine the neutron-neutron scattering length, a_{nn} , using the $\pi^- + {}^2\text{H} \rightarrow 2n + \gamma$ capture reaction was conducted at LAMPF (E1286) during the summer 1993 with collaborators from Los Alamos National Laboratory, the University of North British Columbia, the Rudjer Boskovic Institute in Croatia, the University of Texas-Austin, the Joint Institute of Nuclear Research in Dubna, and the University of Tübingen in Germany. The neutron detection efficiencies of the 24 liquid scintillators used in the experiment are being measured at TUNL over a neutron energy range compatible with E1286. The ${}^2\text{H}(d, n){}^3\text{He}$ reaction has been used to calibrate the efficiency of 11 of the detectors used in E1286 and 3 of the detectors currently being used in the TUNL a_{nn} and a_{np} measurements. Measurements were made at discrete neutron energies between 5.0 and 13.0 MeV. Each detector was placed at 0° and 60° relative to the incident deuteron beam direction to cover the above energy range. The data were collected in runs of about $10\ \mu\text{C}$ of integrated beam current on the target cell. A total 100 runs were made. Three parameters, time-of-flight, pulse shape and pulse height, were written to tape for each event. The data are being replayed with several threshold settings on the pulse height. Preliminary calibrations of six of the detectors are complete.

In addition to the single detector calibrations, measurements were made on multi-detector configurations that simulated the experimental conditions of E1286. These data will assist in determining the influence of attenuation and double-scattering in the E1286 data.

A series of runs for low-energy neutron detector calibration is underway using the fission neutrons from an 80-nCi ${}^{252}\text{Cf}$ source. Space and hardware allow two detectors to be calibrated simultaneously. However, this relatively weak source strength requires that each detector be exposed for about 7 weeks. New data acquisition hardware and software have been developed to allow such a prolonged experiment to co-exist with the rest of the TUNL experimental programs.

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2.5 Nucleon Form Factors

2.5.1 Measurement of Electric and Magnetic Form Factors of the Neutron

A. Crowell, C. R. Howell, W. Tornow, R. L. Walter, and the G_E^n - G_M^n Collaboration

A group at TUNL is collaborating on measurements of the electric and magnetic form factors of the neutron, G_E^n and G_M^n , respectively, at five Q^2 points: 0.30, 0.50, 1.0, 1.5 and 2.0 (GeV/c)². The measurement at $Q^2 = 0.30$ (GeV/c)² is scheduled to run during the Fall 1995 in the South Hall at the MIT-Bates Linear Accelerator Center. Beam time for the 0.50 and 1.0 (GeV/c)² points have been approved to run in Hall C at CEBAF (PR-89-005). We anticipate beam time at CEBAF for the G_E^n and G_M^n measurements will start during the Fall 1996. The G_E^n measurement will use the polarization transfer technique $D(\vec{e}, e\vec{n})p$ suggested by Arnold, Carlson and Gross [Arn81]. Polarized electrons will be used to electrodisintegrate deuterons in an unpolarized liquid deuterium target. The scattered electrons and outgoing neutrons are detected in coincidence at angles in the kinematic region of electron-nucleon quasi-free scattering. The longitudinal-sideways and longitudinal-normal polarization transfer coefficients $D_{LS'}$ and $D_{LN'}$ will be measured using the Kent-State large neutron polarimeter [Mad89]. Calculations by Arenhövel [Are87] show that $D_{LS'}$ in the quasi-free region in e-d scattering is sensitive to the electric form factor of the struck nucleon and insensitive to details of the deuteron wave function. By measuring both $D_{LS'}$ and $D_{LN'}$ in the same experiment, the dependence of the ratio of G_E^n to G_M^n ($g \equiv G_E^n/G_M^n$) on the helicity of the incident electrons can be eliminated. Since g is directly proportional to the ratio of $D_{LN'}$ to $D_{LS'}$, the helicity dependence in g cancels in the ratio. To measure $D_{LN'}$ a magnet will be placed in front of the polarimeter to precess the neutron spin through 90°. The spin orientation magnet will be a single dipole in the Bates experiment and a series of three dipoles in the CEBAF measurements. Our group at TUNL has accepted the task of mapping the fields of these 18-kG magnets.

The G_M^n determination requires an absolute measurement of the electron-neutron coincidence cross section. For these measurements an accurate calibration of the neutron detector efficiency is needed at the energies of the recoil neutron ($T_n = 160, 267, 532, 799$ and 1064 MeV) for the five Q^2 points listed above. Our plan is to use the $\gamma + p \rightarrow \pi^+ + n$ reaction for the efficiency calibration. The reaction will be induced using virtual photons from the electron beam in Hall C. The π^+ associated with the emitted neutron will be detected in the high-momentum spectrometer in Hall C. In the Bates experiment the front plane of scintillators (the polarimeter analyzer) will be used for the G_M^n measurement. A new detector is being designed at Hampton University to be used for the G_M^n measurement at CEBAF. The new design will improve the neutron detection efficiency by about a factor of two. The G_M^n measurement at $Q^2 = 1.0$ (GeV/c)² will be the thesis project of Alex Crowell.

In June 1994, the collaboration conducted a ten-day run at IUCF to calibrate the

polarimeter at neutron energies of 124 and 160 MeV. The neutrons were produced using the $^{14}\text{C}(\text{p}, \text{n})^{14}\text{N}$ (2.31 MeV, 0^+) reaction at 0° . The analysis of the data is progressing on schedule. A proposal has been submitted to the PAC at Saturne to calibrate the polarimeter at 15 neutron energies in the range from 100 to 1100 MeV. The hope is to have beam time at Saturne during early Spring 1996.

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3 Dynamics of Very Light Nuclei

3.1 Polarized-Beam and Polarized-Target Reactions

3.1.1 A Polarized Solid ^3He Target for Neutron-Transmission Experiments

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

In the past year we have completed measurements of polarized neutron-polarized ^3He scattering in the few MeV region. Measurements of the total cross-section differences $\Delta\sigma_T$ and $\Delta\sigma_L$ have been obtained for neutrons with incident energies 1-10 MeV. The results are sensitive to the excited state structure of the alpha particle and may be compared to phase-shift predictions based on a number of analyses of the n - ^3He system. The $\Delta\sigma_T$ results are in agreement with a recent R-matrix analysis of $A = 4$ scattering and reaction data, and lend support to the ^4He level scheme derived from that analysis. The $\Delta\sigma_L$ data is currently being analyzed.

The experiments were performed with the largest polarized solid ^3He target ever used in a nuclear physics experiment [Kei95]. The target, which contains 0.4 moles of ^3He , is polarized to 38% in the TUNL spin-spin polarized target cryostat by cooling the sample to 12 mK in a 7 Tesla magnetic field. Such a target is suitable for nuclear physics measurements which produce beam heating of a few microwatts and are insensitive to the large magnetic field.

The density of the condensed phases of ^3He corresponds to approximately 100 MPa of room temperature gas. In a neutron transmission experiment, the effectiveness of the target can be described by a figure of merit $(P_t x_3)^2$ where P_t is the target polarization and x_3 the target thickness in atoms/cm². The number of transmitted neutrons that must be counted to achieve a given precision is inversely proportional to $(P_t x_3)^2$. If we compare the TUNL condensed ^3He target ($P_t = 38\%$, $x_3 = 4.3 \times 10^{22}$ atoms/cm²) with a state of the art ^3He gas target ($P_t = 55\%$, $x_3 = 1.9 \times 10^{21}$ atoms/cm²), the figure of merit of the solid target is larger by a factor of 250. For example, our neutron transmission measurement would have required over 150 days to complete with a gas target.

The solid ^3He samples were grown directly from liquid ^3He at 1.1 K. The target cell is constructed of beryllium copper alloy for strength and high thermal conductivity. To improve the thermal linkage to the solid ^3He , the sample space is filled with 3 mm silver powder packed to 19% of the density of solid silver. The target cell is shown in Figure 3.1-1. The density of the solid in the target was determined by the melting and freezing

Figure 3.1-1: The polarized solid ^3He target cell. The sample space is indicated by the gray shaded portion. The interior dimensions of the target are shown to the right.

Figure 3.1-2: Cooling curve for the ^3He target. Temperature measured with the $^{60}\text{CoCo}$ nuclear orientation thermometer (crosses) and the ^3He melting curve thermometer (circles). Inset: Cooling curve for the ^3He target below 20 mK.

temperature during sample growth. The polarization of the target was determined from the temperature of the target as measured with $^{60}\text{CoCo}$ nuclear orientation thermometry and ^3He melting curve thermometry. A cooling curve for the target is shown in Figure 3.1-2.

There are applications of a solid polarized target for photon scattering experiments [FEL94]. It is also possible to directly exploit the ^3He as a neutron scintillation detector [van76]. We are presently studying the possibility of reconfiguring the TUNL solid ^3He target for this purpose.

[FEL94] *Discussions at TUNL-FELL Workshop, 1994.*

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[van76] R. van Staa, J. Reher, and B. Zeitnitz, Nucl. Instrum. Methods, **136**, 241 (1976).

3.1.2 New Impulse Approximation Calculation for the $\bar{d} + d \rightarrow d + p + n$ Breakup Reaction

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Since $\bar{d} + d \rightarrow d + p + n$ cross-section data suggest that quasifree nucleon-deuteron processes are the dominant feature, we develop, in the spirit of the impulse approximation, a model which is the coherent sum of four terms: neutron-deuteron and proton-deuteron quasifree scattering while the other nucleon in either the target or the projectile behaves as a spectator. It can be shown that these four terms correspond to the lowest order diagrams in the Born series expansion of the t-matrix for $\bar{d} + d \rightarrow n + p + d$. In the framework of the AGS equations [Alt70], the breakup amplitude may be written as the sum of two terms involving both the $2 + 2 \rightarrow 2 + 2$ and $2 + 2 \rightarrow 1 + 3$ half-shell amplitudes which may be obtained from the solution of the set of coupled integral equations. If only the lowest order diagrams are considered (the amplitudes are zero for the $2 + 2 \rightarrow 2 + 2$ term and the one-nucleon exchange Born term for $2 + 2 \rightarrow 1 + 3$), the breakup amplitude at a c.m. energy E can be written in terms of three-nucleon t-matrices for $1 + 2 \rightarrow 1 + 2$ embedded in four-particle space through an energy shift that equals the kinetic energy of the spectator nucleon relative to the center of mass of the underlying three-nucleon subsystem. The four terms (two in T_2 and two in T_1) in Equation 3.1 are needed order to account for the identity of deuterons in the initial state and nucleons in the final state.

$$T = T_2 + T_1 = \left\langle 1\delta'k'_d; \frac{1}{2}u'_1k'_1; \frac{1}{2}u'_2k'_2 \right| T(E) \left| 1\delta_1k; 1\delta_2 - k \right\rangle \delta(k'_1 + k'_2 + k'_d) \quad (3.1)$$

$$T_2 = \frac{1}{\sqrt{2}} \left\{ \left\langle 1\delta' \frac{1}{2}u'_1; Q'_2 \right| Z(\epsilon_2) \left| Q_2^+; 1\delta_1 \frac{1}{2}u \right\rangle \chi_d \left[q_2^+; \begin{pmatrix} \frac{1}{2} & \frac{1}{2} \\ u & u'_2 \end{pmatrix} \begin{pmatrix} s & l \\ s_z & m \end{pmatrix} \begin{pmatrix} 1 \\ \delta_2 \end{pmatrix} \right] \right. \\ \left. + \left\langle 1\delta' \frac{1}{2}u'_1; Q'_2 \right| Z(\epsilon_2) \left| Q_2^-; 1\delta_1 \frac{1}{2}u \right\rangle \chi_d \left[q_2^-; \begin{pmatrix} \frac{1}{2} & \frac{1}{2} \\ u & u'_2 \end{pmatrix} \begin{pmatrix} s & l \\ s_z & m \end{pmatrix} \begin{pmatrix} 1 \\ \delta_2 \end{pmatrix} \right] \right\} \quad (3.2)$$

$$T_1 = \frac{1}{\sqrt{2}} \left\{ \left\langle 1\delta' \frac{1}{2}u'_2; Q'_1 \right| Z(\epsilon_1) \left| Q_1^+; 1\delta_2 \frac{1}{2}u \right\rangle \chi_d \left[q_1^+; \begin{pmatrix} \frac{1}{2} & \frac{1}{2} \\ u & u'_1 \end{pmatrix} \begin{pmatrix} s & l \\ s_z & m \end{pmatrix} \begin{pmatrix} 1 \\ \delta_1 \end{pmatrix} \right] \right. \\ \left. + \left\langle 1\delta' \frac{1}{2}u'_2; Q'_1 \right| Z(\epsilon_1) \left| Q_1^-; 1\delta_2 \frac{1}{2}u \right\rangle \chi_d \left[q_1^-; \begin{pmatrix} \frac{1}{2} & \frac{1}{2} \\ u & u'_1 \end{pmatrix} \begin{pmatrix} s & l \\ s_z & m \end{pmatrix} \begin{pmatrix} 1 \\ \delta_1 \end{pmatrix} \right] \right\} \quad (3.3)$$

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where Z is the three-nucleon t -matrix, χ_d is the deuteron wave function, and

$$Q_i' = -\frac{2}{3}k_i' - k_d', Q_i^\pm = -\frac{2}{3}k_i' \mp k, \quad (3.4)$$

$$q_i^\pm = k_i' \pm \frac{1}{2}k, \epsilon_i = E - \frac{4}{3}k_i'^2, \quad (3.5)$$

$$E + 2\epsilon_d - k^2 = 0, \quad (3.6)$$

and

$$E + \epsilon_d - k_1'^2 - k_2'^2 - \frac{k_d'^2}{2} = 0. \quad (3.7)$$

All momenta $\vec{k}$ are in the four nucleon c.m. system. The momenta $\vec{k}$, $\vec{k}_d'$ and $\vec{k}_i$ are of the incident deuteron, the outgoing deuteron and the outgoing nucleons ($i = 1, 2$), respectively. The δ_i' and u (δ_i' and u_i') represent the spin projections of the initial (final) deuteron(s) and nucleon(s).

Assuming that deuteron "one" is polarized, then T_2 and T_1 in Equation 3.1 correspond to target breakup and projectile breakup, respectively. Given the on-shell relation of Equation 3.6, the three-body t -matrix Z is on-shell on the left side ($\epsilon_i = E - \frac{4}{3}k_i'^2 = -\epsilon_d + \frac{3}{2}Q_i'^2$) and off-shell on the right side ($\epsilon_i \neq -\epsilon_d + \frac{3}{2}(Q_i^\pm)^2$). Before realistic 3N calculations were available, one used measured elastic nucleon-deuteron cross sections to predict the $d + d \rightarrow d + p + n$ breakup cross section. That approach had two shortcomings. First it ignored the fact that nucleon-deuteron quasifree amplitudes are off-the-energy-shell in deuteron-induced deuteron three-body breakup. It has been shown [McI72] that using off-shell amplitudes can change the calculated cross section significantly. Second and more importantly, using only free nucleon-deuteron elastic scattering cross sections, does not take into account the correct interference effect between different poles.

The tensor observables T_{kq} are compute from Equation 3.1 as

$$\begin{aligned} T_{kq} \text{Tr}\{T^\dagger T\} &= \text{Tr}\{T^\dagger T \tau_{kq}\} \\ &= \sum_{\substack{\delta_1 \delta_2 \\ \delta_1' \delta_2'}} \langle 1\delta_1 1\delta_2 | T^\dagger T | 1\delta_1' 1\delta_2' \rangle \langle 1\delta_1' 1\delta_2' | \tau_{kq} | 1\delta_1 1\delta_2 \rangle \\ &= \sum_{\delta_1 \delta_2 \delta_1'} \sum_{u_1' u_2' \delta'} \langle 1\delta_1 1\delta_2 | T^\dagger | \frac{1}{2}u_1' \frac{1}{2}u_2' 1\delta' \rangle \langle \frac{1}{2}u_1' \frac{1}{2}u_2' 1\delta' | T | 1\delta_1' 1\delta_2' \rangle \hat{k} C_{\delta_1 q \delta_1'}^{1u1}. \end{aligned}$$

In all our calculations we take the Hulthen wave function for the deuteron and calculate for each ϵ_i the half-shell $n + d \rightarrow n + d$ t -matrix using for the N-N interaction a rank one Yamaguchi separable potential for the channels: 1S_0 , 3S_1 - 3D_1 , 1P_1 3P_0 , 3P_1 and 3P_2 . In each partial wave the parameters are fitted to the low energy properties of the N-N force such as the scattering length, the effective range, the deuteron binding energy and the deuteron

Figure 3.1-3: Yields for the $\bar{d} + d \rightarrow d + d + n$ reaction as a function of S for the angles $\theta_d = +17^\circ$ and $\theta_p = -17^\circ$. Data and curves are described in the text.

quadruple moment [Fon95]. The parametrization of the 3S_1 - 3D_1 force corresponded to a 5.5% D-state in the deuteron. Although the deuteron wave function we used is not fully consistent with the 3S_1 - 3D_1 interaction used to generate Z , one expects the contribution to the cross section and analyzing powers from the D-state of the deuteron to be small in the quasifree region.

Predictions of our model are shown in Figures 3.1-3 and 3.1-4 in comparison to TUNL data [How93] for the $\bar{d} + d \rightarrow d + p + n$ reaction at an incident deuteron energy of 12 MeV. In these measurements the deuteron and proton were detected at 17° on opposite sides of the incident beam axis. The data and calculations are shown as a function of S , the distance along the kinematic locus in the $E_d - E_p$ plane. The calculations were normalized to fit the peak value of the yields spectrum in Figure 3.1-3. Our calculations give a very good description of the shape of the quasi-free enhancement. This is a big improvement over previous impulse-approximation calculations [Val72]. In Figures 3.1-3 and 3.1-4 the solid curves are full calculations with both T_2 and T_1 in Equation 3.1, the dotted curves are calculations with only T_2 , and the dashed curves are calculations that include T_2 and T_1 but not their interference. One immediately sees from Figure 3.1-3 that about 40% of the cross section for the 17° angle pair is due to the interference of the two terms and that the interference is needed to give the correct shape of the spectrum. All analyzing powers in Figure 3.1-4 are well described by the calculation. It is clear from these comparisons that the interference between terms is needed to describe the spin observables. Our calculations

Figure 3.1-4: Analyzing powers for the $\bar{d} + d \rightarrow d + d + n$ reaction as a function of S for the angles $\theta_d = +17^\circ$ and $\theta_p = -17^\circ$. Data and curves are described in the text.

were compared to the data of Howell *et al.* [How93] at several angles, and the results were similar to those obtained at 17° .

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3.1.3 Analyzing Power Measurements of D(d, d)D at $E_d = 3$ MeV and 4.75 MeV

B. J. Crowe III, C. R. Brune, W. H. Geist, H. J. Karwowski, E. J. Ludwig, K. D. Veal and K. A. Fletcher¹

Discrepancies between resonating group model (RGM) calculations of some tensor analyzing powers and previous experimental data at $E_d = 6$ –10 MeV [Grü72] for the $A = 4$ system has led us to extend our previous measurements of this system [Fle94]. We are now beginning an investigation of D(d, d)D at energies below the deuteron-breakup threshold in order to test predictions of both RGM and R-matrix theories. Especially interesting here is the importance of certain spin-flip matrix elements which have been set to values which exceed expectations in RGM calculations [Hof93] adjusted to fit the existing data.

We have recently measured the tensor analyzing powers A_{zz} and A_{yy} for D(d, d)D elastic scattering at incident deuteron energies of 3 and 4.75 MeV. At each energy the data were collected over an angular range in the lab of 20–60 degrees using the TUNL FN tandem accelerator. Thin, durable deuterated-carbon targets were bombarded by polarized deuteron beams produced by the TUNL polarized-ion source. Particles exiting the reaction were viewed by two pairs of symmetrically-placed detector telescopes containing ΔE detectors with thicknesses between 6 and 16 μm .

Our results for A_{zz} at 4.75 MeV are shown in Figure 3.1–5 along with a prediction of A_{zz} from an R-Matrix parameterization [Hal95]. The reasonable agreement between theory and experiment obtained for A_{zz} does not appear to hold for the case of the A_{yy} data obtained at this energy. Theoretical calculations at 3 MeV are underway.

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- [Fle94] K. A. Fletcher *et al.*, Phys. Rev. C, 49, 2305 (1994).

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Figure 3.1-5: Comparison of $A_{zz}(\theta)$ data for $D(d, d)D$ scattering with a theoretical prediction from an R-matrix parameterization (solid curve) at 4.75 MeV.

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[Hof93] H. M. Hofmann, 1993, private communication.

3.2 Measurements of D-States of Very Light Nuclei by Transfer Reactions

A direct result of the nucleon-nucleon (N-N) tensor force in few-body systems is the presence of non-spherical components in the nuclear wave functions, or D-states [Eri85,Leh90]. The tensor force is a crucial component of the nuclear force, responsible for most of the binding for the 3- and 4-nucleon systems [Eri85]. Models based only on pairwise N-N forces, however, fail to account for the triton binding energy and this has led to the introduction into some models of a phenomenological 3-nucleon force, adjusted to yield the correct tri-nucleon binding energy but also affecting other physical observables. The measurement of D-state observables, affected by the tensor force in the N-N interaction and the inclusion of 3-body forces, can provide a sensitive tests of these models. One such observable which can be compared directly to the results of exact calculations of the ground states of few-body systems is η , the asymptotic D- to S-state ratio. Our program in recent years has been to determine η for nuclei with $A < 7$ from comparisons of DWBA calculations and experiment for tensor analyzing power (TAP) angular distributions for a variety of nuclei. Cases chosen for study have minimum theoretical uncertainty in their interpretation.

3.2.1 The D-State of ^3H using Sub-Coulomb (d, t) Reactions

B. Kozłowska, Z. Ayer, H. J. Karwowski and E. J. Ludwig

We have now completed our measurements and analysis of TAPs in sub-Coulomb (d, t) reactions. A value of η for the triton (η_t) has been extracted by comparing the TAP data with distorted-wave Born approximation (DWBA) calculations. These reactions were studied at sub-Coulomb energies in order to maximize the reliability of the DWBA calculations. A paper has been published in *Physical Review C* containing our η_t value which is slightly smaller in magnitude than that predicted using several different methods of solving Faddeev calculations [Fri88, Ish88].

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[Ish88] S. Ishikawa and T. Sasakawa, Few-Body Syst., **1**, 143 (1988).

[Leh90] D. R. Lehman, 1990, Proc. Int. Conf. on Polarization Phenomena in Nuclear Physics, Paris, France.

3.2.2 The D-State of ^3He from $(d, ^3\text{He})$ Reactions

Z. Ayer, H. J. Karwowski, B. Kozłowska and E. J. Ludwig

Similar to the (d, t) analysis described in the previous sub-section, we have extracted four independent values of η for ^3He from theoretical comparisons with TAPs measured in $^{93}\text{Nb}(d, ^3\text{He})^{92}\text{Zr}$, $^{63}\text{Cu}(d, ^3\text{He})^{62}\text{Ni}$, and $^{89}\text{Y}(d, ^3\text{He})^{88}\text{Sr}$ reactions. These values were found to be consistent with each other and were combined to yield a final η value of $-0.0380 \pm 0.0026 \pm 0.0011$. The error in η includes the statistical error in the measurement, effects of using different sets of optical potentials in the analysis and uncertainties in the beam polarization. It does not include uncertainties arising from the absence of tensor potentials which have been used to help describe deuteron elastic scattering TAP angular distributions. The inclusion of these same potentials in calculations of $(d, ^3\text{He})$ TAP observables seriously degrades the quality of comparisons with the present experimental data. The present statistical uncertainty obtained for η is smaller than obtained previously. This work has been submitted for publication in *Physical Review C*.

