CONTENTS

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 Collaboration[1]

The nucleon-nucleon force is composed of the strong parity conserving (PC) interaction, and the weak parity nonconserving (PNC) interaction. Since the weak interaction violates parity conservation, it 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. Absent enhancements, the parity violating effects are expected to be small, since the PNC interaction has a strength of order 10^{-7} relative to the PC interaction. Polarized low-energy neutron scattering has proven a rich field for testing 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 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. A set of measurements of the pseudoscalar term $(\vec{\sigma}\cdot\vec{k})$ in the total cross section of p-wave resonances, σ_p, has been performed by determining the longitudinal asymmetry

$$P = \left(\sigma_p^+ - \sigma_p^-\right) \Big/ \left(\sigma_p^+ + \sigma_p^-\right)$$

up to neutron energies of several hundred eV. In the two-level approximation

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

where $M = \left\langle s \middle| V^{PNC} \middle| p \right\rangle$ 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 the two-level approximation is abandoned 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 yielded root-mean-squared matrix elements with values $M \approx 1$ meV. This agrees well with the expected estimate $M_{theor} = M_{sp} / N^{1/2}$, where the single particle matrix ele-

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[1] Los Alamos National Laboratory, Los Alamos, NM 87545; TRIUMF, Vancouver, BC V6T 2A3; Joint Institute for Nuclear Research, 141980 Dubna, Russia; Kyoto University, Kyoto 606-01, Japan; National Laboratory for High Energy Physics, 1-1 Oho, Tsukuba-shi 305, Japan; University of Technology, P.O. Box 5046, 2600 GA, Delft, The Netherlands.

ment is taken as $M_{sp} \approx 0.5$ eV and $N \approx 10^6$ is the number of quasiparticle 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 [Bow90] and ^{232}Th [Fra91]. 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 the workshop on time reversal invariance and parity violation held in Dubna.

The polarized proton filter system consists of 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 ~70% were achieved.

The new high count-rate 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. Fast discriminators are used to produce a fixed shape pulse for each neutron detected. These 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 detector now is finished. The detectors are pure CsI, 12" long and approximately 4"x4" 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 located in the 56-meter counting house. The evacuated beam pipe through which the polarized beam is transported from the spin-flipper to the target is wrapped with wire to provide a guide field to maintain the spin orientation of the neutrons.

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, ^{107}Ag, and ^{109}Ag, and performed a capture measurement on ^{113}Cd (with a preliminary version of the capture detector). The experimental asymmetry $\varepsilon = (N_+ - N_-) / (N_+ + N_-)$ is shown in Figure 1.1-1 for the 63-eV p-wave resonance in ^{239}U. Note that this is approximately a 100σ effect. Preliminary analysis yields the following numbers of parity violations with greater than 2.3σ statistical significance –– ^{238}U (5), ^{232}Th (8), ^{115}In (10), ^{107}Ag (3), ^{109}Ag (3), ^{113}Cd (4). The unexpected sign correlation in ^{232}Th longitudinal asymmetries remains. Excluding ^{232}Th, the new data yield longitudinal asymmetries which have 18 plus values and 11 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. The correlation remains very interesting from a nuclear structure viewpoint.

Two review papers based on TRIPLE results have been published. G.E. Mitchell is a co-author of "Recent Advances in the Study of Parity Violation in the Compound Nucleus" [Bow93] and N.R. Roberson is a co-author of "Recent Developments in the Study of Parity Violation in Neutron p-Resonances" [Fra93].

We continue to plan for neutron tests of time-reversal invariance. These experiments are challenging, since they require both a polarized neutron beam and a polarized or aligned target. They have attracted our interest because of the large enhancements associated with CN resonances. We are negotiating with the National Laboratory for High Energy Physics (KEK) at Tsukuba, Japan. We could utilize the unique capabilities developed there for polarizing and analyzing neutron spins with laser-pumped ^{3}He cells for future tests of time reversal invariance.

[Bow90] J.D. Bowman *et al.*, Phys. Rev. Lett. **65**, 1192 (1990).

[Bow93] J.D. Bowman, G.T. Garvey, Mikkel B. Johnson and G.E. Mitchell, Ann. Rev. Nucl. Part. Sci. **43**, 829 (1993).

[Fra91] C.M. Frankle *et al*., Phys. Rev. Lett. **67**, 564 (1991).