3.2.3 Investigation of the D-state of ^6Li using $(^6\text{Li}, d)$ and $(^6\text{Li}, \alpha)$ Reactions

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Although ^6Li D-state parameters are expected to be smaller than those for lighter nuclei, their determination can be quite interesting, since D-state effects arise from both the tensor forces and from n- and p-orbitals outside the ^4He core. Three-body (αNN) models of ^6Li predict a small and positive $\eta(^6\text{Li})$, but also predict the wrong sign for the quadrupole moment [Leh90]. Other models predict a negative $\eta(^6\text{Li})$ [Nis83]. The $(d, ^6\text{Li})$ and $(^6\text{Li}, d)$ reactions can provide a means of determining the d- α component of $\eta(^6\text{Li})$. However cross section, VAP, and TAP angular distributions obtained at TUNL for the $^{64}\text{Zn}(d, ^6\text{Li})^{60}\text{Ni}$ reaction, have revealed that direct α transfer cannot always be assumed to be the predominant reaction mechanism [Bow92]. Analyses of these data show that excitation of the low-lying 3^+ state in ^6Li contributes significantly to the reaction mechanism at deuteron

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Figure 3.2-1: Theoretical predictions for T_{20} for $^{58}\text{Ni}(^6\text{Li}, d)^{62}\text{Zn}$ and $^{28}\text{Si}(^6\text{Li}, d)^{32}\text{S}$ at 50 MeV assuming a negative D- to S-state ratio (solid curve) of -0.0145 or positive ratio of the same magnitude (dashed curve). A direct α -cluster transfer is assumed.

energies below 20 MeV. In contrast, data at 45 MeV show angular distribution patterns consistent with direct α transfer [Jac79].

We have now identified suitable target nuclei, such as ^{58}Ni and ^{28}Si , which can be used to study the $(^6\text{Li}, d)$ reaction with higher-energy, polarized ^6Li beams obtained at Florida State University. At energies between 30 and 50 MeV, a simple, direct-reaction mechanism is expected to predominate and facilitate the determination of D-state parameters. Our exact finite-range DWBA calculations, using the computer code FRESKO, have indicated that quantities such as T_{20} show a clear dependence on the magnitude and sign of the η parameter, as shown in Figure 3.2-1. Information about the reaction mechanism obtained from VAP and TAP measurements for $(^6\text{Li}, d)$ will also aid in establishing the validity of spectroscopic factors extracted for this reaction assuming a direct-alpha transfer. Discrepancies are apparent between the spectroscopic factors obtained for the various alpha-transfer reactions [Chu78].

Additional information about the ^6Li D-state can be obtained from $(^6\text{Li}, \alpha)$ reactions. These reactions might be measured simultaneously with $(^6\text{Li}, d)$ using an appropriate combination of transmission and stopping detectors. Preliminary calculations for this reaction reveal a considerable sensitivity to magnitude and sign of the D-state parameters. They also have the advantage that there are no spin-dependent optical-model potentials in the exit channel.

A recent study of detector systems designed for measurement of the reaction products from ^6Li -induced reactions has been conducted at Florida State. It appears that telescopes consisting of silicon ΔE detectors along with CsI-photodiode E detectors will provide an excellent system for measuring the deuterons of interest.

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3.3 Photon-Induced Reactions on Very Light Nuclei

3.3.1 The $^4\text{He}(\gamma, d)^2\text{H}$ Reaction at $E_\gamma = 150\text{--}250$ MeV

B. J. Rice, E. A. Wulf, G. Feldman, N. R. Kollb, R. E. Pywell, G. A. Retzlaff, D. M. Skopik, D. E. Tiller, H. R. Weller

Figure 3.3-1: Top view of experimental setup for detecting two deuterons from the photo-disintegration of ^4He . The ΔE paddles for the seven telescopes are not shown.

The four-nucleon system serves as a critical testing ground for much of the theory of few body systems. Recent advances in few-body calculation techniques, which require accurate data to test the theory, have illuminated the paucity and/or inconsistency of data in certain systems at or above pion threshold. The $^4\text{He}(\gamma, d)^2\text{H}$ reaction with $E_\gamma = 150\text{--}250$ MeV exemplifies this lack of high-quality data. In the past thirty years five separate measurements have yielded an uncertainty of a factor of 100 in the (γ, dd) cross section [Sil84, ORi95].

We have designed, constructed, and tested an experimental setup at the Saskatchewan Accelerator Laboratory (SAL) with the goal of producing a definitive measurement of this cross-section. SAL contains a six-section linear accelerator with a Pulse Stretcher Ring (PSR) capable of producing 300 MeV electrons with a tagged γ -ray production of 10^8 photons/second and more than 100 times greater untagged flux. We used a 7.5 cm diameter cylindrical liquid helium cell suspended vertically from a LHe cryostat to provide a large number of target nuclei. The detectors, pictured in figure 3.3-1, were BC-400 plastic scintillators organized into "arms" to the left and right of the incident beam direction. One arm consisted of seven plastic ΔE -E telescopes centered about the target cell. The other arm, composed of a 1.5 meter plastic bar with fourteen thin plastic paddles in front to serve as ΔE 's, was aligned to detect the recoil deuterons. This geometry provided a two-charged-particle coincidence that helped reduce the background from competing channels.

The test run was completed in July 1995. The smallness of the cross-section (less than 1 nb/sr) and the presence of many competing channels with much higher cross sections made the choice between running untagged and tagged a difficult one. As a compromise we ran in both modes, allotting the bulk of the beam time to untagged operation with its

high count rate. The tagged data, with its additional kinematics information, was taken to provide background estimates for the competing channels. Preliminary results indicate reasonably low background as well as good particle identification. Analysis of these data along with data from a production run in the near future should resolve the discrepancy in the measured value of the cross section. These data will be combined with the LEGS analyzing power data in order to extract the multipolarities of the contributing capture amplitudes (see LEGS submission).

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[Sil84] B. H. Silverman *et al.*, Phys. Rev. C, 29, 35 (1984).

3.3.2 The ${}^4\text{He}(\gamma, d){}^2\text{H}$ Reaction at $E_\gamma = 185\text{--}330$ MeV

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Studies of the four-nucleon system over the past 30 years indicate the need for continued research into photonuclear reactions involving this system with center of mass energies of several hundred MeV. One class of studies using polarized beams and the ${}^2\text{H}(d, \gamma){}^4\text{He}$ reaction with $E_d < 100$ MeV [Wel88] stresses the importance of the D-state and the tensor force in this system and merits continued investigation at higher energies. Since 1962, five distinct measurements of the cross section of ${}^4\text{He}(\gamma, d){}^2\text{H}$ (or its inverse) near $E_\gamma = 200$ MeV have resulted in a discrepancy of a factor of 100 [Sil84, ORi95]. This discrepancy coupled with the suggestion that the reaction may be dominated by E1 contributions in the energy regime near $E_\gamma = 213$ MeV [Sil84, Are76] constitute additional justification for further studies of ${}^4\text{He}$ at these energies.

With these questions in mind we have studied the angular and energy dependence of the reaction ${}^4\text{He}(\gamma, d){}^2\text{H}$ over the range of $E_\gamma = 185\text{--}330$ MeV. These data were taken at the Laser Electron Gamma Source (LEGS) at Brookhaven National Laboratory and involved

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Figure 3.3-2: Histogram of energy deposited in the NaI crystals of the "14 inch" and "Bar" detector arms. For this data the 14 inch detector was at $\theta_{\text{cm}} = 45^\circ$ and $E_\gamma = 288\text{--}318$ MeV. The plot shows a dominant pd distribution (fit with a dashed curve) with a small dd bump (fit with a solid curve).

the use of a liquid helium target developed by a group from the University of Rome. ΔE - E telescopes consisting of plastic scintillator paddles and NaI crystals and arranged into "arms" to the left and right of the incident beam direction were used to measure d-d coincidences. The cross section and vector analyzing power were measured at nine angles from $\theta_{\text{lab}} = 28$ to 130 degrees. These are the first polarized γ -ray data for this reaction or its inverse in this energy regime.

The analysis of the data is in progress. This analysis has been complicated by poor particle identification in one of the detector arms. Since we are unable to distinguish between a proton and a deuteron in this arm, the npd channel, which is nearly 100 times larger than the dd channel, provides a substantial background to the events of interest. As a result we have had to kinematically reconstruct each event. LEGS is a tagged backscattered photon facility, so we use the incident γ -ray energy and information from one reaction particle (including particle identification, kinetic energy, and reaction angle) to reconstruct events. Unfortunately, the second reaction angle is not known precisely, so pd background remains in the dd kinematic region. The final step, depicted in Figure 3.3-2, involves fitting the pd background and subtracting this from the data to obtain a good dd event count.

The extraction of cross section and vector analyzing power data as functions of energy and angle is nearing completion. Preliminary results provide an upper limit of 2 to 9 nb/sr

differential cross section, narrowing the discrepancy in cross section measurements from a factor of 100 to less than a factor of 10. We expect to be able to comment definitively on the question of E1 contributions as soon as analysis of the cross section and analyzing power data is complete. Once final results have been obtained we will perform a transmission matrix element (TME) analysis to determine the importance of the D-state in this energy regime.

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[ORi95] G. V. O'Rielly, Ph.D. thesis, SAL, 1995.

[Sil84] B. H. Silverman *et al.*, Phys. Rev. C, **29**, 35 (1984).

[Wel88] H. R. Weller and D. Lehman, Ann. Rev. Nucl. Sci., **38**, 563 (1988).

3.4 Radiative-Capture Reactions with Polarized Beams

3.4.1 Radiative Capture of Polarized Protons by Deuterium in the Energy Range $E_p(\text{lab}) = 80\text{--}0$ keV

G. J. Schmid, R. M. Chasteler, M. A. Godwin, C. M. Laymon, R. M. Prior, B. J. Rice, D. R. Tilley and H. R. Weller

The $D(\vec{p}, \gamma)^3\text{He}$ reaction has been studied in the energy range $E_p(\text{lab}) = 80\text{--}0$ keV ($E_{\text{cm}} = 53.3\text{--}0$ keV). The quantities measured were the cross-section, $\sigma(\theta, E)$, the astrophysical S-factor, $S(\theta, E)$, the vector analyzing power, $A_y(\theta, E)$, and the γ -ray polarization $P_\gamma(\theta)$. The primary goal of the present work has been to extract, with better accuracy than previous results [Gri63], the $D(p, \gamma)^3\text{He}$ electric dipole (E1) and magnetic dipole (M1) cross-section and S-factor components over the energy region $E_p(\text{lab}) = 80\text{--}0$ keV. The novel contributions of the current work include the following: the use of polarized beams for the purpose of measuring $A_y(\theta)$ (sensitive to E1/M1 mixing); and the use of a high purity germanium (HPGe) γ -ray detector. The high intrinsic resolution of the HPGe detector (4.2 keV at $E_\gamma = 5.5$ MeV) has allowed us to directly observe the energy dependence of the $D(p, \gamma)^3\text{He}$ reaction in our spectra. By measuring angular distributions with this detector, we have thus been able to obtain the $\sigma(\theta)$, $S(\theta)$, and $A_y(\theta)$ observables as a function of $E_p(\text{lab})$.

In the present $D(\vec{p}, \gamma)^3\text{He}$ experiment, the procedure followed was to stop an 80 keV proton beam in a heavy water (D_2O) ice target. This created a range of incident beam energies from $E_p(\text{lab}) = 80\text{--}0$ keV. For an HPGe lab angle of 90° , this spread in incident beam energies translated into a spread of outgoing γ -ray energies from $E_\gamma = 5.49$ to 5.54

Figure 3.4-1: $D(\vec{p}, \gamma)^3\text{He}$ full energy peak spectrum (for $\theta_{\text{lab}} = 90^\circ$) shown along with a convolution fit (solid curve).

MeV. Figure 3.4-1 shows a typical HPGe full energy peak spectrum acquired for the γ -rays in $D(\vec{p}, \gamma)^3\text{He}$. This particular spectrum was acquired at $\theta_{\text{lab}} = 90^\circ$ (other spectra were acquired at $\theta_{\text{lab}} = 0, 30, 60, 105$, and 120°). The sloping of the peak on the low energy side is due to the energy dependence of the $D(\vec{p}, \gamma)^3\text{He}$ yield. In order to extract the energy dependence of the $D(\vec{p}, \gamma)^3\text{He}$ S-factor, $S(E_{\text{cm}})$, two separate data analysis procedures were undertaken. The first involved simply binning the full energy peak into a series of energy regions based on incident beam energy. The yields acquired for each energy bin were then used (along with information about the proton stopping cross section, the HPGe detector efficiency, etc.) to calculate cross sections, S-factors and vector analyzing powers for each energy region. The second data analysis method used was a convolution fit to the raw spectrum as shown by the solid line in Figure 3.4-1. In the convolution fit procedure, the effects of the HPGe detector response function were removed from the raw spectra in order to create "deconvoluted" yield spectra. These deconvoluted yield spectra could then be used in order to fix the absolute magnitude and slope of a linear $D(\vec{p}, \gamma)^3\text{He}$ S-factor function.

Figure 3.4-2 shows by the solid data points the S-factor results of the binning analysis on the raw spectra. The solid line in Figure 3.4-2 shows the results of the deconvolution analysis. The open points in Figure 3.4-2 are the previous results of Griffiths *et al.* [Gri63]. One important thing to notice about Figure 3.4-2 is that the current results lie 41-52% lower than the previous results over the energy region studied. Although erroneous stopping cross section values in the Griffiths *et al.* analysis should lower their quoted S-factor values by 10-15% over the energy region studied, this correction will not be sufficient to resolve the

Figure 3.4-2: The current binning results (solid points) and the current deconvolution results (solid line) for $D(\vec{p}, \gamma)^3\text{He}$ are shown along with the previous experimental results (open points) and the theoretical calculations of Schiavilla *et al.* (dashed and dotted curves). Systematic error is included in the data points.

discrepancy with the current results [Sch95a]. The dotted curve in Figure 3.4-2 represents the preliminary results of a three-body calculation for the $D(\vec{p}, \gamma)^3\text{He}$ reaction [Shi95] which includes only the nucleonic degrees of freedom in the electromagnetic operator (i.e. the impulse approximation). The dashed line in Figure 3.4-2 is the same calculation whereby the non-nucleonic degrees of freedom (i.e. the meson-exchange current effects) have been added in. Disagreement between the full theoretical S-factor result and the current experiment S-factor result is clearly indicated. The concordance between theory and experiment with regards to the vector analyzing power is somewhat better, as shown in Figure 3.4-3.

By performing a transition matrix element fit to the current total S-factor and vector analyzing power data for $D(\vec{p}, \gamma)^3\text{He}$, the E1 and M1 S-factor components can be extracted. A three-body calculation for the M1 S-factor at zero energy has been done [Fri91], and can be compared with our extracted value. The three-body calculation predicts an M1 $S(0)$ of 0.108 ± 0.004 eVb. This is significantly higher than the currently extracted value of 0.079 ± 0.008 eVb (including systematic error).

The importance of the $D(p, \gamma)^3\text{He}$ reaction in protostellar evolution has been described by Stahler [Sta88]. The fact that our measured $D(\vec{p}, \gamma)^3\text{He}$ S-factor is 41-52% lower than currently believed could affect astrophysical calculations dealing with protostellar evolution.

Figure 3.4-3: The theoretical prediction of Schiavilla *et al.* for the $D(\vec{p}, \gamma)^3\text{He}$ vector analyzing power (dashed and dotted curves) shown along with the current data (solid points).

The $D(p, \gamma)^3\text{He}$ reaction rate should not be of importance in main-sequence solar fusion because of the bottleneck caused by the weak p-p fusion reaction [Rol88].

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[Gri63] G. M. Griffiths *et al.*, Can. J. Phys., 41, 724 (1963).

[Rol88] C. E. Rolfs and W. S. Rodney, *Cauldrons in the Cosmos*, University of Chicago Press, 1988.

[Sch95] G. J. Schmid, Ph.D. thesis, TUNL, 1995.

[Shi95] R. Schiavilla and M. Viviani, private communication, 1995.

[Sta88] S. W. Stahler, Astrophys. J., 322, 804 (1988).

3.4.2 T_{20} Measurements for $^1\text{H}(d, \gamma)^3\text{He}$ and the P-Wave Component of the Nucleon-Nucleon Force

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

Figure 3.4-4: The $T_{20}(\theta_{\text{lab}} = 90^\circ)$ data that we have acquired in the current $^1\text{H}(\vec{d}, \gamma)^3\text{He}$ experiment (open data points), shown along with a previously published data point at $E_d(\text{lab}) = 10$ MeV (solid data point).

Measurements of $T_{20}(\theta_{\text{lab}} = 90^\circ)$ for $^1\text{H}(\vec{d}, \gamma)^3\text{He}$, in the energy range $E_d(\text{lab}) = 12.7$ – 19.8 MeV, have been compared with the results of new exact three-body Faddeev calculations using separable versions of the Paris and Bonn-A nucleon-nucleon (NN) potentials. A strong sensitivity of the T_{20} observable to the NN P-waves is noted. In particular, we find that for T_{20} in $^1\text{H}(\vec{d}, \gamma)^3\text{He}$, the $^3\text{P}_1$ component is the dominant NN P-wave piece. This contrasts with the results of polarized n-d scattering experiments, whereby the $^3\text{P}_0$ component has been shown to be the most important NN P-wave piece [Tor91].

Figure 3.4-4 shows the current $^1\text{H}(\vec{d}, \gamma)^3\text{He}$ data from 12.7 to 19.8 MeV plotted along with a previous point at 10 MeV [Goe92]. The point at 19.8 MeV has been averaged with a previously existing point [Vet85]. The dashed curve is a three-body calculation which neglects the NN P-wave force, while the solid curve is the same calculation which includes the NN P-waves. The importance of the NN P-waves in determining this observable is clearly noted. Furthermore, Table 3.4-1 shows the results of a series of calculations done at 8 MeV which separately turn on the NN P-wave components (in the intermediate rescattering state) in order to identify the dominant NN P-wave piece (the NN P-waves in the ground state and continuum state do not play a very important role here). Turning on the $^3\text{P}_1$

Calculation	$T_{20} (\theta_{lab} = 90^\circ)$	Δ (rel. to calc. #3)
1. No NN P-waves	-.0563	—
2. NN P-waves in gnd. state only	-.0559	—
3. NN P-waves in gnd. state & continuum	-.0455	—
4. $(-)+ {}^1P_1$ in int. rescatt. state	-.0497	-.0042
5. $(-)+ {}^3P_0$ in int. rescatt. state	-.0359	.0097
6. $(-)+ {}^3P_1$ in int. rescatt. state	-.0302	.0153
7. $(-)+ {}^3P_2$ in int. rescatt. state	-.0432	.0023
8. $(-)+ {}^1P_1, {}^3P_0, {}^3P_1, {}^3P_2$ in int. rescatt. st.	-.0221	.0235

Table 3.4-1: Results of Faddeev calculations for ${}^1H(\vec{d}, \gamma){}^3He$ at $E_{d_{lab}} = 8$, done to identify the dominant NN P-wave piece.

component clearly has the largest effect on the T_{20} observable and is thus identified as the dominant NN P-wave piece.

[Goe92] F. Goeckner *et al.*, Phys. Rev. C, 45, R2536 (1992).

[Tor91] W. Tornow *et al.*, Phys. Lett., B257, 273 (1991).

[Vet85] M. C. Vetterli *et al.*, Phys. Rev. Lett., 54, 1129 (1985).

3.4.3 The ${}^1H(\vec{d}, \gamma){}^3He$ Reaction at 80-0 keV

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Over the past two years the Radiative Capture Group at TUNL has been studying the reaction ${}^2H(\vec{p}, \gamma){}^3He$ with incident beam energies of 80-0 keV, corresponding to center-of-mass energies 54-0 keV [Sch95a, Sch95b]. Recent low-energy few-body calculations [Fri91] have highlighted the role of meson-exchange currents (MEC) in this system. The goal of our research is to test the current theory and motivate the generation of improved theories.

In order to further our understanding of the 3He system at very low energies we have begun studying the reaction ${}^1H(\vec{d}, \gamma){}^3He$ using both tensor polarized and unpolarized deuterons with incident lab energies of 80-0 keV, or center of mass energies 27-0 keV. This range of energies was obtained by stopping an 80 keV deuteron beam in an H_2O ice target. The emitted gamma rays were detected using two large high-purity germanium detectors with 4 keV resolution at 5.5 MeV. We have measured angular distributions of both the cross section (from 0 to 90 degrees) and the tensor analyzing power T_{20} (from 0 to 150 degrees).

Figure 3.4-5: $T_{20}(\theta)$ data for the $^1\text{H}(\vec{d}, \gamma)^3\text{He}$ reaction at $E_d = 80-0$ keV. The curves are the results of simultaneous TME fits (using $E1$ and $M1$ terms only) to T_{20} and cross section data from this reaction and A_y and cross-section data from the $^2\text{H}(\vec{p}, \gamma)^3\text{He}$ reaction at $E_p = 40-0$ keV. The curves highlight the sensitivity of the $M1$ terms to the asymmetry in T_{20} .

We have begun a transition matrix-element (TME) analysis of these data simultaneously fitting them together with the cross-section and vector analyzing power data from the reaction $^2\text{H}(\bar{p}, \gamma)^3\text{He}$ at lab energies 40-0 keV (center-of-mass energies 27-0 keV). Preliminary results indicate that E1 transitions to the S- and D-states of ^3He as well as M1 transitions must be included in order to fit the data. We have used a recent three-body Faddeev calculation [Leh94] of the ^3He system to impose constraints upon our fitting routines. This calculation gives essentially equal amplitudes and phases for the $^2\text{P}_2$ and $^2\text{P}_4$ E1 transition amplitudes. The best fits to the data (using E1($l=1$) and M1($l=0$) terms only) under these constraints give M1 contributions to the total cross section as large as 30%.

Since we have T_{20} data that extend from 0 to 150 degrees, we have been able to determine the fore-aft asymmetry of T_{20} , which has in turn provided information on the distribution of M1 strength among the s-wave amplitudes. Fore-aft asymmetry in T_{20} must arise from interference between radiations having opposite parity (in this case E1 and M1), and between interfering terms whose s and s' triangulate to 2. Preliminary results (see figure 3.4-5) suggest that the $^4\text{S}_4$ strength accounts for one half or more of the total M1 strength. This result is especially important since this ratio is sensitive to the detailed treatment of meson-exchange currents in the calculations. We hope in the near future to compare this interesting result with ongoing theoretical calculations using a variational technique that includes both Coulomb and MEC effects [Sci95].

[Fri91] J. L. Friar *et al.*, Phys. Rev. Lett., 66, 1827 (1991).

[Leh94] D. R. Lehman, 1994, private communication.

[Sch95a] G. J. Schmid, Ph.D. thesis, TUNL, 1995.

[Sch95b] G. J. Schmid *et al.*, submitted to Phys. Rev. Lett., 1995.

[Sci95] R. Schiavilla, private communication, 1995.

3.4.4 Measurement of Vector and Tensor Analyzing Powers for $^1\text{H}(\vec{d}, \gamma)^3\text{He}$ at Very Low Energies

Lijun Ma, H. J. Karwowski, C. R. Brune and E. J. Ludwig

Measurement of the analyzing powers of the $^1\text{H}(\vec{d}, \gamma)^3\text{He}$ reaction plays an important role in understanding low-energy few-body capture reaction mechanisms, especially meson-exchange current effects and Coulomb effects. The reaction is also interesting because it serves as one of the leading reactions in proton-proton chain burning process in the standard solar model.

Figure 3.4-6: The energy dependence of A_{zz} at 90° and 0° .

We have measured full angular distributions of A_y , A_{yy} and A_{zz} for this reaction. A vapor-condensed ice target was bombarded by 330 keV deuterium ions, which were accelerated through the upgraded Low Energy Beam Facilities (LEBF). The reaction gamma rays were measured using two large volume high-purity germanium detectors which have efficiencies of 127% and 145%. We placed detectors symmetrically and used the fast spin-flip scheme to determine analyzing powers independently. The energy dependence was extracted using the MINUIT fitting routine [Ma94] at each measured lab angle i.e. 0° , 35° , 60° , 90° , 120° , 135° .

The measured energy dependence of A_{zz} at 0° and 90° is shown in Figure 3.4-6. The error bars on the data points correspond to the one-sigma confidence level. For center-of-mass energies from 35 keV to 110 keV, A_{zz} is negative at 90° , while at 0° , it is consistently positive. More data analysis and theoretical calculations based on the refined resonating group model are now in progress.

[Ma94] L. Ma *et al.*, TUNL Progress Report XXXIII, 1993-1994.

3.4.5 Low-Energy Polarized-Proton Capture on ${}^6\text{Li}$

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Previous [Cha94] and ongoing (described elsewhere in this report) studies of the ${}^7\text{Li}(\vec{p}, \gamma_0){}^8\text{Be}$ reaction at 80 keV in this laboratory reveal large analyzing powers and the presence of a considerable p-wave contribution to the reaction. As part of a systematic investigation of the low-energy radiative-capture process, we have used 80 keV protons directly from the TUNL Intense Polarized Ion Source to measure cross-section and analyzing power angular distributions for the reaction ${}^6\text{Li}(\vec{p}, \gamma){}^7\text{Be}$. Data were acquired using two large high-purity germanium detectors, one of which was kept fixed at 90° . The other detector had an active NaI shield and was used to acquire data at 5 angles from 0 to 120 degrees. A thick target of enriched ${}^6\text{Li}$ was used to stop the beam so that integrated yields were obtained. Figure 3.4-7 illustrates the results for capture to the ground state of ${}^7\text{Be}$. The angular distribution of γ -rays, illustrated in part A of the figure, is nearly isotropic and the analyzing power, displayed in part B, varies only slightly from zero. The cross-section and analyzing power angular distributions for the ${}^6\text{Li}(\vec{p}, \gamma_1){}^7\text{Be}$ reaction are similar. These results can be contrasted with ${}^7\text{Li}(\vec{p}, \gamma_0){}^8\text{Be}$ reaction studies in which 20% anisotropies and analyzing powers of about 0.4 (at 90°) are seen.

Values of $A_y(\theta = 90^\circ)$ other than zero and cross-section asymmetries between angles symmetric about $\theta = 90^\circ$ are the result of interference between amplitudes of opposite parity. No such interference is required to explain the current data. However, we have performed several transition matrix element (TME) analyses of the ${}^6\text{Li}(\vec{p}, \gamma_0){}^7\text{Be}$ reaction.

Figure 3.4-7: Angular distribution (A) and analyzing power (B) for the ${}^6\text{Li}(\vec{p}, \gamma_0){}^7\text{Be}$ reaction at $E_p = 80-0 \text{ keV}$

An analysis in which the number of contributing TME's was reduced to a single E1-s-wave and an M1-p-wave amplitude by making some reasonable assumptions results in a best fit, shown in Figure 3.4-7, that contains only a $(.1 \pm .1)\%$ M1 contribution to the cross section. If one makes a different, less reasonable, two amplitude assumption, in which the TME's are chosen to yield a large M1 contribution, the same fit results with a $(4 \pm 4)\%$ M1 contribution. In these two-amplitude analyses, there is a quadratic ambiguity between the E1 and M1 matrix elements. We have assumed that the M1 TME has the smaller amplitude.

Our results are in agreement with simple direct capture calculations that predict insignificant M1-p-wave strength. At these low energies, the p-wave contribution to the direct proton capture reaction in other p-shell systems, ${}^7\text{Li}(\vec{p}, \gamma){}^8\text{Be}$ for example, is generally predicted to be negligible. A difference between the ${}^7\text{Li}(\vec{p}, \gamma){}^8\text{Be}$ reaction in which evidence for a large p-wave contribution is seen and the present reaction which does not require any p-wave strength for its description is the relative widths and positions of p-wave resonances in the product nuclei. We are currently performing calculations to compare the effects of resonant tails in these two reactions.

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

3.4.6 The ${}^7\text{Li}(\vec{p}, \gamma){}^8\text{Be}$ Radiative Capture Reaction at 80 keV

M. A. Godwin, R. M. Chasteler, C. M. Laymon, R. P. Prior, G. J. Schmid, D. R. Tilley, H. R. Weller

Over the last year we have been studying the ${}^7\text{Li}(\vec{p}, \gamma){}^8\text{Be}$ reaction at energies $E_p = 80\text{--}0$ keV. We have been most interested in examining proton capture to the isospin-mixed 2^+ states (16.62 and 16.92 MeV) in ${}^8\text{Be}$ in order to examine the p-wave contributions in this reaction. This reaction is closely related to the ${}^7\text{Be}(p, \gamma){}^8\text{B}$ reaction since the 2^+ , $T = 1$ ground state of ${}^8\text{B}$ is the isospin analog of the $T = 1$ part of the 2^+ states in ${}^8\text{Be}$. Of these two excited states, the 16.62 MeV state is expected to be much more dominant than the 16.92 MeV state [Man81] in our reaction. We have studied the radiative capture to the 16.62 MeV state of ${}^8\text{Be}$ by stopping an 80 keV proton beam in our ${}^7\text{Li}$ target. The spectrum of gamma rays produced (which will be spread out due to the stopping of the beam) is dominated by the 108 keV width of the final state. This excited state of ${}^8\text{Be}$ subsequently decays to two alpha particles virtually 100% of the time.

The spectrum shown in Figure 3.4-8a depicts γ -ray events detected by the large (128%) high purity germanium (HPGe) detector when run in singles mode for approximately 100 hours with 25 μA of polarized proton beam on a thick ${}^7\text{Li}$ target. Note that no evidence for the third excited state ($E_\gamma = 698$ keV, $\Gamma \approx 110$ keV) is seen. In order to separate the associated γ -ray from background we are performing a coincidence experiment, detecting the 698 keV γ -ray and one alpha particle simultaneously. When this coincidence with the alpha-scintillator is required the result is Figure 3.4-8b. This requirement substantially reduces the background, and we are left with a peak depicting the third excited state. The data have been fit using a least-squares procedure based on Minuit, by applying a quadratic exponential background and a Breit-Wigner shaped resonance to the spectra. Thus, yields may be extracted for the various angles where the experiment has been performed. Shown in Figure 3.4-9a is the relative cross section for capture to the third excited state, normalized to yields going to the ground state, while Figure 3.4-9b shows the analyzing power data extracted from these yields. A transition matrix element (TME) analysis of the data has been performed, including one s-wave, E1 and one p-wave, M1 partial wave. The results are shown as a dashed curve in Figure 3.4-9. Because of the quadratic nature of the equations involved, two solutions are found, both of which are mathematically valid. One consists of 0.1% M1 admixture, the other 0.1% E1.

In order to distinguish between these we wish to measure the polarization of this 698 keV γ -ray. When a photon of this energy enters the germanium detector, it will sometimes lose a portion of its energy due to Compton scattering. The plan is to detect the scattered gamma ray in the NaI annulus and detect the residual energy in the HPGe detector. With

Figure 3.4-8: a) γ -ray spectrum obtained in detector system. b) Same spectrum as part a) but in coincidence with an alpha event in the scintillator.

Figure 3.4-9: Data gathered for a) the relative cross section and b) the analyzing power for the ${}^7\text{Li}(\bar{p}, \gamma_3){}^8\text{Be}$ reaction at $E_p(\text{lab}) = 80-0$ keV. The dashed curves represent a TME fit to the data.

this we may measure an up-down, left-right asymmetry, and thus deduce the polarization of the incident radiation. This project is currently underway.

To conclude, we have begun a detailed study of proton capture to the 2^+ , $T = 0 + 1$ states of ^8Be . The reaction is related to the $^7\text{Be}(p, \gamma)^8\text{B}$ reaction since the 2^+ , $T = 1$ ground state of ^8B is the isospin analog of the $T = 1$ part of the 2^+ states in ^8Be and must therefore possess the same space-spin wavefunction. Unfortunately, the $^7\text{Be}(p, \gamma)^8\text{B}$ reaction is very difficult to measure and no experiments have been performed involving the direct detection of γ -rays. By detecting alpha particles from ^8B , cross-section measurements exist as low as $E_p = 134$ keV [Fil83]. Our experiment allows us to study a closely related reaction at much lower energies. In addition, we use a polarized beam, measure γ -rays directly, and can even measure the polarization of these γ -rays. A detailed study of our reaction should lead to a deeper understanding of the $^7\text{Be}(p, \gamma)^8\text{B}$ reaction, and thus a more reliable extrapolation of low-energy cross sections and the astrophysical S-factor.

[Fil83] B. W. Fillippone *et al*, Phys. Rev. C, 28, 2222 (1983).

[Man81] S. Manglos *et al*, Phys. Rev. C, 24, 2378 (1981).

3.4.7 The $^7\text{Li}(\bar{p}, \gamma)^8\text{Be}$ Radiative Capture Reaction to the Ground and First Excited States

M. A. Godwin, R. M. Chasteler, C. M. Laymon, R. P. Prior, G. J. Schmid, D. R. Tilley, H. R. Weller

In addition to data for the third excited state, we have also obtained new data using our 128% HPGe detector for capture to the ground and first excited states of ^8Be . Shown in Figure 3.4-10a and Figure 3.4-10b are the relative cross-section and analyzing power data vs. lab angle for the γ_0 transition. The circles represent the previously published NaI data of Chasteler *et al*. [Cha94]. At energies of 100 keV or less, it has been assumed in previous work [Cec92] that s-wave capture (E1) would dominate the reaction. It is clear from the anisotropic behavior of the cross section and the non-zero analyzing powers that multipole radiation other than E1 is involved. In fact, analysis of the data shows the presence of significant p-wave strength, which could reduce the astrophysical S factor by 7%-38%. Our preliminary new measurements reproduce these analyzing power data, with significant statistical improvement. Figure 3.4-10c and Figure 3.4-10d show the same observables for capture to the first excited state. The previously unpublished data of Chasteler *et al*. [Cha94] are again shown as circles. Here the data indicate no unusual behavior; the cross section is uniform and the analyzing power is zero. Our preliminary new data show the same effects.

Figure 3.4-10: Shown here are the cross-section and analyzing power data for capture to the ground state and first excited state of ${}^8\text{Be}$. In all four pictures the NaI data of Chasteler *et al.* are shown as circles and the preliminary HPGe data are shown as squares. The curves represent the TME fit of Chasteler.

Since the proton beam stops in the target, this data represents an integrated yield from 80-0 keV. Proton energies of 20 keV or less are significant for astrophysics (in fact the astrophysical S factor is a representation of the zero-energy cross section), and thus it would be quite interesting to examine these observables at lower energies. The measured width of the ground state is quite small ($\Gamma_{c.m.} = 6.8$ keV), and is clearly separated from natural background ($E_\gamma \approx 17.3$ MeV). Because of these properties and because of the excellent energy resolution of the large HPGe detector that we are using, we plan to deconvolute (or at least bin) the γ_0 data and obtain analyzing power and cross-section data as a function of energy as well as angle. A similar procedure has been successfully employed by Schmid [Sch95] for the ${}^2\text{H}(p, \gamma)$ reaction and is soon to be published.

[Cec92] F. E. Cecil *et al.*, Nucl. Phys., A59, 75 (1992).

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

[Sch95] G. J. Schmid, private communication, 1995.

3.4.8 Comment on the ${}^7\text{Li}(p, \gamma){}^8\text{Be}$ Reaction at Energies of Astrophysical Interest

H. R. Weller and R. M. Chasteler

The results of two recent publications [Rol94, Zah95] are reconsidered. These papers argue that the p-wave effects seen in the ${}^7\text{Li}(p, \gamma){}^8\text{Be}$ reaction below $E_p = 80$ keV, reported in [Cha94], can be accounted for by considering the low-energy tail of the p-wave resonance at $E_p = 441$ keV. It is shown that the cross section and analyzing power data require an order-of-magnitude more p-wave strength when considered together.

Recently reported polarized proton capture data on ${}^7\text{Li}$ indicated a substantial p-wave contribution to this reaction at energies below $E_p = 80$ keV [Cha94]. These results are important in that they could impact the manner in which cross sections are extrapolated below $E_p = 100$ keV in order to obtain astrophysical S-factors.

There have been two recent papers which have addressed this result [Rol94, Zah95]. These papers argue that the results of [Cha94] can be accounted for by considering the p-wave contribution near 80 keV due to the tail of the 1^+ resonance at $E_p = 441.4$ MeV. It is argued in [Rol94], for example, that the interference of this resonance-tail p-wave strength with the s-wave direct-capture strength (E1) can account for the results of [Cha94]. This paper was written to point out that this is not the case. It is also pointed out in this paper that there was an error in [Rol94] in their equation for a_1 . In the work of [Zah95] only the angular distribution of the cross section was considered and when the analyzing power, A_y , is considered simultaneously their results are not sufficient.

In summary, this note has shown that the data of [Cha94] cannot be accounted for by the tail of the 1^+ p-wave resonance at $E_p = 441$ keV in the ${}^7\text{Li}(p, \gamma){}^8\text{Be}$ reaction. The fore-aft asymmetry in the cross section along with the measured analyzing power at 90° require at least an order-of-magnitude more p-wave strength than that expected from the tail of this resonance. The physical origin of this anomalous p-wave strength remains unaccounted for.

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

[Rol94] C. Rolfs and R. W. Kavanagh, Z. Phys. A, **350**, 93 (1994).

[Zah95] D. Zahnow *et al.*, submitted for publication, 1995.

3.4.9 Low-Energy Proton Capture on ${}^9\text{Be}$

R. M. Prior, C. M. Laymon, E. A. Wulf, M. A. Godwin, D. R. Tilley, H. R. Weller

Continuing our investigation of low-energy radiative capture on light elements, we are beginning a study of ${}^9\text{Be}(p, \gamma){}^{10}\text{B}$. Because of nearby levels of ${}^{10}\text{B}$ it is expected that there may be effects on the analyzing power of ${}^9\text{Be}(p, \gamma){}^{10}\text{B}$. Data will be acquired for the excitation of several excited states of ${}^{10}\text{B}$.

The first data will be taken in the summer of 1995. Polarized protons from the intense polarized ion source will be accelerated to 80 keV by the source high voltage. The beam energy at the target will be increased to 100 keV by biasing the target to -20 kV. This is necessary because the cross section for ${}^9\text{Be}(p, \gamma){}^{10}\text{B}$ is over an order of magnitude less than the previously studied reactions with Li targets. Increasing the beam energy from 80 keV to 100 keV increases the reaction yield by a factor of 5. Data will be taken with 2 high-efficiency, high-purity germanium detectors. Beam intensity and the target condition will be monitored by detecting with solid state detectors the alpha particles and deuterons from the ${}^9\text{Be}(p, \alpha){}^6\text{Li}$ and the ${}^9\text{Be}(p, d){}^8\text{Be}$ reactions.

3.4.10 Fluctuation Effects in Radiative Capture to Unstable Final States: A Test via the ${}^{89}\text{Y}(\bar{p}, \gamma){}^{90}\text{Zr}$ Reaction at $E_p = 19.6$ MeV

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The work on this experiment has been completed and has been published in the July 1995 issue of Physical Review C. The abstract is listed below. In short, the γ -ray spectra from proton capture on ^{90}Zr has been extensively studied, utilizing a 19.6 MeV polarized beam from the TUNL tandem accelerator. The purpose of this experiment was to examine radiative capture reactions leading to bound and continuum final states which have excitation energies above those for which direct-semidirect (DSD) processes dominate, but below the statistical region. Non-zero values of the analyzing power and fore-aft asymmetry above a γ -ray energy of 15 MeV suggest the presence of direct reactions. An extended DSD theory has been developed, central to this is the inclusion of fluctuation effects. This corresponds to compound nuclear damping of single-particle states formed during radiative capture. The results for capturing to final states at higher excitation energies may be explained by including both direct-semidirect and Hauser-Feshbach mechanisms. No large contributions from multistep processes are observed in this work, although the effects of these mechanisms are not fully explained.

We have developed an extended direct-semidirect (DSD) model for fast nucleon capture to virtual single-particle configurations that subsequently damp into the compound nucleus or (at sufficiently high excitation energies) escape into the continuum. The inclusion of final-state fluctuation effects is an important feature in this model. To test the model we have measured the spectra of gamma rays from approximately 10 MeV to the endpoint in the $^{89}\text{Y}(\bar{p}, \gamma)^{90}\text{Zr}$ 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 anti-coincidence shielded NaI detectors at angles of 30°, 55°, 90°, 125° and 150° with respect to the incident beam. The spectra show significant analyzing powers and forward peaking of the angular distributions. These features allow for discriminations between compound processes and direct processes. Analyzing powers and fore-aft asymmetries were observed for gamma energies below those associated with direct-semidirect transitions to known bound final states. We have also performed Hauser-Feshbach calculations of the statistical component of the gamma emission, which dominates below approximately 15-16 MeV. The extended DSD model reproduces the spectral shapes and analyzing powers above this energy quite well. There is no evidence in the present reaction that additional mechanisms, such as multistep compound or multistep direct emission, are required.

4 The Many-Nucleon Problem

4.1 Nuclear Astrophysics

4.1.1 Measurement of the $^{17}\text{O}(\text{p}, \alpha)^{14}\text{N}$ Reaction at Stellar Energies

J.C. Blackmon, A.E. Champagne, M.A. Hofstee, M.S. Smith,¹ R.G. Downing² and G.P. Lamaze²

When a star evolves from the main sequence and enters the giant branch, its atmosphere rapidly expands and becomes convective. This convective envelope dredges up material processed by nuclear burning in the interior and changes the relative abundances of elements in the star's atmosphere [Ibe91]. The oxygen-isotopic abundance ratios have been shown to be a sensitive tracer of the dredge-up process and could provide important constraints on mixing theory. However, such a comparison suffers from a large uncertainty in the $^{17}\text{O}(\text{p}, \alpha)^{14}\text{N}$ reaction rate (see e.g. [ElE94a]).

At stellar energies, the $^{17}\text{O}(\text{p}, \alpha)^{14}\text{N}$ rate is believed to be dominated by a resonance at $E_p = 70$ keV, corresponding to $E_x = 5.673$ MeV in ^{18}F . [AS87]. At such low energies, the resonance strength is directly proportional to the proton width. However a direct measurement of this strength has proven to be very difficult because of Coulomb-barrier considerations and because of the low energy of the emitted alpha particle. The stripping reaction $^{17}\text{O}(^3\text{He}, \text{d})^{18}\text{F}$ was studied by Landre *et al.* [Lan89], and a proton width of $\Gamma_p = 70_{-57}^{+40}$ neV was deduced from a DWBA analysis of their angular-distribution data. However, this width is in disagreement with an upper limit of $\Gamma_p \leq 3$ neV obtained from a direct $^{17}\text{O}(\text{p}, \alpha)^{14}\text{N}$ measurement in which the resonance was not observed [Ber92].

We have completed our measurements of the $^{17}\text{O}(\text{p}, \alpha)^{14}\text{N}$ cross section at energies of $E_p = 75$ keV, "on resonance," and $E_p = 65$ keV, "off resonance." A description of the experimental apparatus may be found in previous progress reports. Briefly, thick Ta_2O_5 targets were bombarded using an unpolarized beam from the TUNL atomic-beam polarized ion source. Beam currents on target of 400–450 μA were sustained throughout the experiment. Outgoing alpha particles were detected using six implanted silicon detectors mounted in close geometry, with active areas of 3.1 cm^2 , and with no metal electrical contacts on their front faces. In order to shield the detectors from the intense flux of elastically scattered protons, high-quality nickel foils of 0.64 μm thickness were mounted in front of each detector.

Approximately 130 C of charge were collected at $E_p = 75$ keV on targets of enriched

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^{17}O . After gain-matching, the spectra from each detector were summed. The total data are shown in Figure 4.1-1. Because of a damaged Ni foil, only 5 detectors were operational for much of the data collection. Adding the integrated beam on target for each detector yields an equivalent single-detector total of 624^{+19}_{-42} C.

The background in this spectrum arises from several sources: cosmic rays, natural radioactivity, elastic protons, and the reactions $^{10}\text{B}(p, \alpha)^7\text{Be}$, $^7\text{Li}(p, \alpha)^4\text{He}$ and $^6\text{Li}(p, \alpha)^3\text{He}$. After background subtraction, the spectrum was fit using an $^{17}\text{O}(p, \alpha)$ template where the only variable quantity was the number of counts. A peak at the appropriate energy is clearly discernible (Figure 4.1-2).

We also performed a fit in which the location and area of the peak structure was allowed to vary simultaneously with the background. The number of counts in the peak as determined by this fit is $860 \pm 130_{\text{stat}}$. Its location is coincident with the expected location of the $^{17}\text{O}(p, \alpha)$ peak.

In order to ensure that this structure was in fact alphas from the $^{17}\text{O}(p, \alpha)$ reaction, we made another group of targets with natural oxygen isotopic composition. We then alternated the enriched ^{17}O targets with the natural oxygen targets after approximately every 5 C of integrated beam. The total data taken on each type of target was fit as before. The background-subtracted spectra are shown in Figure 4.1-3 along with the best fit $^{17}\text{O}(p, \alpha)$ peak. The total number of counts in the data taken with the ^{17}O target were 465 ± 65 , whereas the number of counts in the natural-oxygen spectrum were 9 ± 54 . We repeated this measurement at a beam energy of $E_p = 65$ keV, i.e. below the resonance energy. The data were analyzed as described above and are shown in Figure 4.1-3. The number of counts at the location of the $^{17}\text{O}(p, \alpha)$ peak was found to be 44 ± 55 . Because this is a resonant structure observed only with the enriched ^{17}O target, and because it is located at the appropriate energy, we identify it as alphas from the 70 keV resonance in $^{17}\text{O}(p, \alpha)^{14}\text{N}$.

The measured thick-target yield implies a most-probable value for the proton width of $\Gamma_p = 22 \pm 3_{\text{stat}} \pm 2_{\text{target}}^{+2}_{-1} \text{beam}$ neV. Since the latter two uncertainties are systematic, we do not combine them. To our knowledge this is the smallest proton-capture width to be measured, but it results in a reaction rate for $^{17}\text{O}(p, \alpha)^{14}\text{N}$ which is as much as a factor of 10 larger than the rate customarily used in model calculations. The error in our measurement of the proton width is small enough to now allow a quantitative comparison between observations of the $^{16}\text{O}/^{17}\text{O}$ ratio in the atmospheres of red giants and stellar-model calculations [ELE94b]. With the new observations that are planned, it will be possible to place significant constraints on convection theory. An article describing this work has recently been published [Bla95].

[AS87] F. Ajzenberg-Selove, Nucl. Phys., A475, 1 (1987).

[Ber92] M. Berheide *et al.*, Z. Phys., A343, 483 (1992).

Figure 4.1-1: Total of all data taken at $E_p = 75$ keV with enriched ^{17}O targets. The smooth curve is the best fit to the background. The region where the resonance in $^{17}\text{O}(p, \alpha)^{14}\text{N}$ is expected is indicated.

Figure 4.1-2: Difference between the raw data and background fit shown in Figure 4.1-1. Also shown is a fit assuming an $^{17}\text{O}(p, \alpha)^{14}\text{N}$ peak.

Figure 4.1-3: Differences between collected data and best-fit backgrounds for enriched targets (on and off-resonance) and targets of natural composition (on-resonance). Also shown are the $^{17}\text{O}(p, \alpha)^{14}\text{N}$ peaks fit to the background-subtracted data.

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[ElE94a] M. F. ElEid, Astron. Astrophys., **285**, 915 (1994).