[Fra93] C.M. Frankle, S.J. Seestrom, N.R. Roberson, Yu.P. Popov and E.I. Sharapov, Phys. Part. Nucl. **24**, 401 (1993).

[Fra94] C.M. Frankle *et al.*, *Time Reversal Invariance and Parity Violation in Neutron Reactions,* ed. C.R. Gould, J.D. Bowman and Yu.P. Popov (World Scientific, Singapore, 1994) p. 204.

[Pen94] S.I. Penttila *et al*., *ibid*., p. 198.

[Yen94] Yi-Fen Yen *et al.*, *ibid,* p. 210.

Figure 1.1-1 Transmission yield in the vicinity of the 63.5-eV p-wave resonance in ^{238}U (bottom) and transmission asymmetry ε (top).

1.1.2 Parity-Violation Tests with Charged Particles

J.F. Shriner, Jr.[1], *G.E. Mitchell*

Parity-violation tests with charged particles are under consideration. Such tests in light- to medium-mass nuclei (A≤50) would complement the measurements with neutron resonances in heavy nuclei by the TRIPLE collaboration (Section 1.1.1). 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, and 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 have searched these data for adjacent resonances which have the same spin but opposite parity and which have a measured alpha width for the natural parity resonance. Sixty-two pairs of resonances were identified which met these criteria.

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

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

where $\rightarrow (\leftarrow)$ denotes polarization in the direction of (opposite to) the beam. Since to first order A_z is proportional to V, the matrix element of H_{PV}, the ratio A_z/V is a suitable measure of the relative enhancements due to the resonances. We also calculated the analyzing power component A_x. Since A_x also is proportional to V, A_x/V is a suitable measurement of the enhancement in measurements of that quantity.

We then generalized to consider every unnatural parity resonance observed in our data, whether or not the adjacent level had the same angular momentum and opposite parity. We adopted the following criteria: Two-state 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 8 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 the (p,α_0) reactions; we also calculated the value of A_z for the (p,α_0) reaction integrated over 4π. With these constraints the number of unnatural parity resonances considered rose to 134.

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[1] Tennessee Technological University, Cookeville, TN.

The results depend dramatically on energy, angle, and the specific resonance parameters. A suitable figure of merit for $A_z(\theta)$ is $\beta_{P_z} = (A_z / V)^2 \, d\sigma / d\Omega$, with a corresponding quantity applying for $A_x(\theta)$, 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 1.1-1.

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 a recent paper [Shr94]. At present the feasibility of these experiments is under consideration. The proposed experiments require a number of developments, including improvement in the polarized beam stability, improved understanding of the spatial dependence of the beam polarization, and development of large-solid-angle detectors.

Figure 1.1-2 The quantities A_z/V, $d\sigma/d\Omega$, and β_P as a function of energy at $\theta_{c.m.} = 180^\circ$ for a pair of resonances in ^{40}Ca. The vertical arrows at the top indicate the locations of the two resonances.

[Shr94] J.F. Shriner, Jr., and G.E. Mitchell, Phys. Rev. C**49**, R616 (1994).

1.2 Time-Reversal-Invariance Measurements

1.2.1 A Test of P-even Time Reversal Invariance with MeV Neutrons

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

We present results from a search for parity-conserving, time reversal noninvariance (PC TRNI) in nuclear physics recently carried out at TUNL. The measurement investigates the PC TRNI fivefold correlation (FC) term $\vec{s}\cdot\left(\vec{I}\times\vec{k}\right)\vec{I}\cdot\vec{k}$ in the neutron-nucleus forward scattering amplitude. Here, $\vec{s}$ is the spin of the neutron, $\vec{k}$ is the momentum of the neutron, and $\vec{I}$ is the spin of the target. The first measurement of the FC was reported by Koster [Kos91]. In the present work we use the $D\left(\vec{d},\vec{n}\right)$ source reaction and a higher target alignment to gain a factor of fifteen improvement in sensitivity to the FC term, yielding the most precise direct test of parity-conserving time reversal invariance in nuclear physics.

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

$$\sigma^{\pm}=\sigma_0\left(1+\sqrt{\frac{15}{8}}P_n\hat{t}_{20}A_5\sin 2\theta\right)$$

where P_n is the polarization of the neutron beam, $\hat{t}_{20}$ is the tensor alignment of the holmium target with respect to the crystal symmetry axis, 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 2θ angular signature of the FC term. A sequence of measurements of the transmission asymmetry $\varepsilon_5(\theta) = [N^+(\theta) - N^-(\theta)]/[N^+(\theta) + N^-(\theta)]$ as a function of angle θ, can be fit to the form C + D sin 2θ (C, D constants) to yield

$$A_5 = D/\left(\sqrt{\frac{15}{8}}P_n\hat{t}_{20}n\sigma_{tot}\right)$$

where n = 0.058 atoms/b is the target thickness and σ_{tot} is the total cross section (5.0 b at E = 6.7 MeV).