[ElE94b] M. F. ElEid, 1994, private communication.

[Ibe91] I. Iben, Jr., Astrophys. J. Supp. Ser., **76**, 55 (1991).

[Lan89] V. Landre *et al.*, Phys. Rev. C, **40**, 1972 (1989).

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

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The Be abundance in low-metallicity stars is an important probe of cosmic-ray and Big-Bang nucleosynthesis, as well as stellar evolution models [Boe93]. In particular, significant Be depletion is observed in some stars. This depletion presumably results from the mixing of material from the stellar surface with material from the interior where the temperature is sufficient for the ${}^9\text{Be}(p, d)$ and ${}^9\text{Be}(p, \alpha)$ reactions to be effective. A previous measurement [Sie73] found the low-energy cross section in both reaction channels to be dominated by a broad ($\Gamma_{\text{tot}} \approx 120$ keV) s-wave 1^- resonance at $E_p = 330$ keV. At lower energies a significant but very uncertain contribution was attributed to an opposite-parity subthreshold state. This uncertainty is reflected in the estimated $S(0)$ value (summed over both reaction channels) of 35^{+45}_{-15} MeV-b. The $S(0)$ value essentially determines the reaction rate, as the effective energy for this reaction at stellar temperatures is ~ 7 keV. The existence of a state at 6.57 MeV excitation in ${}^{10}\text{B}$ (20 keV below the ${}^9\text{Be} + p$ threshold) has been established by many experiments, but spin and parity assignments are not definitive. For example, an analysis of ${}^9\text{Be}({}^3\text{He}, d)$ angular distributions [Bla80] favors negative parity for this state.

We have measured $A_y(\theta)$ and $\sigma(\theta)$ for both channels at seven energies in the range $80 \leq E_p \leq 330$ keV, using the LEBF facility. The proton beam was incident on targets consisting of $\approx 10 \mu\text{g}/\text{cm}^2$ ${}^9\text{Be}$ evaporated onto thin carbon foils. The reaction products were detected using Si detectors covered with Ni foils which stop elastically scattered protons with energies below ≈ 200 keV.

The analyzing power data are sensitive to the interference between states of opposite parity, and will help determine the role of the subthreshold state. As a first step in the analysis, we plan to compare our results to predictions calculated from previously reported R -matrix parameters [Sie73]. The analyzing power data measured at a mean proton energy of 321 keV are shown in Figure 4.1-4. We find the largest analyzing power in the (p, d) channel to be at this energy, near the peak of the s-wave resonance.

[Bla80] L. Bland and H. T. Fortune, Phys. Rev. C, **21**, 11 (1980).

Figure 4.1-4: Analyzing power data measured at a mean proton energy of 321 keV, near the peak of the s-wave resonance.

[Boe93] A. M. Boesgaard and J. R. King, *Astron. J.*, **106**, 2309 (1993).

[Sie73] A. J. Sierk and T. A. Tombrello, *Nucl. Phys.*, **A210**, 341 (1973).

4.1.3 Measurement of the ${}^7\text{Li}(n, \gamma){}^8\text{Li}$ Cross Section at $E_n = 1\text{--}1000$ eV

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D. C. Ralston, S. Raman¹ and M. S. Smith¹*

The flux of high-energy solar neutrinos is directly proportional to the rate of the ${}^7\text{Be}(p, \gamma){}^8\text{B}$ reaction which is the most uncertain rate in the proton-proton chain. It is determined from an extrapolation of existing ${}^7\text{Be}(p, \gamma){}^8\text{B}$ cross section data ($E_p > 100$ keV) to solar energies. This procedure is complicated by the relatively poor agreement amongst the different data sets. However, this uncertainty is not the source of the solar neutrino problem. Although more accurate measurements will not resolve the solar neutrino problem, they will play an important role in its interpretation.

A recent measurement of a substantial p-wave analyzing power in the ${}^7\text{Li}(p, \gamma){}^8\text{Be}$ reaction may have implications for this extrapolation procedure [Cha94]. A similar p-wave contribution to the ${}^7\text{Be}(p, \gamma){}^8\text{B}$ cross section would imply a substantial reduction in the predicted flux of ${}^8\text{B}$ neutrinos. However, the source of this effect has not been identified conclusively. Unfortunately, a similar analyzing-power measurement using a ${}^7\text{Be}$ target is not feasible owing to the high flux of gamma radiation produced in the decay of ${}^7\text{Be}$. Nonetheless, it is possible to measure the analog reaction, ${}^7\text{Li}(n, \gamma){}^8\text{Li}$. In this case, p-wave capture would manifest itself as a deviation from the expected $1/v$ behavior of the cross section at low energies. Because incident protons and neutrons sample different parts of the nuclear interior, observation of p-wave strength in ${}^8\text{Li}$ does not necessarily have implications for ${}^8\text{B}$. On the other hand, pure s-wave capture in ${}^8\text{Li}$ would imply s-wave capture in ${}^8\text{B}$ (neglecting the small d-wave component at low energies). In addition, the ${}^7\text{Li}(n, \gamma){}^8\text{Li}$ reaction involves the same target as was used above and this may help to untangle the source of the p-wave strength in ${}^8\text{Be}$.

We have begun measurements of the excitation function for the ground-state transition in ${}^7\text{Li}(n, \gamma){}^8\text{Li}$ over the energy range $E_n = 1\text{--}1000$ eV. These experiments have been carried out at the Oak Ridge Electron Linear Accelerator (ORELA). Gamma rays were detected using a heavily-shielded Ge detector placed approximately 26.5 cm from a target containing 25 g of ${}^7\text{Li}$ and 0.39 g of ${}^{10}\text{B}$. Containers of ${}^6\text{LiH}$ were placed between the target and the Ge detector in order to attenuate the flux of scattered neutrons at the detector. The 0.478 MeV gamma ray arising from the ${}^{10}\text{B}(n, \alpha\gamma){}^7\text{Li}$ reaction was used to measure the neutron flux. Because the region of interest ($E_\gamma = 2.03$ MeV) is near a gamma ray produced by neutron capture in Ge, spectra were also taken using a Be scatterer in order to measure

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Figure 4.1-5: Gamma-ray spectrum for neutron energies from 28.74 eV to 115 eV

the background from neutron capture in the detector. A sample spectrum is shown in Figure 4.1-5. We are determining the ${}^7\text{Li}(n, \gamma){}^8\text{Li}$ cross section relative to that for the comparably well-known ${}^{10}\text{B}(n, \gamma){}^{11}\text{B}$ cross section. Analysis of the data is currently in progress.

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

4.1.4 Sodium and Aluminum in Globular Clusters

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Because the stars in the globular clusters are old and coeval, their evolutionary paths have been used to infer the age of the galaxy. Overall, clusters are chemically homogeneous groups, but within a given cluster there can be a wide range in the abundances of particular

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elements. Some of these abundance variations may be interpreted in terms of stellar burning and evolution. For example, trends in C vs. N could simply indicate operation of the CN cycle during the main sequence. In addition, clusters of roughly the same age can exhibit marked chemical differences, particularly in the strength of CN. Some clusters as a whole can be characterized as "CN strong" while other clusters, which appear to be in the same evolutionary state, are "CN weak" [Nor88]. Although there is no evidence to suggest that these effects have any bearing on galactic age estimates, they do indicate that cluster chemistry is more complicated than what is assumed in deriving an age.

More recent observations show that within a cluster, the abundances of Na and Al are correlated with CN and anti-correlated with O. The interpretation of these observations has been controversial: On one hand, it can be argued that since these stars are not massive enough to produce or destroy Na and Al, these abundances and the overall CN signature reflect variations in the primordial gas from which the cluster formed [Sne92]. The fact that abundance variations exist within a given cluster may imply that the cluster developed rapidly, before homogenization could occur. However, the fact that cluster main sequences are rather narrow implies that the primordial gas was quite homogeneous in composition. In other words, this scenario requires significant fine-tuning of the initial conditions. On the other hand, it has been suggested [Lan93] that all of these observations can be accounted for if the envelopes of these stars are deeply mixed with the interior.

The mixing scenario produces Na and Al within the NeNa and MgAl cycles at low temperature. Our work on the reactions in the MgAl cycle indicates that mixing will not go deep enough to produce the Al signature. The situation regarding Na is not as clear because of large uncertainties (of up to factors of 10^4) in the rates of several key reactions: $^{22}\text{Ne}(p, \gamma)^{23}\text{Na}$, $^{23}\text{Na}(p, \gamma)^{24}\text{Mg}$, and $^{23}\text{Na}(p, \alpha)^{20}\text{Ne}$. At the energies of interest, the cross sections for these reactions are too small to permit direct resonance measurements and therefore we have begun to study them via (^3He , d) spectroscopy.

Implanted ^{22}Ne and evaporated $^{23}\text{NaBr}$ targets were bombarded at $E(^3\text{He}) = 20$ MeV. Outgoing deuterons were detected using 18 cm-long position-sensitive Si telescopes in the focal plane of the TUNL split-pole spectrometer. Unfortunately, noise in the clean-power system limited the resolution obtained to about 50 keV which was not adequate to cleanly identify the states of interest. However, we have partially analyzed the data obtained with the ^{22}Ne target. A spectrum obtained at $\theta_{\text{lab}} = 10^\circ$ (Figure 4.1-6) shows a number of known states in ^{23}Na . The uncertainty in the rate of the $^{22}\text{Ne}(p, \gamma)^{23}\text{Na}$ reaction arises from possible states at $E_x = 8.862$ and 8.894 MeV which would correspond to resonances at $E_{\text{cm}} = 68$ and 100 keV, respectively. The region near the former state is obscured by the first-excited state of ^{17}F . However, our preliminary results indicate that the latter state, if it exists, is quite weak.

We are currently addressing the noise problem in the Si detectors and further measurements are planned.

Figure 4.1-6: Deuteron spectrum from the $^{22}\text{Ne}(^3\text{He}, d)^{23}\text{Na}$ reaction at $\theta_{\text{lab}} = 10^\circ$. The locations of possible $^{22}\text{Ne} + p$ resonances are denoted by arrows.

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4.1.5 Nuclear Astrophysics with Radioactive Beams

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During astrophysical explosions, temperatures and densities reach extreme values. Under these conditions, nuclear reactions will proceed on time scales of fractions of a second

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to minutes. Thus any nuclei produced with comparable or longer half lives will become targets for subsequent nuclear reactions. Some of these reactions are thought to be crucial to our understanding of the explosive event itself, but direct measurements require the use of radioactive beams. The HRIBF facility at Oak Ridge is designed to provide beams of proton-rich radioactive nuclei for both nuclear-structure and nuclear-astronomy studies. First beams are scheduled for late 1995 to early 1996.

Since our measurements involve extreme inverse kinematics, we can take advantage of kinematic focusing to detect recoils with high efficiency. However, because typical beams and recoils have nearly identical momenta, clean separation of the recoils requires selection on the basis of velocity. The experimental nuclear-astronomy effort at the HRIBF is centered around the Daresbury Recoil Separator (DRS) which was transferred to ORNL in 1994. The DRS separates reaction products from the incident beam in two long (1.2 m) crossed-field velocity filters. In addition to the velocity filters, there are also 3 sets of quadrupole triplets for focusing, 2 sextupole magnets to correct for 2nd order aberrations, and a dipole magnet which provides a q/m focus. The total device weighs 90 tons and is 13 meters in length.

The DRS was shipped from Daresbury to Oak Ridge in the fall of 1994, and installation of the spectrometer began in early 1995. All of the elements arrived from Daresbury in excellent condition. Presently, all of the magnets have been mounted on their stands and aligned, and installation of the electrostatic components of the velocity filters is underway. All of the power supplies have been switched to US power requirements and tested. The physical layout of the DRS is nearly unchanged from its original configuration, however we plan to run different optics in order to improve beam rejection. The chief change is the addition of a new velocity focus between the two filters. The instrumentation at this location will be built at TUNL as will two target chambers. One chamber is designed to be used with arrays of BaF₂ detectors while the second will accommodate large Si detectors. Another addition to the DRS is a new time-of-flight leg at the exit to the device. This is under construction at Yale. Tests of the original focal-plane detector at Yale have indicated that it will perform to our requirements.

Our initial measurements of the $^1\text{H}(^{17}\text{F}, ^{18}\text{Ne})\gamma$ and $^1\text{H}(^{17}\text{F}, ^{14}\text{O})^4\text{He}$ reactions will examine the transition from the Hot CNO cycle to heavier nuclei. We have also continued to access the feasibility of a $^1\text{H}(^7\text{Be}, ^8\text{B})\gamma$ measurement. The chief problem here appears to be the risk of activation in the tandem and beam transport owing to the long (53 day) half life of the beam. However, initial calculations suggest that radiation levels will be tolerable.

4.2 High-Spin Spectroscopy and Superdeformation

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 gaps in the single-particle energy levels, leading to strong variations in nuclear shape. Our research program focuses on two major areas: (I) Studies of nuclear properties associated with very elongated nuclear shapes (superdeformed shapes), and (II) Investigations of the evolution of nuclear collectivity as a function of particle number and also as a function of angular momentum and excitation energy. Among the collective modes investigated are the rotational excitations of prolate and oblate deformed nuclei, and octupole vibrational states in spherical nuclei. We have recently published the results of a study of dipole bands in the weakly deformed oblate nucleus ^{196}Pb [Moo95].

With the construction and near completion of the GAMMASPHERE detection system at Lawrence Berkeley Laboratory, the experimental sensitivity for the study of nuclear collectivity has increased by orders of magnitude. We have now performed several experiments at this facility and a paper describing our investigation of superdeformation in ^{191}Hg has recently been published [Car95].

4.2.1 Search for the Two-Phonon Octupole Vibrational State in ^{208}Pb

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The first excited state of the doubly magic nucleus ^{208}Pb has $J^\pi = 3^-$ and is interpreted as a one-phonon vibration of octupole character. The collectivity of this level is inferred from the observed $B(E3)$ value of 34 Weisskopf units. The vibrational nature of this state leads to the expectation of a multiplet of 2-phonon octupole states with $J^\pi = 0^+, 2^+, 4^+$, and 6^+ at roughly twice the energy of the 3^- state (i.e., around 5.2 MeV). While examples of multi-phonon quadrupole vibrational states are well known (see, for example, Reference [Apr87]), the expected 2-phonon octupole multiplet in magic nuclei has yet to be unambiguously identified.

An experiment to search for members of the 2-phonon octupole multiplet in ^{208}Pb was recently performed at GSI by bombarding a thin ^{208}Pb target with ^{208}Pb beams at an energy of about 10% above the Coulomb barrier. A 2485 keV γ -ray was observed to be in coincidence with the $5^- \rightarrow 3^-$ and $3^- \rightarrow 0^+$ transitions in ^{208}Pb and was attributed to the depopulation of one of the members of the 2-phonon multiplet [Wol92]. In a subsequent experiment performed at HMI, targets of ^{208}Pb were bombarded with ^{64}Ni and ^{82}Se beams.

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A 2485-keV γ -ray was also observed in these measurements. However, the 2485-keV line was assigned to ^{207}Pb [Sch92, Sch93], attributed to the decay of states populated in single-neutron transfer reactions on the basis of coincidence relationships with transitions in ^{65}Ni and ^{83}Se .

In order to confirm the placement of the 2485 keV γ -ray and to search for other members of the 2-phonon multiplet, we have performed a series of experiments using the recently upgraded ATLAS facility to provide 1305 MeV beams of ^{208}Pb to bombard thick (~ 50 mg/cm²) targets of ^{208}Pb and ^{209}Bi . Gamma rays were measured using the Argonne-Notre Dame BGO Gamma Ray facility, consisting of 12 Compton suppressed Ge detectors surrounding an array of 50 BGO scintillators. A total of approximately 2.2×10^6 $\gamma - \gamma$ coincidence events were recorded for each of the targets. Gamma-ray energies and intensities in ^{208}Pb and other Pb isotopes were extracted from both the Pb and Bi target data sets. The spectra presented in Figure 4.2-1. were produced from Pb and Bi target $\gamma - \gamma$ coincidence matrices by placing gates on the $3^- \rightarrow 0^+$ (2614 keV) transition in ^{208}Pb . The identification of known coincident γ -rays is labeled. It is important to note that the 2485 keV line is observed to be only very weakly in coincidence with the gating transition in the Pb target data and not at all in the Bi data set. Furthermore, there are very few unidentified γ -rays seen in coincidence with these gates. A comparison of the spectra obtained from the two targets clearly shows that there is a substantial probability for the simultaneous excitation of both the target and projectile on the ^{208}Pb target.

From the coincidence spectra, we have determined the relative intensities of γ -rays in ^{208}Pb . The partial decay scheme of ^{208}Pb relevant to our measurement is presented in Figure 4.2-2. The widths of the arrows are proportional to the measured intensities of the transitions. The intensities have been corrected for detector efficiency and internal conversion. States with spin up to $14\hbar$ were populated in the present reaction. We have observed the majority of the transitions between high-spin states reported in Reference [Sch93]. From the difference in the γ -ray intensity feeding and de-exciting levels in ^{208}Pb , we have extracted the relative direct feeding strength. The direct feeding strength of the 5^- state is roughly 40% of that of the 3^- state and the higher-lying states are populated with 10% or less of the intensity of the 3^- state. As demonstrated in Figure 4.2-2, our experimental sensitivity is such that we can identify transitions in ^{208}Pb with intensities of $\sim 0.1\%$. We find no unidentified discrete transitions in ^{208}Pb to this intensity level which can be associated with the decay of 2-phonon states.

An examination of Figure 4.2-1 reveals that there are very few unidentified discrete lines in the energy region expected for the decay of the 2-phonon multiplet (i.e., $E_\gamma \sim 2.0$ –2.8 MeV). In the pure harmonic approximation, assuming $E3$ transitions, one would expect a decay half-life for the 2-phonon states of about 8×10^{-12} seconds, nearly a factor of 3 longer than the stopping times of the recoiling Pb nuclei in our target. If, for example, the decay of the 6^+ and/or 4^+ members of the multiplet proceeds via $E1$ transitions to the 5^- state, the lifetimes could be much shorter and the resulting γ -rays would be strongly

Figure 4.2-1: Coincidence spectra gated on the $3^- \rightarrow 0^+$ transition in ^{208}Pb obtained from the ^{208}Pb target (top) and the ^{209}Bi target (bottom) data sets. The strongest line (at $E_\gamma = 583$ keV) is the $5^- \rightarrow 3^-$ transition in ^{208}Pb .

PB208 Level Scheme

(data taken from Pb208*Pb208 angles)

Figure 4.2-2: Decay scheme for ^{208}Pb obtained from the ^{208}Pb target data set. The widths of the arrows are proportional to the transition intensities. The level energies and transition energies are indicated in keV. The numbers in parenthesis correspond to the measured intensities and the uncertainties in the intensities, respectively.

Doppler broadened. We have searched our data for broad structures in coincidence with the transitions in ^{208}Pb . While real quasi-continuum γ -rays are observed to be in coincidence with transitions in ^{208}Pb , there is little evidence for Doppler-broadened lines in the energy region expected for the decay of two-phonon states. If one assumes the maximum Doppler shift and integrates the quasi-continuum over the corresponding bin size, the intensity in the quasi-continuum amounts to less than 5% of that of the $3^- \rightarrow 0^+$ transition. Therefore, we are able to set limits on the decay of two-phonon states of $\sim 0.1\%$ and 5% for stopped and Doppler shifted transitions, respectively.

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4.2.2 Lifetime Measurements in Identical Superdeformed Bands

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The phenomenon of the so-called "identical" superdeformed (SD) bands (i.e., bands with transition energies or moments of inertia identical to those in neighboring nuclei) has been one of the most surprising and inexplicable results in nuclear structure physics to date. A large number of cases are now known to exist in both the $A \sim 150$ and $A \sim 190$ regions of superdeformed nuclei, but a satisfactory understanding of these observations is still lacking. Theoretical suggestions range from the possible presence of a new symmetry to subtle cancellation effects, from the continuous readjustment of the mean field with increasing angular momentum to new terms in the collective Hamiltonian. Our approach to this problem is to perform DSAM lifetime measurements to determine the deformation associated with pairs of identical SD bands. We have carried out experiments using Phase I of GAMMASPHERE, consisting of 55 Compton suppressed Ge detectors, on identical SD bands in $^{151,152}\text{Dy}$.

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Figure 4.2-3: Fraction of full Doppler shift, $F(\tau)$, for transitions in the SD bands of ^{151}Dy and the yrast SD band of ^{151}Dy

In the Dy measurement, we used the reactions $^{122}\text{Sn}(^{34}\text{S}, xn)^{156-x}\text{Dy}$ with 175 MeV beams provided by the 88" cyclotron at LBL. The target consisted of 1.0 mg/cm^2 ^{122}Sn on a thick Au backing. Since SD bands in both Dy isotopes are populated at this beam energy and the recoiling nuclei slow down and stop in the same target/backing combination, our experiment amounts to a "differential" lifetime measurement, i.e., it is free from the systematic uncertainties associated with stopping power formulations. Therefore, we are able to make a direct comparison of the deformation in the two nuclei.

Some five SD bands are now known [Nis95] to exist in the nucleus ^{151}Dy . One of these, band 4 in the notation of Reference [Nis95], has transition energies corresponding to the mid-point of the transition energies of the yrast SD band of ^{152}Dy and is proposed [Nis95] to be the identical band of the ^{152}Dy yrast band. We have extracted the fraction of the full Doppler shift, $F(\tau)$, for transitions in the SD bands of ^{151}Dy and the yrast SD band of ^{152}Dy . Preliminary results are presented in Figure 4.2-3. As can be seen in Figure 4.2-3, within the experimental error bars the fractional Doppler shifts indicate very similar lifetimes for the transitions within the bands. It does appear that band 4 in ^{151}Dy has slightly larger Doppler shifts than those in the other bands in this nucleus and those in the yrast band in ^{152}Dy . This result suggests that while the differences in deformation between the bands may be small, the "identical" bands may not actually be so identical. We are in the process of performing detailed DSAM simulations in order to extract transition quadrupole moments for these bands, the results of which will allow the comparison to theoretical predictions.

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4.2.3 Lifetime Measurements in ^{184}Pt

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This study is one of a series of Doppler Shift Attenuation Method (DSAM) lifetime measurements in light platinum isotopes to investigate shape-coexistence and shape transitions in these nuclei. Previous measurements of lifetimes in the yrast band of ^{184}Pt [Gar86] have established that there is a sharp increase in the transition quadrupole moment, Q_t , at low spin followed by a rapid and significant decrease in the backbending region.

The present measurements were undertaken with the goal of determining the behavior of Q_t above the backbending region, and in the excited bands based on intruder configura-

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Figure 4.2-4: Lineshape fits to the 644 keV transition in ^{184}Pt . The panels in the left (middle) column present fits (heavier line) to the spectra measured in the backward (forward) rings of GAMMASPHERE, while the rightmost panel shows the fit to the 90° spectrum. The arrows indicate the unshifted γ -ray energy.

tions. The reaction $^{124}\text{Sn}(^{64}\text{Ni}, 4n)^{184}\text{Pt}$ at 275 MeV was used to populate high-spin states in ^{184}Pt . The target consisted of 1.0 mg/cm^2 ^{124}Sn on a thick Pb backing. The early implementation of GAMMASPHERE, consisting of 36 Compton suppressed Ge detectors, was used to measure the γ -rays. The data were sorted into $\gamma - \gamma$ coincidence matrices in which the γ -ray energies measured in an individual "ring" of GAMMASPHERE (i.e., those detectors located at constant polar angle with respect to the beam direction) were histogrammed against the γ -ray energies measured in any other detector. Coincidence gates were then set on those transitions in the bands of interest which were emitted after the recoiling ^{184}Pt nuclei had come to rest in the backing. A total of 7 spectra were obtained (corresponding to the 7 rings in the GAMMASPHERE's early implementation) for both the yrast and excited bands in ^{184}Pt .