The holmium target is rotated from 0° to 360° and back to 0° 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 6.7 MeV, where the deformation effect cross section crosses zero [Kos94]. The monitor-normalized asymmetry $\varepsilon_5(\theta)$ for a sequence of 688 runs is shown in Figure 1.2-1.

Figure 1.2-1 The normalized detector asymmetry $\varepsilon_5(\theta)$ as a function of run number. Each value corresponds to four minutes of data at a given angle in the sequence 0° → 360° → 0°.

There is no evidence for a sin 2θ variation in the asymmetry, and a fit to these data yields a coefficient D = (2.9 ± 5.9) x 10^{-6}. The PC TRNI spin correlation coefficient A_5 = (1.1 ± 2.3) x 10^{-5} is consistent with time reversal invariance.

The A_5 value can be converted to a TRNI optical potential value of V_5 using the calculation of Hnizdo and Gould [Hni94]. We find V_5 = 1 ± 1 keV, from which an order of magnitude estimate of $\alpha_T \sim V_5/(50 \text{ MeV}) \sim 2 \times 10^{-5}$ is inferred. To compare to the values of α_T quoted by Haxton [Hax94], a microscopic calculation of V_5 is needed, for example, using the T-violating $\rho^{\pm}$ exchange potential of Simonius [Sim75]. Such calculations are in progress [Eng94]. Preliminary results show that a term of form of the FC does indeed emerge from a microscopic folding model calculation, but its magnitude is smaller than the above estimate due to the spin dependent structure of the ρ exchange potential.

This is the most precise direct test of parity-conserving time reversal invariance in nuclear physics. An improvement of a factor of five to ten appears possible using a larger solid angle and segmented plastic detector.

[Kos91] J. E. Koster *et al.*, Phys. Lett. **B267**, 23 (1991).
[Kos94] J. E. Koster *et al.*, Phys. Rev. **C49**, 710 (1994).
[Hni94] V. Hnizdo and C. R. Gould, Phys. Rev. **C49**, R612 (1994).
[Hax94] W. C. Haxton, A. Höring and M. J. Musolf (to be published).
[Sim75] M. Simonius, Phys. Lett. **B58**, 147 (1975).
[Eng94] J. Engel (private communication).

1.2.2 A microscopic T-violating optical potential: Implications for neutron-transmission experiments

J. Engel[1], *C.R. Gould, V. Hnizdo*

Until now there has been no credible way to connect the results of aligned-target, polarized-neutron transmission experiments to fundamental sources of T-violation. Within the standard model, T-violating P-conserving (TVPC) effects must be tiny, but in extended models this may not be the case. Here we take a first step in using neutron-transmission experiments to test any such models: Through the construction of a microscopic T-violating optical potential, we show how to relate the TVPC observable A_5 [Kos91, Hni94]—related to the difference between total cross sections for spin-up and spin-down neutrons on an aligned target—to TVPC meson-nucleon coupling constants. The problem of constraining fundamental models of T-violation then reduces to physics at the meson/nucleon scale -- namely a description of the effective TVPC vertex in terms of quarks and gluons.

The unique TVPC ρ-exchange interaction is [Sim75, Hax94]

$$V^{\rho}_{1,2} = \frac{m_\rho^3 g_\rho^2 \bar{g}_\rho \mu_V}{4\pi M^2} \frac{e^{-m_\rho r_{12}}}{m_\rho^3 r_{12}^3} \left(1 + m_\rho r_{12}\right)(\sigma_1 - \sigma_2)\cdot \mathbf{l}\left[\tau_1 \times \tau_2\right]_3 \ ,$$

where $\mathbf{r}_{12} = \mathbf{r}_1 - \mathbf{r}_2$, $\mathbf{l} = \mathbf{r}_{12} \times \frac{1}{2}(\mathbf{p}_1 - \mathbf{p}_2)$, μ_V = 3.70 n.m. is the isovector nucleon magnetic moment, M is the nucleon mass, g_ρ = 2.79 is the normal strong ρNN coupling, and $\bar{g}_\rho$ is a dimensionless ratio of the TVPC coupling to g_ρ. This notation is taken from [Hax94], where limits on $\bar{g}_\rho$ were deduced from limits on the electric dipole moments of the neutron and ^{199}Hg.