The measured Doppler broadened γ -ray lineshapes are compared to lineshapes calculated using the analysis code LILFI [Eml89, Eml87]. This code uses the TRIM85 [Zie85] electronic and nuclear stopping powers and allows the fitting of both the state lifetime and side-feeding lifetimes as free parameters. Examples of lineshape fits to the 644 keV transition in the excited band of ^{184}Pt are presented in Figure 4.2-4. Preliminary results indicate that the Q_t values in the excited band are somewhat larger than those in the yrast band and that the Q_t values in the yrast band increase again following the first backbend. The analysis of these data is continuing and the results will be compared to detailed cranked shell-model calculations in order to determine the deformation driving properties of the single-particle orbitals involved in these bands.

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4.3 Phenomenology of Preequilibrium Nuclear Reactions

The exciton model of preequilibrium nuclear reactions provides a simple way to describe the continuum energy and angular distributions of particles emitted during energy equilibration in light particle induced reactions at incident energies of about 14 to 200 MeV. Over the years the model has proven to be quite adaptable to the inclusion of additional physics as well as remarkably successful at describing experimental results. Because of its

simplicity, its physical transparency, its utility, and its adaptability, the exciton model continues to be used in spite of the development of more microscopic and quantum mechanical models.

Work on the exciton model and the code PRECO-E has progressed by using relatively simple physical concepts and appealing to available data to direct choices between alternative formulations and to provide values for key model parameters that cannot be obtained from independent sources. Current work is concentrated on (nucleon, nucleon) or (N, N) reactions, which are the most straightforward to address.

4.3.1 Multiple Preequilibrium Emission

C. Kalbach Walker

It was originally expected that the main region of applicability of the exciton model would extend up to incident energies of about 60 MeV. In recent years, however, there has been increasing interest in energies up to around 200 MeV. Thus the exciton model, like other preequilibrium models, needs to be modified to allow more than one particle to be emitted during the nuclear equilibration process. Fortunately, in the exciton model this is a relatively straightforward process. All of the necessary equations and parameters are carried over directly from primary emission. On the other hand, a significant reprogramming effort is required to modify the code PRECO-E because of all of the extra physics that has been added to the model. This reprogramming has been completed and is in the last stages of study.

For the statistical geometry dependent hybrid (GDH) model [Bla83] and the quantum mechanical Feshbach-Kerman-Koonin (FKK) model [Cha94], the approximation has been made to consider only secondary preequilibrium emission that follows directly on primary preequilibrium emission. This so called "simultaneous" emission was thought (and later demonstrated [Cha94]) to be dominant, and inclusion of secondary emission after one or more two-body internal interactions substantially increased the calculational effort. In the exciton model and particularly in the code PRECO-E [Kal91] it is virtually no extra work to consider all secondary emission. This is what has been done.

Currently multiple preequilibrium emission is considered only after primary emission of either a proton or a neutron, even though primary emission of particles up through mass 4 is calculated. Likewise only secondary emission of nucleons is considered. From a physical standpoint, the nucleon channels should be the main ones involved in multiple preequilibrium emission, and neglecting the complex particle channels greatly reduces calculation time.

For the primary residual nuclei which can undergo secondary preequilibrium emission, PRECO-E is programmed to recalculate the mean square matrix element for the internal interactions using the excitation energy of the emitting nucleus. This is the more physical

Figure 4.3-1: Importance of secondary preequilibrium emission. The solid curve gives the full exciton model result while the dashed curves show the primary and secondary preequilibrium components and the evaporation component. The points show the data.

result and gives better agreement with experiment than using the energy of the original composite nucleus.

Secondary preequilibrium emission accounts for about 35–50% of the reaction cross section for 90 MeV projectiles (with the amount decreasing with increasing A) and about 60% for ^{90}Zr at 160 MeV. Primary emission is almost totally preequilibrium. Comparisons with the $^{58}\text{Ni} + p$ data at 90 MeV [Kal83, Wu79] are given in Figure 4.3-1. All of the PRECO-E calculations were run with shell structure and collective pairing effects included using standard default parameter values. Isospin was assumed to be mixed.

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4.3.2 Exciton Model Input and Assumptions

C. Kalbach Walker

With the inclusion of secondary preequilibrium emission, the research effort is becoming more focussed on illucidating various physics questions related to the exciton model input and assumptions. Several issues in this category have been addressed.

Most of the general input needed for exciton model calculations for (N, N) reactions, including the initial particle-hole configuration and the pairing and shell gaps, is well specified [Kal95]. Recent work [Kal94, Kal95] also indicated preliminary values for model-specific parameters for systems at incident energies of 18 to 25 MeV, and confirmed that isospin is conserved in the preequilibrium phase of the reaction, though it appears to be substantially mixed at equilibrium. At 90 MeV, isospin appears to be mixed, but other model input is unchanged.

Symmetry energies for calculations where isospin is conserved are sometimes derived from the Q-values of (p, n) reactions. These, however, should not be appropriate for exciton model calculations since they contain the effects of shell structure and the pairing interaction which are included separately in the calculations. Thus PRECO-E has been coded to use the volume and surface (V+S) symmetry energy terms from the semi-empirical mass formula. Since the Q-value derived energies generally fall in the range between the V and V+S results, the sensitivity of exciton model calculations to the choice between these options was studied. Results for 18 MeV (p, p') spectra show that using only the volume term yields too much cross section for the neutron rich targets and destroys the systematic agreement previously obtained with experiment.

Another question studied was the assumed functional dependence of the mean square residual matrix elements causing nuclear equilibration. Because the interactions are both residual and effective they cannot be derived *a priori*. In 1973 [KC73] I determined empirically that for initial $n = 3$ states in nucleon induced reactions the values of M^2 varied as $E^{-1}A^{-3}$, and they were assumed to be independent of the exciton number. Later, theoretical work by Gadioli *et al.* [Gad73] based on nuclear matter calculations suggested that E/n rather than E was the pertinent parameter, and this was eventually adopted. The effect was to reduce the amount of preequilibrium emission from the more complex (higher n) states populated later in the equilibration process. When comparisons with data [Kal95] indicated that more late-stage preequilibrium emission would be helpful in PRECO-E, calculations were run replacing n with its initial value of 3. In all cases slightly improved agreement is obtained. Thus it can now be concluded that the theoretical exciton number dependence does not carry over to the residual M^2 in the exciton model.

In extending this work to higher incident energies, new physical effects may need to be

considered. For instance, it was observed [Kal88] that the physical parameter determining the degree of forward peaking of continuum angular distributions changes dramatically at bombarding energies between 100 and 160 MeV. There is a substantial body of both (p, p') and (p, n) data in this energy region which can be interrogated to look for such effects in the energy spectra. A preliminary look suggests that the surface peaking of the initial target-projectile interaction which is evident at incident energies of 40 to 100 MeV [Kal85] has disappeared by 160 MeV, perhaps indicating an effectively longer range of the interaction due to pion exchange. There is also an indication from one pair of spectra that using the standard value of $M_{pn}^2/M_{pp}^2 = 0.6$ underestimates the experimental (p, n) to (p, p') yield ratio suggesting that a higher value is needed. This work is in an early stage.

Work is continuing on developing a full set of global input parameters for the exciton model, particularly with regard to the residual two-body matrix elements, the systematics of isospin conservation with target mass and incident energy, and the transitions in behavior at bombarding energies around the pion rest mass.

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4.4 High Resolution Studies at Münster and Bochum

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Significant improvements have been made to the energy resolution characteristics of the 400-keV Münster accelerator [Sch92]. The HV terminal ripple is usually less than 12 V, and under favorable circumstances less than 4 V. For many of these experiments windowless gas targets were used. The target thickness could be varied from less than a monolayer of target material to relatively thick targets. The stability and reproducibility of the ion beam energy

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were less than 3 eV. The German group now has moved to Ruhr Universität Bochum, where there is a Tandem Dynamitron accelerator. Recent results include significant improvements in high resolution depth profiling utilizing heavy ions from the Dynamitron and observation of replica resonances which reflect atomic excitation processes.

4.4.1 Energy Loss Phenomena

The quantized energy loss of 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 called 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 not contribute to the yield. The Lewis effect is only observed with very good energy resolution and very clean targets. To analyze such data the energy loss process must be well understood. Since for gas targets the Doppler effect is greatly reduced, we have studied the Lewis effect and related energy loss phenomena in windowless gas targets. Energy loss spectra were obtained for gas targets ranging from ultra-thin targets to 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 ^{21}Ne we observed a very pronounced Lewis peak—the first observation of the Lewis effect in a gas target.

For very good energy resolution and thin targets, atomic excitation effects must be included. These excitations 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. 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 Ne target. Similar results were observed for a resonance in $^{23}\text{Na}(p, \gamma)^{24}\text{Mg}$. With the measured collision spectra, the thick-target yield curve was correctly simulated. These results were published recently [Sch94].

4.4.2 High Resolution Depth Profiling

The very high stopping power at projectile energies of a few hundred keV makes low energy resonances attractive for depth profiling measurements. To achieve the full potential, excellent beam energy resolution is required, and the target should be free of surface contaminants and cooled to reduce the Doppler spread. In our initial experiments [Sch93] 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.

In recent measurements [Bec95] we determined precisely the resonance parameters of a low energy resonance ($E_p = 151$ keV) in the $^{18}\text{O}(p, \alpha)^{15}\text{N}$ reaction. We then studied

this resonance in inverted kinematics. This resonance occurs at $E_{\text{oxygen}} = 2.70$ MeV in the $^1\text{H}(^{18}\text{O}, \alpha)^{15}\text{N}$ reaction and thus is accessible to single-ended 3-MV accelerators. With the relatively good energy resolution of the Bochum Dynamitron, and the favorable characteristics of this resonance, our first results are comparable to those obtained using this approach at higher energy resonances. This resonance may be suitable as a new standard for depth profiling measurements with solid targets. Our studies with gas targets suggest that analysis of Doppler broadening in these reactions is sufficiently sensitive to reflect vibrational and rotational motion in the hydrogen molecules. Such investigations might be applied to the determination of bond strengths of hydrogen on the surface of solids.

4.4.3 Vibrations of Solid Neon

A cryogenic target UHV system has been built to study narrow nuclear resonances [Ber95a]. The crucial part of the system is a liquid helium cooled sample holder mounted on a goniometer. With this target system we have studied the 272 keV resonance in $^{21}\text{Ne}(p, \gamma)^{22}\text{Na}$ at temperature of ~ 8 K. An extremely large Lewis effect is observed (peak to plateau of ~ 2.5 to 1). The shape of the Lewis peak is affected by both electronic stopping and motion of the target atoms. Since the Doppler contribution is strongly reduced for a gas target, we studied this same resonance with a gas target under similar low temperature conditions. We used the information from these energy loss spectra in fitting the observed Lewis peak. The resulting experimental value for the Doppler width [Ber95b] agrees with estimates using an effective temperature calculated from the standard Debye temperature for bulk solid neon.

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

R. M. Chasteler, C. M. Cheves, D. R. Tilley, H. R. Weller

TUNL efforts in nuclear data evaluation and dissemination are summarized as follows:

4.5.1 Data Evaluation Activities

$A = 3, 4$: 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 A*474 (1987) 1, and "Energy Levels of Light Nuclei, $A = 4$ ", D.R. Tilley, H.R. Weller and H. Hasan, *Nuclear Physics A*541 (1992) 1. TUNL continues to survey the literature and compile references for $A = 3$ and 4 on a regular basis and occasionally carries out literature searches for few-nucleon information in response to requests from researchers.

$A = 5-20$: TUNL now carries on literature coverage for this mass region on a continuing basis, compiling a bibliographical listing of relevant experimental and theoretical work, utilizing several resources including Monthly Updates from the National Nuclear Data Center (NNDC), Current Contents on Diskette with Abstracts, and Physics Abstracts. The review of $A = 16-17$ was completed in late 1993 and published as "Energy Levels of Light Nuclei, $A = 16-17$ ", D.R. Tilley, H.R. Weller and C.M. Cheves, *Nuclear Physics A*564 (1993) 1.

The review of $A = 18-19$ is complete. Preliminary versions were issued ($A = 18$ in January 1994 and $A = 19$ in July 1994), and copies were mailed out to solicit corrections and suggestions. The final manuscript, entitled "Energy Levels of Light Nuclei, $A = 18-19$ ", was submitted to *Nuclear Physics A* in July 1995. In addition, TUNL has completed entry into the NNDC Evaluated Nuclear Structure Data Files (ENSDF) of adopted levels, decay data, and (for the first time in this mass region) reaction data for $A = 18-19$.

Work has begun on the $A = 20$ evaluation. A preliminary version, written in collaboration with S. Raman of Oak Ridge National Laboratory, is expected in the fall of 1995.

4.5.2 World Wide Web Services

In the fall of 1994, the TUNL Nuclear Data Evaluation Group began developing its informational services on the World Wide Web (<http://www.tunl.duke.edu/NuclData>). This is part of an effort by the entire Nuclear Data Network to make its work more easily accessible to a larger community of basic and applied research workers. The capabilities of this new method of providing evaluated nuclear data were demonstrated at the NSAC/DNP Long Range Planning Town Meeting held in Durham, North Carolina in January 1995. The TUNL group has been encouraged by the response to this demonstration and by similar indications of interest from the applied scientific community. For example, the group was asked for and submitted (in collaboration with B. Doyle of Sandia National Laboratory) an abstract for a paper at the Ion Beam Analysis Conference (IBA-12) which took place in Tempe, Arizona in May 1995.

Currently, the following items are available:

- Energy Level Diagrams for $A = 4-20$ nuclei in the style of Fay Ajzenberg-Selove.

These diagrams provide a good overview of the major features of a nucleus.

- Abridged versions of the $A = 16, 17, 18$, and 19 evaluations. Full text, tables, and references are available, with search capabilities and hypertext links for navigating through the document. Adobe Acrobat technology allows these platform-independent documents to appear on the screen just as they would on the printed page.
- Adopted levels and decay data in ENSDAT style for $A = 3-20$ nuclei as well as reaction data for $A = 18$ and 19 . This format is very similar to the Nuclear Data Sheets for higher-mass nuclei and is based on the information found in the NNDC Evaluated Nuclear Structure Data Files.
- Information on the status of the evaluations, lists of all published $A = 3-20$ compilations, instructions for obtaining reprints and preprints, and links to other Nuclear Data centers.

The TUNL group plans to release all future preprints and publications on WWW in the form described above, in addition to continuing publication in *Nuclear Physics A*. The WWW release will allow the reviews to be updated more frequently and made available to more researchers. In addition we have received permission from the publishers of *Nuclear Physics A* to provide abridged versions of Fay Ajzenberg-Selove's earlier "Energy Levels of Light Nuclei" for $A = 5-20$, giving the user quick electronic access to nuclear information from several back issues of the Ajzenberg-Selove reviews. Our goal is to provide, in one convenient location, all available forms of evaluated data for the light-mass nuclei.

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 3129 hours during the period September 1, 1994 through July 10, 1995. The accelerator operated at terminal potentials ranging from 0.47 MV to 6.9 MV during this period. Beams accelerated during this period include polarized and unpolarized protons and deuterons, and also ^3He . The terminal operating potential during the reporting period is shown graphically in Figure 5.1-1.

A histogram showing the fraction of experimental time spent at various terminal potentials is given in Figure 5.1-2. The large number of days spent at 5.1 MV are due to the intensive efforts of the few body research group. The Low-Energy Beam Facility (LEBF) was operated 3900 hours during this same period. Normally when the LEBF was in operation, the tandem was used approximately one hour per day for beam polarization measurements. Tandem experiments requiring unpolarized beams can be run simultaneously with the LEBF unless excessive background radiation is produced in the area of the LEBF. This excluded simultaneous operation during most of the period covered by this report. The remaining time was required for tandem openings, building maintenance, beam line changes, and ion source upgrades.

The tandem was opened for maintenance in August, 1994 after 17,910 hours of operation, and again in May of this year for routine maintenance. The Pelletron chains were inspected in August of 1994 and fret corrosion was discovered in three links of the high-energy chain. These failing links were replaced and the chain is operating normally. During this tank opening, several bad bearings in the Pelletron charging system were discovered. Because of this, and due to the age of the bearings, we decided to replace all Pelletron bearings, and also the idler and pickoff pulleys. Several failed column resistors were located during a check of the resistor grading strings and were replaced. During this opening, a small CCD TV camera was installed in a position where it could image the low-energy charging chain. This camera was intended to be used to monitor the chain remotely without a tank opening, thus providing a means to detect mechanical failures in their infancy. The camera worked for several months before it failed—apparently from a tank spark.

During the June opening, a new camera was installed and a second camera was also installed to view the High Energy chain. Spark protection devices were installed to harden

the camera's circuitry from tank sparks. During this opening we also installed two large diameter (14") capacitive pickoff plates in the tank to improve the signal to noise ratio in this circuit. These plates increased the signal by a factor of ten which should improve the performance of the terminal stabilizer feedback when using this signal. In addition the terminal stripper box was raised by 0.100" to bring it into better alignment with the acceleration tubes when the tank is at pressure. Initial reports indicate that the transmission is improved as evidenced by the 75% transmission obtained at 0.47 MV on the terminal immediately after the maintenance opening. The stripper box was opened and the foil stripper chain was connected to a new terminal amplifier which provides fast feedback from the TPS slit error to the stripper foil. The slit error signal is transmitted from ground, up the low energy column on a bare plastic fiber optic strand to the terminal amplifier which has a fiber optic receiver followed by a $\pm 300V$ amplifier. A new set of stripper foils were also loaded at this opening. A foil change typically lasts for one to three years in our machine.

5.1.2 Spare Accelerator Tubes

Funds were obtained from the DOE in 1993 to enable us to purchase two spare accelerator tube sections for the FN tandem. These two tubes will compliment the two spare tubes on hand at LLNL-CAMS. A formal agreement will enable both laboratories to draw on these spare tubes in the event of a tube failure. Delivery of these was made in early January of 1995, and one of the tubes (#1) was found to be damaged in shipment. The tube was returned to the factory for repairs of several failed glue joints, and was returned to TUNL in June.

5.1.3 Higher Voltage Operation

A number of experiments are planned which will require the tandem to operate at 10 MV. At present, we are restricting the maximum terminal voltage to 9.5 MV until we can adjust the accelerator tube spark gaps. This replacement will require a lengthy opening as there are over 1100 spark gaps to be removed and new ones to be installed. Another modification being implemented is the replacement of the spring connections between the accelerator tubes and the column. Tubes #1 and #2 have had nearly all of these old springs removed and wire leads installed with screwed connections which should be much more stable.

5.2 KN Accelerator Operation

C. R. Westerfeldt, E. G. Bilpuch, E. P. Carter, M. A. LaBonte, G. E. Mitchell, J. F. Shriner, G. A. Vavrina, P. M. Wallace

Figure 5.2-1: TUNL KN operating potential for reporting period 1 Sep. 95-11 July 95.

The TUNL KN high energy-resolution accelerator operated a total of 2252 hours during the period September 1, 1994 through June 19, 1995. During the first five months of 1995, this accelerator operated for 48% of the available time. This single-ended Van-de Graaff operated at terminal potentials ranging from 0.99 MV to 3.51 MV during this same period. A histogram showing the number of days of operation at the logged terminal potentials is shown in Figure 5.2-1.

The accelerator was opened 11 times during this period for maintenance and repairs. Repairs included three ion source changes, replacement of the charging belt, two replacements of the focus power supply, two replacements of the corona regulator needles, three drive motor and/or alternator bearing changes, installation of a new drivemotor (on indefinite loan from the University of Washington - Seattle), and a number of repairs to the rf ion source oscillator. In addition, two rebuilt Palladium gas leaks were installed to replace two that were failing. A thermo-mechanical gas leak was also installed for Helium-4 to enable preliminary testing with He-4 beams.

Some of our difficulties with the rf ion source were traced to low output from the terminal alternator. The Selenium rectifier bridges in the exciter circuit for the alternator were replaced with a single Silicon bridge which occupies about 1% of the space of the two original bridges and costs even less. This bridge has operated successfully for over 940

hours and has survived numerous tank sparks with simple MOV protection on the input and output.

The majority of the maintenance openings during this reporting period were caused by premature failures in drivemotor bearings, and poor performance of the charging belt. After a good motor and a new charging belt were installed, the accelerator has operated very well and no major system changes are planned for the near future.

5.3 Atomic Beam Polarized Ion Source

T. B. Clegg, A. J. Mendez, C. D. Roper, J. D. Dunham

5.3.1 Routine Operation and Maintenance

The TUNL intense atomic beam polarized ion source has been used for experiments during 55% of the calendar days during the past year; 50% of the days for production of polarized ions (126 days for polarized $H^\pm$ and 57 days for polarized $D^\pm$) and 5% for unpolarized H and D ion beams. The use of these beams was divided as follows: 21% for experiments solely in the low-energy target areas, 10% in the high-energy target areas, and 24% for experiments which utilized beams accelerated into both areas. In addition, 54 and 43 days were scheduled, respectively, for source modifications/testing and for routine maintenance.

Overall, the source has operated extremely well during the entire year, and its output beam intensities have slowly improved. Unusual events which affected operation were repeated failures of components which regulate the cesium oven temperature determining the vapor density for charge-exchange, and occasional difficulties associated with our efforts to modify beam extraction lens elements and to prepare for spin-filter polarimeter installation (see below).

Three manuscripts [Cle95a, Cle95b, Din95] describing polarized source systems and performance were published in Nuclear Instruments and Methods.

5.3.2 Spin-Filter Polarimeter

The Spin-Filter Polarimeter (SFP) project, which was undertaken with the goal of providing on-line beam polarization measurements for all polarized ion source users, was already underway last year. The concept was described in last year's progress report. Since then, considerable work has been completed: calculations underlying design choices for major systems were made, actual designs for all experimental systems were finalized, mechanical and electronic systems have almost all been fabricated, and installation and initial testing

of major systems into the atomic beam polarized source is underway. These activities are described in more detail below.

Ion Beam Optics Studies

Last year, when positive beams were extracted directly from the ECR ionizer of the ABPIS, typical H^+ or D^+ intensities were 20–35 μA for polarized and 100–400 μA for unpolarized ions, respectively. When H^- or D^- beams were desired, these positive ions underwent charge exchange in cesium vapor to produce 3–6 μA for polarized or 15–40 μA for unpolarized ions. Experimental needs have continued to demand improved beam intensities.

Our long-used beam extraction system consisted of concentric, biased apertures and tubes along the axis of an 80–130 mT solenoidal B -field, which extended from the ECR ionizer until it was terminated abruptly just beyond the cesium charge-exchange canal/lens 4. Over this axial region, the clearance diameter for passage of beam ranged between 22 and 43 mm. The first two gaps formed an accel-decel lens system, extracting ions from the ECR plasma at energies up to ~ 8 keV before decelerating them to ~ 1 keV. The extracted ~ 500 eV, H^+ (~ 1000 eV, D^+) beam was then focused by two subsequent gap lenses through the 13 cm long Cs canal, centered 25 cm downstream. Further beam acceleration to energies of 20–80 keV occurred after emerging from the region of strong axial B -field.

Following reports of improved performance at IUCF [Der94a], we made limited experimental tests of new gridded apertures for the first three elements extracting beam from the ionizer. Marginal improvement in beam intensity was initially observed, but sputtering of the 85% transparent, 0.3 mm thick molybdenum grids quickly degraded their performance, completely destroying them after two weeks of continuous operation. We then returned to using our original ungridded apertures.

Measurements showed that substantial beam loss ($> 150 \mu A$) occurs on individual lens electrodes in our beam transport system when 4–5 μA of polarized D^- beam was extracted. To understand better the origin of these losses and to optimize the design of lens elements which incorporated the SFP, we have modeled computationally the existing and proposed beam extraction and transport systems.

A program was written to generate ions near the ionizer extraction aperture by Monte-Carlo and subsequently follow individual trajectories by numerically integrating the differential equations of motion. The necessary E - and B -fields were calculated by the Los Alamos code POISSON [Poi87] using the known optimized source operating parameters. In addition to calculating the ion trajectories, the program also generated phase-space diagrams, from which the beam emittance could be estimated, and maintained a record of the number of ions striking each lens element.

These calculations revealed that the most critical electrodes in our system were those in the accel-decel region where the beam was initially extracted from the ECR ionizer. Strong

radial E -field components gave rise to motional $\vec{v}_r \times \vec{B}_z$ fields which imparted angular momentum around the beam direction to the extracted ions. This led to rapid beam emittance growth. We found that reducing the diameter of the ionizer, lens 1 and lens 2 apertures reduced the size of these radial E -field components and thus the angular motion of the extracted ions. Reducing the apertures to 2.5 cm diameter from 3.5 cm for the ionizer and lens 1 and from 3.8 cm for lens 2 had the calculated effects of reducing the D^+ beam emittance by half and of increasing the number of transmitted ions by approximately 25%. The D^- beam emittance remained essentially unchanged with the smaller apertures, but the transmitted intensity nearly doubled. The smaller lens apertures were then made and installed.

This extraction lens modification produced a significantly reduced beam intensity. However, when we removed completely the ionizer aperture, making a 7.3 cm diameter opening, while keeping the smaller lens 1 and 2 apertures, we obtained the highest polarized ion beam intensities to date: 60 to 80 μA of polarized H^+ or D^+ and up to 8 μA of polarized H^- or D^- . However, this configuration extracted ionized nitrogen, which is used as a buffer gas to sustain the ionizer plasma. The extracted nitrogen ions sputtered the lens 1 and lens 2 extraction apertures rapidly, shortening run time between maintenance periods from 3 months to 3-4 weeks. We subsequently reduced this sputtering significantly, but not completely, by using tantulum rather than stainless steel disks as lens 1 and lens 2 apertures. We finally solved the sputtering problem, while maintaining largely the increased beam intensities, by reinserting the 3.5 cm diameter ionizer aperture.

In addition to testing the effects of changing aperture sizes in attempting to solve the sputtering problem and improve beam transport, we also tried using different buffer gases for the ionizer. Since both H and D have sputtering rates which are at least two orders of magnitude lower than those of N, we replaced the N_2 with H_2 for D ion beams and with D_2 for H ion beams. We found that an approximately 10% increase in $H^\pm$ currents could be achieved using the D_2 buffer gas. This is similar to the results experienced at IUCF, where now D_2 is routinely used as an ionizer plasma buffer gas. However, using H_2 as a buffer gas for D^+ beams presented a problem since the charge-to-mass ratio for H_2^+ is close enough to that of D^+ that the Wien Filter and analyzing magnets cannot separate the two beams. This is, of course, not a problem when D^- beams are desired. Although it was found that the extracted beam currents and polarizations were at least as good using the H_2 or D_2 buffer gases as those obtained using N_2 as a buffer, the plasma stability was not as good, and beam tuning became more difficult. For this reason, and because of the aforementioned problem of background H_2^+ in the D^+ beams, it was decided to continue using N_2 in the ionizer, and to use the 3.5 cm diameter ionizer aperture to alleviate the sputtering problem.

Having achieved improved source beam intensities and having essentially eliminated the sputtering problem, it remained to investigate the effect on beam transport of the SFP systems. Calculations indicated that installation of the SFP should not significantly decrease the source beam intensity. The worst case calculation, with no accelerating voltages

between lens 4 and lens 5b, showed that the ions can essentially drift through SFP without substantial loss. Preliminary testing for approximately two weeks with the SFP installed in the source has indicated that this is probably not the case. Further calculations and experimental testing are needed to determine whether adequate output beam can be obtained with the SFP system in place, or whether the beam transport system can be modified to achieve the required performance.

Installation

Major modifications of the ABPIS were required to install the SFP. Figure 5.3-1 shows a section of the source with the SFP installed. At present, the source has been lengthened by ~30 cm to accommodate the SFP vacuum chamber and the coil/flux return assembly designed to provide the required uniform axial magnetic field. This modification included: addition of seven new coils identical to those producing the field for the ionizer region; changes to all of the lens structures from lens 3 downstream; addition of two new lens elements, lens 5a and the spin-filter cavity itself; installation of the new SFP vacuum chamber; installation of a new, shorter acceleration tube between the Wien Filter and ground, and shortening of the acceleration tube between the Wien Filter and the last chamber on the high-voltage frame.

As of this writing, all of the electronics required for the proper operation of the modified atomic beam polarized source with the SFP have been installed. The hardware both external and internal to the vacuum system (with the exception of the photomultiplier tube and its mounting hardware) are in place. Initial testing of ion beam extraction and beam transport has begun. We will continue the SFP installation and testing while providing as well as possible the beams needed for the laboratory's usual polarized ion experimental program.

Instrumentation

A block diagram of instrumentation relevant to the SFP is shown in fig. 5.3-2. The system has been installed essentially as described in the 1994 annual report, with minor changes. The most significant modification provides the ability to affect spin state control from the PC via the Kiethley WORKHORSE crate. This utilizes a digital I/O board in the WORKHORSE along with an external logic circuit built in-house. The system gives the user a software toggle between his own external spin-state control hardware for normal running and PC/WORKHORSE control for polarization measurements using the SFP.

At present, the two new power supplies for lens 5a and the SF are controlled by plastic rods, the same as the other lens supplies. To implement fully the SFP, these supplies must be under WORKHORSE control. The current plan is to convert all lens supplies over to remote programming using sets of digital potentiometers located both in a ground potential rack at the ion source and in the accelerator control room. One important note

Figure 5.3-1: Layout of the ABPIS ion beam extraction region from lens 3 to lens 5b showing the installed SFP systems.

concerning the lens 5a and SF supplies is that they are floating at lens 4 (Cs oven) potential. This simplifies zeroing the voltages between these two elements and the Cs oven, which is required when acquiring a polarization spectrum with the SFP. Consequently, the meters on the supplies give the voltage relative to lens 4 rather than relative to frame ground. Further, the isolation amplifier which allows the WORKHORSE to program these supplies is only rated for 2.5 kV. Therefore it is imperative that the lens 4 voltage always be less than 2.5 kV.

Theoretical Concerns

As discussed in the last annual report, the SF cavity performance was modeled realistically by solving the quantum mechanical four-level equations [Men94]. These calculations

Figure 5.3-2: Block diagram of the electronics associated with the SFP.

led to the design of a new cavity whose central section is 10 cm shorter than that of the cavity used in the proof-of principle tests [Lem93]. Since the last report, more calculations have been completed which model the performance of another planned SFP system at IUCF [Der94b]. In this context, the performance as a function of beam velocity was investigated. As reported, adequate state selection and efficiency can be obtained for protons up to about 20 keV and for deuterons up to about 40 keV.

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5.3.3 A High Accuracy Beam Current Integrator for Fast Spin-Flip Experiments

W. S. Wilburn

Fast spin-flip experiments require accurate beam current integration for normalizing detector count rates. Beam current integrators based on precision voltage-to-frequency converters are used for this purpose. As the spin-flip rate of the polarized ion source increases, fewer beam current integration pulses are counted during each spin state. This can cause a problem since the beam current integrators currently used (Brookhaven Instrument Corporation) have a full-scale frequency of only 200 Hz. At a spin-flip rate of 10 Hz a

maximum of 20 integrator pulses are counted for each spin state. The digitization error associated with such a small number of pulses can easily become a substantial fraction of the total measurement uncertainty. For this reason, a high-rate integrator has been developed which retains the absolute accuracy and stability of the present units, but which has a full-scale frequency of 500 kHz.

The beam current integrator is designed so that the analog and digital circuits are kept completely separate for noise suppression. The basic circuit consists of a current-to-voltage amplifier followed by a voltage gain stage and then a voltage-to-frequency converter. The analog board is housed in a separate shielded enclosure and is powered by an isolated supply. Output pulses are sent to the digital board via optocouplers. On the digital board, TTL and NIM level digital outputs are generated. In addition, a frequency-to-voltage converter reconstructs the analog signal to drive the front panel meter and an external analog output.

Tests of the integrator indicate that it has better accuracy than previous units. The absolute accuracy is 0.015% of full scale (compared to 0.02%) with a maximum non-linearity of 0.01%. The integrator has been successfully used in the recent time-reversal invariance measurements. In the future it will be used in parity-violation measurements and other experiments requiring fast spin-flip.

5.4 Improvements to the Low-Energy Beam Facility

P. F. Bertone, C. R. Brune, B. J. Crowe III, W. H. Geist, H. J. Karwowski, E. J. Ludwig, and K. D. Veal

The Low-Energy Beam Facility (LEBF) at TUNL accepts polarized or unpolarized beams from the atomic-beam polarized ion source. The ion source provides positive or negative beams with energies up to 80 keV; the minitandem accelerator increases the energy of negative beams by twice the minitandem voltage, ultimately yielding a positive beam. Alternatively, the minitandem can be grounded, allowing the ion-source beam to pass through without charge exchange or further acceleration. There are currently two beamlines operating on LEBF, one terminating in a 107-cm-diameter high-voltage scattering chamber, and the other consisting of a general-purpose scattering chamber and a target chamber used for γ -ray measurements. During the past year we have continued to improve LEBF, as follows.

We have upgraded the maximum voltage of the minitandem from 125 kV to 200 kV. Higher-voltage operation required the installation of new acceleration tubes, which were purchased from HVEC Europa. New quadrupole magnets were installed, as the existing electrostatic quads were insufficient to focus the higher-energy beam. The new quads are also very compact, and create the space necessary for the longer acceleration tubes. We have also installed a longer insulator to support the minitandem, and a new power supply

Figure 5.4-1: The yield of protons from the $^3\text{He}(d, p)$ reaction measured at $\theta_{\text{lab}} = 150^\circ$, plotted as a function of on-target energy. The squares and triangles were obtained using 80 keV D^- ions from the source and a potential on the minitandem to increase the beam energy. The circles were obtained with 40 keV D^+ ions from the source and the minitandem grounded. In all cases the potential on the high-voltage chamber was varied between 0 and -200 kV to further increase the on-target energy.

capable of providing $+200$ kV for the minitandem. The upgraded minitandem has been successfully tested up to $+200$ kV, and the beam-energy calibration has been established by measuring narrow nuclear resonances.

The high-voltage scattering chamber can be raised to potentials up to -200 kV, yielding an on-target energy of up to 680 keV with the minitandem, or 280 keV with the more-intense positive beam from the ion source. We recently installed the isolation transformer, high-voltage power supply, safety fence, and fiber-optic transmission system for sending detector signals to ground potential. An excitation function of the $^3\text{He}(d, p)$ reaction measured using the high-voltage chamber is shown in Figure 5.4-1. The on-target energy was varied between 40 and 530 keV, demonstrating the capabilities of the instrument (the experiment

was done before completion of the minitandem upgrade).

5.5 Polarimeters

5.5.1 Determination of Low-Energy Proton Polarization via the ${}^6\text{Li}(\bar{p}, {}^3\text{He}){}^4\text{He}$ Reaction

C. R. Brune, H. J. Karwowski, E. J. Ludwig and L. Ma

Several generic features of nuclear reactions conspire to make the determination of proton-beam polarization via nuclear reactions more difficult at low energies than at higher energies. The design goal of an efficient polarimeter is to maximize the statistical figure of merit σA_y^2 , while satisfying other practical criteria (reasonable target and detector requirements, low background, etc...). At low energies, angular-momentum barrier considerations strongly favor *s*-wave processes. Pure *s*-wave reactions can be shown to have zero vector analyzing power, implying that most low-energy reactions will have a very small A_y . Furthermore, the Coulomb barrier suppresses reaction cross sections at low energies, and limits consideration to low-*Z* targets. Elastic-scattering processes have large cross sections at low energies, but tend to be dominated by Rutherford scattering, which has $A_y = 0$.

Previous measurements of the ${}^6\text{Li}(\bar{p}, {}^3\text{He}){}^4\text{He}$ reaction for $E_p > 400$ keV [Bro68] indicate that it is the best choice for our energy range. This reaction is also used at TRIUMF to determine the proton polarization at the ion-source energy [Buc91]. At $E_p = 324$ keV, the reaction has $A_y(90^\circ) \approx 0.25$ and $\sigma(90^\circ) \approx 4$ mb/sr.

A polarimeter based on this reaction has been constructed and placed in the rear of the LEBF high-voltage scattering chamber. The proton beam is directed onto a target consisting of $10\text{-}\mu\text{g}/\text{cm}^2$ ${}^6\text{LiF}$ evaporated on a thin carbon foil. The ${}^3\text{He}$ and ${}^4\text{He}$ reaction products are detected with two silicon detectors placed in close geometry on either side of the beam at $\theta_{\text{lab}} = 90^\circ$. The reaction's 4.0-MeV *Q*-value allows foils to be placed in front of the detectors which stop elastically scattered protons, while still allowing the reaction products to pass through. Sample spectra are shown in Figure 5.5-1.

The absolute calibration of the polarimeter has been established by accelerating the beam through the FN Tandem to 6 MeV and determining the polarization independently using the ${}^4\text{He}(\bar{p}, p)$ reaction. Presently, the polarimeter has been calibrated for $E_p = 324$ keV. At this energy, a 1% statistical error in the beam polarization can be obtained in about 15 minutes with 50 nA of beam in the polarimeter. Future plans include extending the calibration to 280 keV (the highest energy available with positive beam from the ion source) as well as to higher energies where the figure of merit is greater.

[Bro68] L. Brown and C. Petitjean, Nucl. Phys., A117, 343 (1968).

Figure 5.5-1: Spin up and down spectra from the $^6\text{Li}(\vec{p}, ^3\text{He})^4\text{He}$ reaction obtained with the right detector and $E_p = 324$ keV, showing the ^4He and ^3He peaks.

[Buc91] L. Buchmann, Nucl. Instrum. Methods, **A301**, 383 (1991).

5.5.2 Low-Energy Proton Polarimeter

R. M. Prior, R. M. Chasteler, H. R. Weller

The design of a low-energy proton polarimeter was described in last year's progress report and has been published (Nucl. Instrum. Methods **A335** 439 (1995)). The abstract follows:

A polarimeter is described for proton beam energies below 100 keV using the ${}^7\text{Li}(p, \gamma){}^8\text{Be}$ reaction. Measurements indicate an analyzing power near 0.4 with yields that would allow a 10% measurement of beam polarization in 1 h for sources producing beam currents on the order of 30 μA .

Following the design proposed in the paper and the last progress report, a polarimeter was constructed and tested. A small vacuum chamber containing a retractable ${}^7\text{Li}$ target was built and installed in the low-energy radiative capture beam line, 2m upstream from the target chamber. When inserted the Li target contacts a high-voltage feedthrough so that the target can be biased to -20 kV, increasing the proton beam energy to 100 keV. Which increases the reaction yield by a factor of 3.3. Two 25-cm x 25-cm NaI detectors are placed on each side of the polarimeter chamber at 90 degrees with respect to the beam direction; the detector faces are 9 cm from the middle of the target.

In use the polarimeter target is inserted into the beam, -20 kV is applied and measurements are made. To return to data acquisition, the high voltage is removed, and the target retracted. The polarimeter has been tested during data runs and is working.

5.5.3 A Low-Energy Deuteron Vector Polarimeter using the $D(\vec{d}, p){}^3\text{H}$ Reaction

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

Existing measurements [Pfa89] of the $D(\vec{d}, p){}^3\text{H}$ reaction indicate that it is a good choice for determining the vector polarization at low energies ($E_d \leq 500$ keV). At $\theta_{\text{lab}} = 90^\circ$ and $E_d = 300$ keV, $A_y \approx 0.3$ and $\sigma \approx 0.9$ mb/sr. In addition, both $A_y(90^\circ)$ and $\sigma(90^\circ)$ vary only slightly from 100 to 500 keV.

An existing polarimeter was modified to measure the deuteron vector polarization via the $D(\vec{d}, p){}^3\text{H}$ reaction using a self-supporting deuterated diamond film. The polarimeter is equipped with two silicon detectors placed in close geometry on both sides of the beam at $\theta_{\text{lab}} = 90^\circ$. A 5- μm thick mylar foil in front of the detectors prevented the elastically

Figure 5.5-2: A deuteron vector polarimeter spectrum at $E_d = 330$ keV. The peak at channel 675 is the proton peak from the $D(\vec{d}, p)^3\text{H}$ reaction. The smaller peak below it results from the $^{12}\text{C}(\vec{d}, p)^{13}\text{C}$ reaction.

Figure 5.5-3: Energy dependence of A_y obtained in the calibration of a polarimeter utilizing the $D(\vec{d}, p)^3\text{H}$ reaction.

scattered deuterons from entering the detectors while allowing the ≈ 3 -MeV protons to pass through without significant energy loss. A sample spectrum is shown in Figure 5.5-2.

The calibration of the polarimeter was accomplished by first accelerating the beam through the FN Tandem to 10 MeV in order to determine the vector polarization using a calibrated high-energy polarimeter. Once the polarization was measured the beam was directed onto the low-energy polarimeter to determine the analyzing power. The polarimeter has been calibrated at energies between 180 and 530 keV. A plot of $A_y(E)$ obtained for the polarimeter calibration is shown in Figure 5.5-3.

[Pfa89] E. Pfaff, 1989, Private communication.

5.5.4 A Deuteron Tensor Polarimeter at Low Energies using the ${}^3\text{He}(\vec{d}, p){}^4\text{He}$ Reaction

W. H. Geist, Z. Ayer, A. C. Hird, H. J. Karwowski, and E. J. Ludwig

To make an efficient polarimeter one would like to maximize the figure of merit, σA^2 , while favorably fixing other variables (background, targets, etc...). Possible reactions to determine the deuteron tensor polarization of low energy beams are the ${}^3\text{H}(\vec{d}, n){}^4\text{He}$, ${}^2\text{H}(\vec{d}, p){}^3\text{H}$, and ${}^3\text{He}(\vec{d}, p){}^4\text{He}$ reactions. The ${}^3\text{He}(\vec{d}, p){}^4\text{He}$ reaction has several advantages over the other two. The ${}^3\text{He}(\vec{d}, p){}^4\text{He}$ reaction has a larger figure of merit than the ${}^2\text{H}(\vec{d}, p){}^3\text{H}$ reaction at energies greater than 100 keV. A broad $\frac{3}{2}^+$ s-wave resonance in the ${}^3\text{He}(\vec{d}, p){}^4\text{He}$ reaction at $E_d = 430$ keV leads to a large and isotropic cross section over a large range of energies around the resonance, while the ${}^2\text{H}(\vec{d}, p){}^3\text{H}$ reaction has a low and anisotropic cross section. In addition the ${}^3\text{He}(\vec{d}, p){}^4\text{He}$ reaction is expected to have $A_{yy} = \frac{1}{2}$ at all angles and $A_{zz}(\theta) = \frac{1}{2}(1 - 3\cos^2\theta)$ due to the single s-wave reaction amplitude. The large Q-value of the ${}^3\text{He}(\vec{d}, p){}^4\text{He}$ reaction results in the production of energetic protons which are much easier to detect than the products from the ${}^3\text{H}(\vec{d}, n){}^4\text{He}$ reaction. The ${}^3\text{He}$ targets are also much safer to use than tritium targets.

A deuteron tensor polarimeter that uses the ${}^3\text{He}(\vec{d}, p){}^4\text{He}$ reaction was built and mounted on a plate that can easily be inserted into the back of the LEBF high-voltage scattering chamber. The ${}^3\text{He}$ targets were made by implanting 0.005-cm tantalum foils with 17 keV ${}^3\text{He}$ ions to achieve thicknesses on the order of 10^{17} ${}^3\text{He}/\text{cm}^2$. The protons were detected to the right and left of the beam at a mean angle of 17.5° by a pair of 1500- μm -thick silicon solid-state detectors each with an active area of 600 mm^2 . A piece of .0125-cm-thick tantalum foil was placed before the detectors which reduced the energy of the protons to around 10 MeV and stopped elastically scattered deuterons.

The polarimeter was calibrated by first accelerating the beam to 7 MeV through the FN Tandem to determine the beam polarization with a calibrated high-energy polarimeter.

Figure 5.5-4: Energy dependence of A_{yy} and A_{zz} obtained in the calibration of the ${}^3\text{He}(\vec{d}, p){}^4\text{He}$ polarimeter containing detectors placed at an angle of $17.5 \pm 9^\circ$. The solid line shows the results of the energy-dependent polynomial fits to the calibration points.

Once the polarization was measured the beam was directed into the low-energy polarimeter to determine the analyzing powers. The polarimeter has been calibrated at energies between 113 and 323 keV for both A_{yy} and A_{zz} . Both $A_{yy}(E)$ and $A_{zz}(E)$ are consistent with values expected for the $\frac{3}{2}^+$ resonance. Both sets of data were fitted with an energy-dependent polynomial so that the analyzing powers could be determined at intermediate energies. Plots of $A_{yy}(E)$ and $A_{zz}(E)$ and their associated energy-dependent polynomial fits are shown in Figure 5.5-4. The tensor polarization of a 250-nA, 320-keV deuteron beam can be determined in 10 minutes with a statistical accuracy of 0.01. Future plans include extending the calibration to 672 keV once the upgrade to the LEBF is completed.

5.5.5 CEBAF Hall B Moeller Polarimeter

C. M. Laymon, R. M. Chasteler, D. R. Tilley, H. R. Weller

We are developing a CEBAF hall B beamline polarimeter that will be used to measure the longitudinal electron beam polarization. The polarization will be determined by observing asymmetries in the yields of beam electrons scattered from electrons with a polarization component parallel and with a polarization component antiparallel to the beam direction. The target for this Moeller scattering will be a magnetized foil.

Calculations indicate that the temperature rise at the center of the Moeller target foil for the expected beam conditions in Hall B should be sufficiently small that beam rasterization will not be necessary. Raster magnets are included in the design and a rasterization scheme that takes the large magnification of the polarimeter into account has been developed so that the polarimeter can be used under unusual beam conditions.

The polarimeter will run in coincidence mode and two detectors will be required. The detector design has been changed so that existing Pb/scintillating fiber blocks that were built as prototype calorimeters for the CEBAF Large Acceptance Spectrometer (CLAS) can be used. Each detector will consist of four blocks with the fibers aligned perpendicular to the direction of electron incidence. The detector will have a box geometry with a length of 24.5 cm (about 15 radiation lengths) and a width of 18.4 cm.

We have begun to address some of the subtle issues that affect precision polarization measurements. In particular, we have made some rough calculations on the effects [Lev94] of the motion of the bound electrons on the polarimeter response. Our results suggest that angular smearing of the scattered electron due to atomic motion is comparable to the angular acceptance of the polarimeter. We are planning computer simulations of the polarimeter in which these effects will be taken into account.

[Lev94] L. G. Levchuk, Nucl. Instrum. Methods, A345, 496 (1994).

5.6 An Inverse Compton Gamma-Ray Source for Nuclear Physics

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In response to a suggestion by Dr. Vladimir Litvinenko of the Duke Free Electron Laser Laboratory (DFELL), a study was begun in the summer of 1994 to investigate the feasibility of producing high intensity beams of polarized γ -rays using Compton backscattered laser light from the 1.2 GeV electrons in the DFELL storage ring. The results of our initial simulations confirmed Dr. Litvinenko's claims. It does appear possible to produce γ -ray beams at this facility with intensities of around 10^3 times larger than that available at other sources.

The essential features and design parameters of the DFELL include a LINAC injector (presently operating at 280 MeV), a 1.2 GeV electron storage ring, and the OK4 undulator. This system is capable of producing and storing in an optical cavity over 10^{13} photons in the deep ultraviolet. It is possible to tune the electron beam in a manner which allows these photons to backscatter from an electron bunch, all within the ring. This leads to an intense beam of almost 100% linearly polarized γ -rays whose energy can be readily tuned from about 10 MeV to greater than 200 MeV with an average flux of 10^7 /MeV-sec. Furthermore, beam energy spreads of less than 1% can be obtained by pure geometrical collimation.

Following these initial investigations, it was decided to organize a Workshop in order to review and explore our ideas and our initial findings with experts in the field. Both the technical aspects of γ -ray production and physics applications were included in the program. The TUNL/DFELL High Intensity Gamma Source (HIGS) Workshop was held Dec. 16-17, 1994. Over 35 scientists from 7 countries attended. The workshop confirmed that the means of production appears to be sound, the expected energies, fluxes, beam polarizations and energy resolution seem obtainable. Such a facility would open up a new series of experimental studies in nuclear physics which are not currently possible.

As Figure 5.6-1 shows, the electron bunches pass through the undulator region where they radiate. The resulting photons are captured in an optical cavity. When the photons are properly synchronized with the electrons, the photons pass through the undulator as the electron bunch returns. If the photons and electrons are traveling in the same direction, there is stimulated radiation from the electrons at the same frequency as the photons in the optical cavity. A second electron bunch can be stored in the ring and timed to meet

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Figure 5.6-1: Layout for TUNL-FEL Inverse Compton backscattered γ -ray target area

the photons traveling in the opposite direction and Compton backscattering can then occur which produces the flux of *gamma-rays*.

Expected γ -ray Output

The electron storage ring is designed to produce 1.2 GeV electrons, (the short term goal is for operation at 1.0 GeV), and with the OK 4 undulator photons can be produced from 2.0 eV (≈ 280 nm) to 12.5 eV (≈ 100 nm), and will be bunched into packets of 2-3 cm length. The resulting time structure of the γ -ray beam for a 3 cm electron packet will be 0.1 ns $\sin^2$ pulses separated by 350 ns. For 12.5 eV photons, where the photon packets are 2 cm long, the pulse width will be 0.067 ns.

In Compton scattering, the energy of a scattered particle is determined by its scattering angle. The average energy of photons hitting an experimental target will, therefore, be a function of position, with the highest energy photons striking the center of the target. This allows the experimenter to choose photons of the appropriate energy by collimating the beam or positioning the target appropriately within the beam. At 48 m, the spot size at 90% $E_{\max}$ is 8.2 mm, with an angular divergence of 1.7×10^{-4} rad (0.01°) for the 1.0 GeV electron, 8.2 eV photon configuration ($E_{\max} = 112$ MeV). Likewise, the energy uncertainty can be reduced by choosing a smaller aperture. The total energy uncertainty as a function of position (DE) arises from two sources: the finite spatial distribution of the electrons, and the uncertainty in electron momentum. A 2% energy resolution for $E_{\max} = 12$ MeV can be achieved with a 5 mm aperture. A plot of the photon flux expected for the case of an energy resolution of 1% is shown in Figure 5.6-2 for a range of γ -ray energies. These results were obtained assuming a 100 mA lasing beam and a 10 mA scattering bunch. The design parameter for the ring is for an average current of 1 A.

Detailed Study of the Energy Distribution of the γ -Ray Beam

The energy spectrum of photons emitted into a small circular aperture centered on the

Figure 5.6-2: Photon Flux at various energies for $DE/E=1\%$

axis of the electron beam has been calculated for a representative range of conditions. The spectrum is characterized by a sharp peak at an energy just below the maximum possible energy computed from the nominal beam energy. Above this energy the spectrum falls precipitously, reflecting the fact that only those electrons in the high energy tail of the bunch can give rise to γ 's with these energies. Below the peak there is a long tail arising primarily from the divergence of the beam and the fact that the Compton cross section is flat within a factor of 2. This tail can, however, be essentially eliminated by proper choice of beam optics parameters. This is illustrated in Figure 5.6-3. The asymmetric shape of the spectra makes characterizing their widths by a single parameter difficult if not misleading. The FWHM is probably the best we can do. Results are summarized in the Figure 5.6-4.

The spectra are found to be relatively insensitive to small variations of important electron beam parameters, such as electron energy and bunch size. The effect of changing collimator size was also examined. Collimators smaller than 1 mm in radius yield little improvement of resolution while sacrificing considerable flux. The resolution quickly worsens for collimators larger than 1 or 2 mm.

Beam Degradation and Lifetime

The production of γ -ray photons by scattering off electrons will deplete the electron population of the scattering bunch, with one electron being lost for every γ -ray produced when making γ -rays above 50 MeV. Below this, the 5% ΔE acceptance of the ring means that no electrons are lost. The 8.2 eV photon-1.0 GeV electron configuration produces 4.7×10^8 photons per second over all energies, and therefore depletes the electron bunch by that amount every second. Because the γ -ray flux is proportional to the number of electrons in the scattering bunch, these electrons must be continually replaced for long term operation.

The linear accelerator can inject new electrons into the storage ring at an average current

Figure 5.6-3: Beam spectra through 1 mm aperture for different values of β Figure 5.6-4: FWHM of gamma beam through 1 mm collimator for E_γ .

of up to 10^{10} new electrons/sec. These electrons can be injected into an existing bunch to replace electrons lost during the scattering process. This available filling rate is high enough to compensate for the electron losses of all the configurations listed in this report.

Background

There are two potential background sources of photons. Synchrotron radiation is present in any storage-ring facility. From the geometry of the TUNL-FELL, this source of photons shines in a cone centered 9° from the z axis in the xz plane. The intensity of the photons decreases exponentially from this direction as $e^{-\gamma\theta}$. For the 1 GeV electrons this puts an acceptance of e^{-300} at 9° on the z axis. In addition to the geometric exclusion of synchrotron radiation from the γ -beam, the synchrotron photon energies are all less than 20 keV and can be filtered from the beam easily.

The second source of background radiation originates from the high-energy electrons interacting with the residual atoms in the evacuated beam line. This bremsstrahlung is directed down the beam axis and is at energies comparable to the electron beam. Since the bremsstrahlung produced by the residual vacuum will be our major source of background, we have recently measured it. A $10'' \times 10''$ NaI detector was placed so as to view the straight section of the ring, on the axis where the γ -beam will be produced. Bremsstrahlung spectra were obtained for stored electron energies of 400, 600 and 800 MeV. These spectra are shown in Figure 5.6-5, along with a simulated curve obtained by convoluting the theoretical bremsstrahlung spectrum with the EGS4 simulation of the NaI response function. The results of these tests confirm our expectations. The bremsstrahlung flux which will be present in the γ -beam on target is of the order of 400/sec, most of which is below 50 MeV, and constitutes less than a 0.1% background contribution to our main flux.

Comparison with other facilities

The γ -ray production capabilities of the proposed TUNL/DFELL γ -ray source compares favorably with other Compton backscatter facilities. We compare our projected output with that of other existing and proposed facilities in Table 5.6-1. All listed parameters are representative of conditions when the highest possible photon energy is produced. The efficiency of the proposed TUNL/DFELL system drops considerably at energies over 200 MeV. The TUNL/DFELL yields are based on two electron bunches with currents of 100 mA and 10 mA. The ring is projected to operate at larger currents which could increase the γ -ray flux.

Applications to Studies in Nuclear Physics

Proposals for a range of nuclear physics experiments which take advantage of the unique features of this polarized γ -ray beam facility are presently being developed. These include measurements of the nuclear polarizability via Compton Scattering, and tests of Chiral Perturbation Theory in pion photo production at threshold.

Figure 5.6-5: Simulated and measured bremsstrahlung spectra for $E_e = 400, 600,$ and 800 MeV

Facility	Technique	Pol. Type	E_{γ}^{max} (MeV)	Flux (kHx/MeV)	P_{γ}	Tag. Eff.	ΔE_{γ} (MeV)
LEGS	Compton	Both	333	33	1.0	1.0	5.0
GRAAL	Compton	Both	1800	6	1.0	1.0	15.0
ROKK-2	Compton	Both	1400	1	1.0	1.0	
Spring-8	Compton	Both	3000	1	1.0	1.0	20
CEBAF	Compton	Both	1800	50	1.0	1.0	1.0
TUNL/DFELL	Compton	Linear	220	10000	1.0	Not Tagged	0.8
Mainz	Coh. Brem.	Linear	400	50	0.4	0.5	2.0
Bonn	Coh. Brem.	Linear	1200	10	0.4	0.5	10.0
CEBAF-B	Coh. Brem.	Linear	1800	50	0.4	0.5	10.0
SAL	Off Brem.	Linear	87	6000	0.4	0.4	0.6
Mainz	$\bar{e}$ Brem	Circular	840	50	0.8	0.5	2.0
Bonn	$\bar{e}$ Brem	Circular	2400	5	0.8	0.5	10.0
CEBAF	$\bar{e}$ Brem	Circular	6000	2	0.8	0.5	20.0

Table 5.6-1: Comparison of existing and proposed γ -ray facilities.

5.7 Data Acquisition Systems

5.7.1 Data Acquisition and Analysis for Hall A at CEBAF

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As part of our instrumentation obligation to the Hall-A collaboration, we are developing the event-analysis software package for the first round of collaboration experiments. The present schedule calls for a fully functional event analyzer by Fall 1995. Summaries of the data acquisition hardware and the event analyzer software are given below.

The CEBAF On-line Data Acquisition(CODA) system will be used for data acquisition in Hall A. The primary data bus for the ADC's and TDC's for the event data is Fastbus. The read out of each crate is orchestrated by a Fermi Lab Fastbus Smart Crate Controller(FSCC) which is programmable via ethernet. In the present design, the data will be transferred from each Fastbus readout controller (ROC) into memory buffers in VME and then into the DAQ workstations (HP-700 series), probably via a high-speed fiber network. The synchronization of the triggers and management of system deadtime are done by the CEBAF custom-designed Trigger Supervisor, which resides in a special VXI/VME crate. Most critical design issues have been settled.

The architecture of the event analyzer is designed to support modular programming. The subroutine modules communicate with each other through common data structures. Because speed is an essential feature of an on-line event analyzer, the analyzer routine is organized in blocks so non-essential analysis cells can be skipped during high data rates. At the exit of each block, a decision is made based on cuts on the data to continue analysis of the current event or to return to get the next event. The first version of the Hall-A event analyzer is now available and can be obtained via anonymous ftp from CEBAF. Some practical aspects of the event analysis software are: (1) All software modules (subroutines) are written in standard FORTRAN 77 for portability. (2) The histograms are booked and filled using CERN HBOOK calls. User interface to the histograms is made convenient by using the CEBAF Test Package (CTP). (3) CERN PAW and PAW++ are recommended for graphical interface to the histogrammed data. (4) The on-line data cuts and tests are done using CTP. (5) User interface to internal program parameters and flags is achieved by using CTP. (6) All software modules have access common data structures that contain the raw digitized data, general run information, and quantities calculated in detector specific routines.

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The organization of the software development is as follows. The analyzer shell and support routines (raw-data decoder, general-use include files, general use kinematics routines, statistical information display, the event display, etc.) will be provided by the Hall-A DAQ group, and detector specific routines are to be written by the detector groups.

We have put in operation a DAQ station at CEBAF to be used for testing Hall-A detector systems and for developing analysis software. Benchmark measurements of data transfer and event analysis speeds are planned for the Fall 1995.

5.7.2 Update to the XSYS Manual

H. R. Setze, C. R. Gould, C. R. Howell, P. R. Huffman, N. R. Roberson, J. R. Walston, and W. S. Wilburn

The manual for the TUNL xSYS data acquisition system was converted into $\text{\LaTeX}$ format and updated to reflect the current system configurations.

A new chapter on data acquisition and analysis was added which contains new examples, including a description of storage and analysis of event data and fast spin-flip. Other chapters remain in their previous form with updates and editorial changes. These include a description the LAMPANEL.DAP data acquisition program with several examples, a section on "photo-logging", descriptions of new CAMAC modules, and descriptions of new xSYS commands. New sections were added on the scaler display system and on running a command file from a FORTRAN image. Several obsolete features were removed and archived in an appendix.

The structure of the new manual is now a single document with a complete table of contents and index. The table of contents is shown below.

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5.8 A Dynamically Polarized Proton Target

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The strength of the nucleon-nucleon tensor force at low energies (1–20 MeV) is determined by the magnitude of ϵ_1 , the $^3S_1 - ^3D_1$ mixing parameter. The value of ϵ_1 may be determined by measuring $\Delta\sigma_{L,T}$ - the difference between the total nucleon-nucleon scattering cross sections with target and projectile spins parallel and anti-parallel. The subscripts L and T refer to the cases in which the spins are parallel and transverse to the beam direction. In our experiments, these differences in spin-spin cross sections are determined by measuring the transmission of polarized neutrons through a polarized proton target. We have measured $\Delta\sigma_T$ over the energy range 2–12 MeV using a statically polarized proton target [Wil93].

A dynamically polarized proton target is being constructed to extend these measurements in the transverse geometry and to perform measurements in the longitudinal geometry. The dynamically polarized target enables one to reverse the target polarization frequently in order to cancel systematic effects. The two day cool-down time of the 10mK statically polarized target made frequent polarization reversal or unpolarized background measurements impractical.

The dynamically polarized target will be located in the 59° beam-line at TUNL. The target is 14 mm square and consists of beads of butanol doped with EHBA-Cr(V). The target polarization will be measured by the NMR method. Also, the product of the target thickness and polarization will be determined from the value of $\Delta\sigma_T$ at 1 MeV. Polarized neutrons will be produced by the $^3\text{H}(p, n)^3\text{He}$ reaction at low energies and by the $^2\text{H}(d, n)^3\text{He}$ reaction at higher energies.

In December, 1993, portions of a dynamically polarized target cryostat based on the PSI design [vdB90] were moved from the University of Texas at Austin to TUNL. In the following months, work began on completing the vacuum system and modifying the cryostat to accept a larger target and to enable the magnet to be mounted in either the longitudinal or the transverse geometry.

During the past year, both the ^4He and the ^3He stages of the cryostat have been operated. The NMR and microwave systems were installed. Baratron pressure sensors were installed and the insert was fitted with a static tube connecting the target region to the baratrons. A commercial liquid helium transfer line was modified to allow for automatic operation and an automatic liquid helium filling system was installed. It was necessary to modify the cryostat to permit trouble-free insertion and extraction of the insert carrying the target. It was also necessary to modify some of the cryostat vacuum and ^3He fittings in order to eliminate leaks. Apparatus used to freeze butanol into spherical beads was constructed and the EHBA-Cr(V) dopant was prepared. Butanol targets with various dopant levels have been prepared. A new klystron power supply has been obtained and the microwave system was modified to allow the forward and reflected microwave power to be monitored. The microwave power delivered to the target was determined to be 20 mW by observing the effect of microwave power on the cryostat operating point. Software to record and process the NMR signal and to monitor the operation of the cryostat has been written and tested and an analog interface for the NMR system was constructed. Recently, we measured the thermal equilibrium NMR signals for a butanol target and the background TE signal for an empty target cup at 1K and dynamically polarized a target at 0.5K. A polarization of approximately 60% was obtained, as determined by the NMR signal area. NMR signals from this test are shown in Figure 5.8-1. The target will be moved into the beam line during the coming weeks.

Also during the past year, a new collimator and detector housing were constructed and a new charged-particle polarimeter was installed in the beam line. A mounting frame which will bring the target to the required height was completed and installed in the beam line. Two runs have been scheduled in the near future to test the beam line optics and to measure the polarization transfer coefficient for the $^3\text{H}(p, n)^3\text{He}$ reaction at low energy.

We will continue to refine the software being used to operate the target system, work to improve the accuracy and stability of the NMR system and to optimize the polarization. We expect to begin measurements of $\Delta\sigma_T$ this winter. We are also investigating the possibility of operating this target as a dynamically polarized deuteron target in order to investigate

Figure 5.8-1: NMR signals for a butanol target. Left: Target at thermal equilibrium at 1K (polarization 0.25%). Right: Target dynamically polarized at 0.5K (polarization 60%). Note the difference in scales. In both cases the signal is averaged for 1000 sweeps.

polarized neutron - polarized deuteron scattering.

Reports on our polarized target work have been made at the 1994 Division of Nuclear Physics meeting [See94] and at the 1994 Southeast Section APS meeting [Rai94].

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5.9 Cryogenic Microcalorimeters

A. E. Champagne, D. G. Haase, D. S. Junkin, M. L. Seely

Cryogenic microcalorimeters operate in the millikelvin temperature regime where the specific heat of materials is so small that incident radiation can produce a measurable rise in temperature. In principal, superb energy resolution can be achieved, at the price of low count rates [Fio93]. Our device is composed of a high-sensitivity thermistor and a radiation absorber, both thermally linked to a dilution refrigerator.

Figure 5.9-1: Thermistor response to a 5.5 MeV alpha particle incident at time = 0 and subsequent thermal relaxation. Signal voltage is proportional to the temperature change of the thermistor. In this case the maximum temperature change is about 80 millikelvin.

High-sensitivity thermistor chips for the calorimeters have been fabricated of phosphorous implanted silicon and are being used in a home-built quick turnaround dilution refrigerator. An amplifier system and computer data acquisition system have been assembled to measure the temperature responses of the thermistors. The amplifier includes a JFET preamplifier operating at 100 Kelvin, placed ten centimeters from the thermistor at 110 millikelvin. The data acquisition system includes a high speed data acquisition card operated by a personal computer.

In the past year modifications to the refrigerator were made to allow lower operating temperatures, and more space for the preamplifier and thermal anchoring of the experiment. Micro-coaxial cables were installed to reduce the noise of the system between the preamplifier and room temperature amplifiers. A centering ring for the mixing chamber was designed and installed to reduce microphonics. The entire cryostat was also placed in a sandbox to isolate the experiment from vibrations in the room.

In our recent tests an ^{241}Am source was mounted in the dilution refrigerator vacuum can. Alpha particles from this source are thermalized by a 0.3 milligram tin absorber attached to the silicon thermistor. The response of the thermistor to an incident alpha particle is shown in Figure 5.9-1. The decay time is determined by the heat capacity and thermal link to the dilution refrigerator. The thermal link has been adjusted to provide an optimal count rate without sacrificing energy resolution.

Software has been written to perform data acquisition, optimal digital filtering [Dep93],

Figure 5.9-2: Energy spectrum of ^{241}Am alpha particles shown with a gaussian fit to the data. The measured energy resolution is 330 keV.

curve fitting, analysis and presentation. An acquired ^{241}Am energy spectrum is shown in Figure 5.9-2. An additional computer will allow real time data analysis and data storage.

Our plan for the next year is to improve the energy resolution of our devices by using more sensitive and symmetrically biased thermistors. The biasing will remove a large portion of our microphonic noise. Higher-sensitivity thermistors have been fabricated and will be tested. After optimizing the energy resolution, we plan to measure the beta spectrum of ^{14}C .

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Appendices

I. Graduate Degrees Awarded

Ph.D. Degrees

1. Timothy C. Black, "Proton-Deuteron Elastic Scattering at Very Low Energy," Ph. D. degree, University of North Carolina at Chapel Hill, *Supervisor*: E. S. Ludwig.
2. Jeffrey C. Blackmon, "Measurement of the $^{17}\text{O}(p, \alpha)^{14}\text{N}$ Cross Section at Stellar Energies," Ph.D. degree, University of North Carolina at Chapel Hill, *Supervisor*: A. E. Champagne.
3. C. Randy Bybee, "Application of the Fourier Transform to Quantum Chaos Studies in Nuclear Physics and Data Acquisition for a Compton-Suppressed Gamma-Ray Detector," Ph.D. degree, North Carolina State University. *Co-Supervisors*: G. E. Mitchell and J. F. Shriner, Jr.
4. Gregory J. Schmid, "Radiative Capture of Polarized Protons by Deuterium in the Energy Range $E_p(\text{lab}) = 80 - 0$ keV," Ph.D. degree, Duke University. *Supervisor*: H. R. Weller.
5. Beata Kozłowska, "Precise Determination of the Asymptotic D- to S-State Ratio of the Triton," Ph. D. degree, Silesian University, Katowice, Poland, *Supervisor*: H. J. Karwowski.

Master's Degrees

1. Matthew A. LaBonte, "Angular Distribution Studies of the $^{29}\text{Si}(p, \gamma)^{30}\text{P}$ Reaction," M.S. degree, North Carolina State University, *Co-Supervisors*: G. E. Mitchell and J. F. Shriner, Jr.
2. William Geist, "A Deuteron Tensor Polarimeter for Low-Energy Experiments," M. S. degree, University of North Carolina at Chapel Hill, *Supervisor*: E. J. Ludwig.
3. Bryan J. Rice, "Cross Section and Vector Analyzing Power Measurements of $^4\text{He}(\bar{\gamma}, d)^2\text{H}$ at $E_\gamma = 185\text{--}330$ MeV," A.M. degree, Duke University, *Supervisor*: H. R. Weller.

4. Quiankun Chen, "Neutron Scattering from ^{209}Bi and the Imaginary Part of the Spin-Orbit Interaction," A.M. degree, Duke University, *Supervisor* R. L. Walter.
5. Bret Crawford, "Parity Violation in Heavy Nuclei," A.M. degree, Duke University, *Supervisor* N. R. Roberson.

II. Publications

Articles Published

1. Effects of the Tucson-Melbourne Three-Nucleon Force on Proton Spectra from Kinetically Incomplete Neutron Deuteron Breakup Experiments, H. Witała, J. Golak, W. Tornow, W. Glöckle and D. Hüber, *Phys. Rev. C* **51** 1095 (1995)
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9. Extraction of Parity Violating Matrix Element from Data on Neutron Resonances, J. D. Bowman, L. Y. Lowie, G. E. Mitchell, E. I. Sharapov and Yi-Fen Yen, *Proceedings of the 3rd International Seminar on Interaction of Neutrons with Nuclei*.
10. Vibrations of Surface Atoms Studied by NRRA, M. Berheide, H. W. Becker, L. Borucki, M. Buschmann, N. Piel, C. Rolfs, W. H. Schulte, G. E. Mitchell and J. S. Schweitzer, *Proceedings of Twelfth International Conference on Ion Beam Analysis*.

11. A Deuteron Tensor Polarimeter for Low-Energy Experiments, W. Geist, Z. Ayer, A. C. Hird, H. J. Karwowski and E. J. Ludwig, Nucl. Instrum. Meth. Phys. Res.
12. A Dispersive Optical Model for the Neutron-Nucleus Interaction from -80 to +80 MeV for Nuclei in the Mass Region $27 \leq A \leq 32$, M. A. Al-Ohali, C. R. Howell, W. Tornow, and R. L. Walter, Proceedings of the Eighth Symposium on Polarization Phenomena in Nuclear Physics (1994).
13. Neutron-Proton Analyzing Power at 12 MeV and Charged πNN Coupling Constant, R. T. Braun, W. Tornow, D. E. González Trotter, C. R. Howell, R. Machleidt, C. D. Roper, F. Salinas, H. R. Setze and R. L. Walter, Proceedings of the Eighth Symposium on Polarization Phenomena in Nuclear Physics (1994).
14. Comment on the ${}^7\text{Li}(p, \gamma){}^8\text{Be}$ Reaction at Energies of Astrophysical Interest, H. R. Weller and R. M. Chasteler, Z. Phys. A.
15. Energy Levels of Light Nuclei, $A = 18-19$, D. R. Tilley, H. R. Weller, C. M. Cheves, and R. M. Chasteler, Nucl. Phys. A.

Articles submitted

1. Tensor Analyzing Power A_{yy} for dp Breakup in the Symmetric Constant Relative Energy Configuration, H. Witała, W. Glöckle, J. Golak, D. Hüber, H. Kamada, W. Tornow, E. J. Stephenson and D. A. Low, Phys. Rev. C.
2. Determinations of the Neutron-Neutron Scattering Length a_{nn} from Kinematically Incomplete Neutron-Deuteron Breakup Data Revisited, W. Tornow, H. Witała and R. T. Braun, Few-Body Syst.
3. Evidence for Large Discrepancies Between Data and Calculations for the Kinematically Incomplete Neutron-Deuteron Breakup Reaction, W. Tornow, R. T. Braun, H. Witała and N. Koori, Phys. Rev. C.
4. Ion-implanted ${}^3\text{He}$ Targets for Very Low-Energy Experiments, A. C. Hird, W. Geist, E. J. Ludwig, Z. Ayer and K. A. Fletcher, Nucl. Instrum. Methods Phys. Res.
5. Determination of the Asymptotic D- to S-state Ratio for ${}^3\text{He}$ via $(d, {}^3\text{He})$ Reactions, Z. Ayer, H. J. Karwowski, B. Kozłowska and E. J. Ludwig, Phys. Rev. C.
6. Polarized Proton Capture by Deuterium and the $D(p, \gamma){}^3\text{He}$ Astrophysical S-Factor, G. J. Schmid, R. M. Chasteler, C. M. Laymon, R. M. Prior, D. R. Tilley and H. R. Weller, Phys. Rev. Lett.

7. Sodium Enrichment in A-F Type Supergiants, M. F. El Eid and A. E. Champagne, *Ap. J.*
8. Shell Corrected Particle-hole State Densities for Preequilibrium Reaction Calculations, C. Kalbach, *J. Phys. G.*
9. Consistent Exciton Model Calculations with Shell Structure, Pairing and Isospin Effects, C. Kalbach, *J. Phys. G.*

III. Conference Reports

1. The TUNL Neutron-Proton Scattering Length Experiment, F. Salinas, C. R. Howell, W. Tornow, D. E. González Trotter, T. S. Carman, Q. Chen, C. D. Roper, H. R. Setze, R. L. Walter, H. Witala, I. Šlaus, H. Tang, Z. Zhou, *Bull. Am. Phys. Soc.* **40** 1045 (1995).
2. The TUNL Neutron-Neutron Scattering Length Experiment, D. E. González Trotter, W. Tornow, C. R. Howell, F. Salinas, T. S. Carman, Q. Chen, C. D. Roper, H. R. Setze, R. L. Walter, H. Witala, D. Schmidt, H. Tang, *Bull. Am. Phys. Soc.* **40** 1045 (1995).
3. Development of a Nuclear Spin-Filter Polarimeter for Low-Energy Hydrogen and Deuterium Beams, A. J. Mendez, C. D. Roper, J. D. Dunham and T. B. Clegg, *Bull. Am. Phys. Soc.* **39** 1404 (1994).
4. Shell-Model Transition Strengths in ^{22}Na , A. A. Adams, G. E. Mitchell, J. F. Shriner, Jr., W. E. Ormand and E. G. Bilpuch, *Bull. Am. Phys. Soc.* **39** 1824 (1994).
5. A Compton-Suppressed Spectrometer for the Study of $^{29}\text{Si}(p, \gamma)$, G. A. Vavrina, C. R. Bybee, J. M. Drake, G. E. Mitchell, E. F. Moore, J. F. Shriner, Jr., E. G. Bilpuch, P. M. Wallace and C. R. Westerfeldt., *Bull. Am. Phys. Soc.* **39** 1825 (1994).
6. A High Resolution Study of $^{29}\text{Si}(p, \gamma)$, P. M. Wallace, E. G. Bilpuch, C. R. Westerfeldt, C. R. Bybee, J. M. Drake, M. A. LaBonte, G. E. Mitchell, E. F. Moore, G. A. Vavrina and J. F. Shriner, Jr., *Bull. Am. Phys. Soc.* **39** 1825 (1994).
7. Parity Violation in Neutron Resonances in Thorium, S. L. Stephenson, C. R. Gould, D. G. Haase, L. Y. Lowie, G. E. Mitchell, B. E. Crawford, N. R. Roberson, J. D. Bowman, C. M. Frankle, A. A. Green, J. N. Knudson, S. I. Penttilä, S. J. Seestrom, Yi-Fen Yen, V. W. Yuan, P. P. J. Delheij, H. Postma, E. I. Sharapov, Y. Masuda, H. M. Shimizu, M. Iinuma, A. Masaike, Y. Matsuda and K. Fukuda, *Bull. Am. Phys. Soc.* **39** 1825 (1994).

8. Study of Gamma Background in an Epithermal Neutron Beam, L. Y. Lowie, J. D. Bowman, A. A. Green, S. I. Penttilä, Yi-Fen Yen and Y. Masuda, *Bull. Am. Phys. Soc.* **39** 1825 (1994).
9. Calculation of Neutron Spin Depolarization Due to Imperfections in a Solenoidal Magnetic Field, B. E. Crawford, N. R. Roberson, J. D. Bowman and S. I. Penttilä, *Bull. Am. Phys. Soc.* **39** 1825 (1994).
10. Spins of Epithermal Neutron p-wave Resonances and Parity Violation, H. Postma, F. Gunsing, F. Corvi, K. Athanassopoulos, F. Becvar, J. D. Bowman, B. E. Crawford, P. P. J. Delheij, C. M. Frankle, K. Fukuda, C. R. Gould, A. A. Green, D. G. Haase, M. Inuma, J. N. Knudson, L. Y. Lowie, A. Masaike, Y. Masuda, Y. Matsuda, G. E. Mitchell, S. Penttilä, N. R. Roberson, S. J. Seestrom, E. I. Sharapov, H. M. Shimizu, S. L. Stephenson, Yi-Fen Yen, and V. W. Yuan, German-Dutch Physical Society Meeting Proceedings, 762 (1995).
11. Chaos in Nuclei: A High Resolution Study of $^{29}\text{Si}(p, \gamma)$, E. F. Moore, E. G. Bilpuch, C. R. Bybee, M. A. LaBonte, G. E. Mitchell, J. D. Shriner, J. F. Shriner, Jr., G. A. Vavrina, P. M. Wallace and C. R. Westerfeldt, Nuclear Chemistry Gordon Conference (1995).
12. A Low-Energy Investigation of p-d Scattering, T. C. Black, Z. Ayer, H. J. Karwowski, E. J. Ludwig and L. C. Ma, *Bull. Am. Phys. Soc.* **39** 1409 (1994).
13. A Determination of Vector Analyzing Power in Low-Energy $D(\bar{p}, \gamma)^4\text{He}$ Reaction, L. Ma, H. J. Karwowski, Z. Ayer, T. C. Black and E. J. Ludwig, *Bull. Am. Phys. Soc.* **39** 1403 (1994).
14. Determination of the Asymptotic D- to S-State Ratio of the Triton from sub-Coulomb (d, t) Reactions, B. Kozłowska, Z. Ayer, R. K. Das, H. J. Karwowski and E. J. Ludwig, Proceedings of the Eighth Symposium on Polarization Phenomena in Nuclear Physics, Bloomington, IN, 90 (1994).
15. Determination of the Asymptotic D- to S-State Ratio for ^3He from sub-Coulomb via (d, ^3He) Reactions, Z. Ayer, E. J. Ludwig, H. J. Karwowski and B. Kozłowska, Proceedings of the Eighth Symposium on Polarization Phenomena in Nuclear Physics, Bloomington, IN, 92 (1994).
16. The Use of the $^3\text{He}(d, p)^4\text{He}$ Reaction for Low-Energy Polarimetry, W. Geist, Z. Ayer, A. C. Hird, K. A. Fletcher, H. J. Karwowski and E. J. Ludwig, Proceedings of the Eighth Symposium on Polarization Phenomena in Nuclear Physics, Bloomington, IN, 338 (1994).

17. A Polarized Proton Target for Investigation of $\Delta\sigma_L$ in n-p Scattering, B. W. Raichle, C. R. Gould, D. G. Haase, M. L. Seely, N. R. Roberson, W. Tornow, W. S. Wilburn, G. W. Hoffman and S. I. Penttilä, *Bull. Am. Phys. Soc.* **39** 1821 (1994).
18. Recent Progress in the Development of Cryogenic Microcalorimeters, D. S. Junkin, A. E. Champagne, D. G. Haase and M. L. Seely, *Bull. Am. Phys. Soc.* **39** 1821 (1994).
19. Superdeformed Nuclei near $A = 190$: Results from the New Generation of Detector Arrays, E. F. Moore, *Bull. Am. Phys. Soc.* **39** 1821 (1994).
20. Measurements of Polarized Neutron-Polarized Scattering and the Tensor Force Controversy, W. S. Wilburn, *Bull. Am. Phys. Soc.* **39** 1821 (1994).
21. The ${}^6\text{Li}(p, \gamma){}^7\text{Be}$ Reaction at 80-0 keV, R. M. Prior, C. M. Laymon, H. R. Weller, D. R. Tilley, *Bull. Am. Phys. Soc.* **40** 961 (1994).
22. The ${}^6\text{Li}(\bar{p}, \gamma){}^8\text{Be}$ Reaction to the $2^+T = 0, 1$ state for $E_p = 80-0$ keV, M. A. Godwin, R. M. Chasteler, C. M. Laymon, H. R. Weller, D. R. Tilley, *Bull. Am. Phys. Soc.* **40** 961 (1994).
23. New Experimental Initiatives in Kaon Electroproduction, S. Beedoe, A. Abokor, S. Danagoulia, C. R. Jackson, S. Mtingwa, O. K. Baker, K. Beard, W. W. Buck, T. Eden, R. Madey, K. M. Maung, L. Tang, R. A. Williams, C. C. Chang and P. Markowitz, *Bull. Am. Phys. Soc.* **40** 993 (1994).
24. Mirror States in ${}^{19}\text{F}$ and ${}^{19}\text{Ne}$ and the Astrophysical ${}^{18}\text{F}(p, \gamma){}^{19}\text{Ne}$ Reaction Rate, N. P. T. Bateman, D. W. Bardayan, Y. M. Butt, A. A. Chen, K. O. Yildiz, B. M. Young, P. D. Parker, M. A. Hofstee and A. J. Howard, *Bull. Am. Phys. Soc.* **40** 1033 (1994).
25. Energy Levels of Light Nuclei, $A = 3-20$, available from Triangle Universities Nuclear Laboratory on the World Wide Web, C. M. Cheves, R. M. Chasteler, H. R. Weller, D. R. Tilley and B. L. Doyle, Twelfth International Conference on Ion Beam Analysis, Arizona State University (1995).
26. Measurement of Γ_γ/Γ for the $E_{\text{max}} = 2.646$ MeV State in ${}^{20}\text{Na}$, M. A. Hofstee, J. C. Blackmon, A. E. Champagne, N. P. T. Bateman, Y. Butt, P. D. Parker, S. Utku, K. Yildiz, M. S. Smith, R. B. Vogelaar and A. J. Howard, to appear in *Nuclei in the Cosmos*.

IV. Invited Talks and Seminars

1. New Results in Nucleon-Nucleon Scattering at Low Energies, W. Tornow, International Symposia on High Energy Spin Physics and Polarization Phenomena in Nuclear Physics, Bloomington, IN (1994).
2. Few-Nucleon Studies with Neutrons, W. Tornow, Seminar at the University of Maryland (1995).
3. Selected Topics of the Few-Nucleon Research Program at TUNL, W. Tornow, 15th European Conference Few-Body Problems in Physics, Peniscola, Spain (1995).
4. Atomic Beam Polarized Sources-Recent Progress and Future Possibilities, T. B. Clegg, International Workshop on Polarized Beams and Polarized Gas Targets, Cologne, Germany (1995).
5. Investigations of Ion Beam Extraction System Performance for the TUNL Polarized Ion Source, A. J. Mendez, J. D. Dunham, K. D. Veal, C. D. Roper and T. B. Clegg, SPIN94, The Eighth International Symposium on Polarization Phenomena in Nuclear Physics, Bloomington, IN (1994).
6. Modeling the Hyperfine State Selectivity of a Short Lamb-Shift Spin-Filter Polarimeter, A. J. Mendez, T. B. Clegg and C. D. Roper, SPIN94, The Eighth International Symposium on Polarization Phenomena in Nuclear Physics, Bloomington, IN (1994).
7. Electromagnetic Field Requirements of a Nuclear Spin-Filter Polarimeter, C. D. Roper, A. J. Mendez and T. B. Clegg, SPIN94, The Eighth International Symposium on Polarization Phenomena in Nuclear Physics, Bloomington, IN (1994).
8. Inelastic Scattering of Polarized Protons at Low Energies From Various Medium and Light-Weight Nuclei, A. Plavko, V. Kudriashov, M. Onegin, T. B. Clegg, H. J. Karwowski and R. Varner, SPIN94, The Eighth International Symposium on Polarization Phenomena in Nuclear Physics, Bloomington, IN (1994).
9. The IUCF/TUNL Spin-Filter Polarimeter, V. P. Derenchuk, A. J. Mendez and T. B. Clegg, SPIN94, The Eighth International Symposium on Polarization Phenomena in Nuclear Physics, Bloomington, IN (1994).
10. Parity Violation in Neutron Resonances, G. E. Mitchell, Applications of Chaos in Many-Body Quantum Physics, Institute for Nuclear Theory, Seattle, WA.
11. Experimental Status of Symmetry Breaking in Chaotic Systems, G. E. Mitchell, International Conference on Chaos in Nuclear Physics, Caen, France.
12. Parity Violation in Charged Particle Resonances, G. E. Mitchell, 13th International Conference on the Applications of Accelerators in Research and Industry, Denton, TX (1994).

13. Experimental Status of Symmetry Breaking in Compound Nuclei, G. E. Mitchell, Wigner Symposium, Guadalajara, Mexico.
14. A Minitandem Accelerator and some Applications, E. J. Ludwig, 13th International Conference on the Application of Accelerators in Research and Industry, Denton, TX (1994).
15. The Use of the $^3\text{He}(d, p)^4\text{He}$ Reaction for Low-Energy Polarimetry, E. J. Ludwig, SPIN94, The Eighth International Symposium on Polarization Phenomena in Nuclear Physics, Bloomington, IN (1994).
16. Some Studies of Few-Body Systems at TUNL, E. J. Ludwig, University of Birmingham, England.
17. Some Studies of Few-Body Systems at TUNL, E. J. Ludwig, University of Cologne, Germany.
18. Some Studies of Few-Body Systems at TUNL, E. J. Ludwig, University of Erlangen, Germany.
19. Recent Electromagnetic Studies of Few Body Nuclei, H. R. Weller, Special Meeting of the German Physical Society, Dresden, Germany (1994).
20. Observation of P-Wave Capture in $^7\text{Li}(p, \gamma)^8\text{Be}$ and Astrophysical Implications, H. R. Weller, Nuclear Theory Institute, Seattle, WA (1994).
21. Very Low Energy Polarized Proton Capture Reactions and Astrophysical Implications, H. R. Weller, The American Chemical Society (ACS) Annual Meeting, Washington, D.C. (1994).
22. Radiative Capture Reactions at Very Low Energies and Implications to Astrophysics, H. R. Weller, The Canadian Physics Society (CAPS), Quebec City, Quebec, Canada (1995).
23. New Results in Radiative Capture Studies at Tandem Energies, H. R. Weller, Invited talk at CIAE Institute, Beijing, China (1994).
24. New Results on Polarized Proton Radiative Capture Reactions below 100 keV and Astrophysical Implications, H. R. Weller, Massachusetts Institute of Technology (1994).
25. New Results on Polarized Proton Radiative Capture Reactions below 100 keV and Astrophysical Implications, H. R. Weller, University of Saskatchewan (1994).
26. New Results on Polarized Proton Radiative Capture Reactions below 100 keV and Astrophysical Implications, H. R. Weller, University of Virginia (1994).

27. New Results on Polarized Proton Radiative Capture Reactions below 100 keV and Astrophysical Implications, H. R. Weller, Univeristy of Cologne, Cologne, Germany (1994).
28. The ^{26}Al Problem: A Case of Dogs in the Night-Time?, A. E. Champagne, Physics Colloquium, Princeton University (1994).
29. Few-Body Physics at Low Energies, H. J. Karwowski, Silesian Univeristy, Katowice, Poland.
30. Investigating the Astrophysically Important $E_x = 2.646$ MeV State in ^{20}Na , M. A. Hofstee, 13th International Conference on the Application of Accelerators in Research and Industry, Denton, TX (1994).
31. Search for the Two-Phonon Octupole Vibrational State in ^{208}Pb , E. F. Moore, 13th International Conference on the Application of Accelerators in Research and Industry, Denton, TX (1994).
32. Neutron-Proton Analyzing Power at 12 MeV and Charged πNN Coupling Constant, R. T. Braun, W. Tornow, D. E. González Trotter, C. R. Howell, R. Machleidt, C. D. Roper, F. Salinas, H. R. Setze, R. L. Walter, SPIN94, The Eighth International Symposium on Polarization Phenomena in Nuclear Physics, Bloomington, IN (1994).
33. Probing the Three-Nucleon Force Using Nucleon-Deuteron Breakup Reactions, C. R. Howell, 13th International Conference on the Application of Accelerators in Research and Industry, Denton, TX (1994).
34. Parity Violation in Neutron Resonances, G. E. Mitchell, Florida State University (1995).
35. Parity Violation in Neutron Resonances, G. E. Mitchell, T. H. Darmstadt (1995).
36. The Dispersive Optical Model and Neutron Scattering from ^{208}Pb and ^{209}Bi , R. L. Walter, China Institute of Atomic Energy, Beijing (1994).
37. A Dispersive Optical Model Description for $n + ^{208}\text{Pb}$ and $n + ^{209}\text{Bi}$, R. L. Walter, Institute of Nuclear Physics, Lisbon, Portugal (1995).

V. Seminars at TUNL

1. Jon Engel, University of North Carolina at Chapel Hill (9/8/94)
Microscopic T-Violating Optical Potential: Implications for Neutron Transmission Experiments

2. Hunter Middleton, Princeton University (9/29/94)
Polarizing Noble Gas Nuclei for Target Applications
3. Samuel Danagoulian, North Carolina A & T State University and Yerevan Physics Institute, Armenia (10/6/94)
Channeling Radiation of Electrons in Monocrystals at 4.5 GeV
4. G. C. Kiang, Director, Academia Sinica, Taipei (10/13/94)
Research Activities at the Academia Sinica Institute of Physics
5. Thomas Clegg, University of North Carolina at Chapel Hill (10/20/94)
A New Atomic Beam Polarized Ion Source for TUNL?
6. Christopher Keith, North Carolina State University (10/27/94)
Polarized Neutron-Polarized ^3He Scattering and the Excited States of ^4He
7. Hartmut Schulte, Bochum (11/3/94)
Influence of Electronic Excitation Processes on Yield Curves of Narrow Resonances
8. Akram Mukhamedzhanov, University of Arkansas (12/1/94)
Classical Nuclear Reactions and Nuclear Astrophysics
9. Peter Parker, Yale University (12/8/94)
Explosive Nucleosynthesis in Novae
10. Jeff Blackmon University of North Carolina at Chapel Hill (1/26/95)
Measurement of $^{17}\text{O}(p, \gamma)$ Cross Sections at Stellar Energies
11. Mart Rentmeester, University of Nijmegen (2/2/95)
The Nijmegen Partial Wave Analysis: A Tool between Experiment and Theory
12. Ian Thompson, University of Surrey and University of Notre Dame (2/8/95)
Structure and Reactions of Halo Nuclei
13. Mark Balbes, Ohio State University (2/9/95)
Birth of a Universe: the Primordial Saga
14. Shaheen Rab, Oak Ridge National Laboratory (2/21/95)
Two Body Effects to Magnetic Moments and $M1$ Transitions in Particle-Particle and Particle-Hole Nuclei
15. Zhiqing Mao, University of Pennsylvania (3/2/95)
Nuclei as Laboratories

16. Albert Young, Princeton University (3/7/95)
Tests of Time Reversal Symmetry
17. Stuart Taylor, Brigham Young University (3/9/95)
Determining Alpha-Muon Sticking: the Bottleneck in Muon Catalyzed Fusion
18. Henry Weller, TUNL, Duke University (3/9/95)
A Proposed Gamma-Ray Source for Nuclear Physics Studies at TUNL
19. Dennis Moltz, Lawrence Berkeley Laboratory (3/28/95)
Studies of the r - p Process Nuclei at the Proton Drip Line
20. James Guillemette, Ohio University (3/30/95)
 $^{10}\text{Be}(\alpha, n)^{13}\text{C}$ Angular Distributions and R-Matrix Calculations
21. Gilbert Hoy, Old Dominion University (4/6/95)
Time Domain Nuclear-Resonant Gamma-Ray Spectroscopy
22. Mark Spraker, Indiana University Cyclotron Facility (4/7/95)
Dissociation of 260 MeV Deuterons
23. Robert Clark, Vanderbilt University (4/11/95)
Low p_T Photon Production in Proton-Nucleus Collisions at 18 GeV/c
24. Vera Hansper, Univ. of Melbourne (4/13/95)
Nuclear Astrophysics at the University of Melbourne
25. Carl van Bibber (Lawrence Livermore National Lab) (5/11/95)
Search for Dark Matter Axions
26. Carl van Bibber (Lawrence Livermore National Lab) (5/12/95)
Shining New Light on the Axion
27. Blaine Norum, University of Virginia, Henry Weller and N. Russell Roberson, TUNL, Duke University (5/18/95)
Status Report on the TUNL-FELL Gamma-Ray Beam Project
28. Thomas Clegg, W. Scott Wilburn, Richard Prior, Ed Ludwig, Calvin Howell, Werner Tornow, Chris Gould, TUNL (7/6/95)
Presentation and Discussion of the Physics Justification for an Improved TUNL Atomic Beam Polarized Ion Source
29. Calvin Howell, TUNL (8/3/95)
The New TUNL Computer System

TUNL Safety Talks

1. Catherine Thomas, Environmental Safety Office, Duke University (6/5/95)
Chemical Safety
2. David Jorgenson, Radiation Safety Office, Duke University (6/6/95)
Radiation Safety and Instrumentation
3. Paul Carter, TUNL, Duke University (6/6/95)
TUNL Safety Systems/Tour of TUNL
4. Larry Lloyd, Safety Office, Duke University (6/7/95)
Fire Safety Presentation and Demonstration
5. Paul Carter, TUNL, Duke University (6/7/95)
Safety and Emergency Procedures at TUNL/Tour of TUNL

TUNL Introduction Lecture Series

1. Mike Mikolajewski, Raleigh Value and Fitting Company (6/9/95)
Tube and Pipe Connections
2. Paul Carter, TUNL, Duke University (6/9/95)
Vacuum Systems in an Accelerator Lab
3. Chris Westerfeldt, TUNL, Duke University (6/9/95)
Principles of Accelerator Control Circuits
4. Tony Mendez, University of North Carolina at Chapel Hill (6/12/95)
The Physics of the TUNL Polarized Ion Source and Beam Polarimetry
5. John Dunham, TUNL, Duke University (6/12/95)
Maintenance of the TUNL Polarized Ion Source
6. Mikell Seely, North Carolina State University (6/13/95)
Polarized Target Technology
7. Sidney Edwards, TUNL, Duke University (6/14/95)
An Overview of the TUNL Electronic Shop and Computer System
8. Dinko González Trotter, Duke University (6/14/95)
Experimental Techniques for Low-Energy Neutron Detection
9. Charles Laymon, Duke University (6/14/95)
Experimental Techniques for Gamma-Ray Detection

10. William Geist, University of North Carolina at Chapel Hill (6/14/95)
Experimental Techniques for Charged-Particle Detection
11. Ross Setze, Duke University (6/15/95)
The Data Acquisition System at TUNL