Figure 1.2-2 shows the optical potential $\bar{U}(r)$ derived from $V^{\rho}_{1,2}$ for neutron scattering from ^{165}Ho. The curve looks very different from a typical volume or surface optical potential, reflecting the nonlocal nature of the Simonius exchange potential. It is small both at the origin and the surface, peaking somewhere in between.

Including the TVPC potential alongside the strong optical potential U [Hni94] in, e.g., the coupled-channels code CHUCK, we can calculate the spin-correlation coefficient A_5 for any value of $\bar{g}_\rho$, or vice versa. Figure 1.2-3 shows A_5 as a function of neutron-energy for $\bar{g}_\rho$ = 1.

The published measurement of A_5 at 2 MeV [Gou94] results in an upper limit on $\bar{g}_\rho$ of about 0.5, a value that must be increased by a factor of about 3 to account for short-range repulsion between nucleons [Hax94]. The additional analysis in Ref. [Hax94] then implies a limit on α_T, the ratio of typical T-violating to strong two-body matrix elements, of about 1.5 x 10^{-2}. A recently completed experiment has improved the bound on A_5 by a factor of about 15, however [Gou94], and a further order of magnitude is anticipated, potentially resulting in bounds on α_T of order 10^{-4}; this would make neutron-transmission experiments competitive with measurements of atomic dipole moments. [Hax94] also derives another limit, roughly an order of magnitude smaller still, from measure-

[1] University of North Carolina, Chapel Hill.

ments of the neutron dipole moment, but that value depends linearly on the parity-violating pion-nucleon coupling, the size of which has been estimated but is not known reliably.

This work has been submitted for publication and is available from the nuclear theory preprint bulletin board under nucl-th/9408003.

[Kos91] J.E. Koster *et al.*, Phys. Lett. **B267**, 23 (1991).
[Hni94] V. Hnizdo and C.R. Gould, Phys. Rev. **C49**, R612 (1994).
[Sim75] M. Simonius, Phys. Lett. **B58**, 147 (1975).
[Hax94] W.C. Haxton, A. Höring, and M. Musolf, to appear in Phys. Rev. D.
[Gou94] C.R. Gould *et al.*, in *Proceedings of the Conference on Intersections between Particle and Nuclear Physics,* St. Petersburg, Florida, 1994 (to be published).

Figure 1.2-2 The radial part of the TVPC optical potential $\overline{U}$ (with $\bar{g}_\rho = 1$).

Figure 1.2-3 The spin-correlation coefficient A_5 as a function of neutron energy for $\bar{g}_\rho = 1$.

1.2.3 Detailed-Balance Time-Reversal-Invariance Tests

J.M. Drake, E.G. Bilpuch, G.E. Mitchell, J.F. Shriner, Jr.[1]

Bunakov and Weidenmüller [Bun89] suggested that large enhancements of time-reversal-invariance (TRI) violation might be observed in tests of detailed balance near two interfering resonances. The magnitude of the enhancement depends on the detailed spectroscopic properties of the resonances involved. We have utilized our large collection of (p,α) resonance data to consider the time-reversal-invariance (TRI) violation enhancement in realistic circumstances. We identified 41 pairs of adjacent resonances which have the same (or probably the same) J^π for the targets ^{23}Na, ^{27}Al, ^{31}P, ^{35}Cl, and ^{39}K.

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

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

[1] Tennessee Technological University, Cookeville, TN.

where $k = 2\pi/\lambda$ and g is the usual statistical factor. The collision matrix elements were evaluated by assuming a Hamiltonian $H = H_0 + iH'$ and following the approach used by Moldauer [Mol68], assuming only internal mixing and only two interfering states. Experimentally determined laboratory widths were then used to obtain the differential cross sections. (In the earlier work [Bun89] generic values were used for the widths.) To first order, Δ is proportional to the matrix element W of the time-reversal-violating part of the Hamiltonian (H').

The results are strongly energy- and angle-dependent, and the maximum values of Δ/W for a pair of resonances also range over several orders of magnitude. Since the relative enhancement varies so strongly with energy, angle and resonance pair, one must consider a specific pair of resonances and specific experimental conditions in order to evaluate the merits of a detailed balance test of time reversal invariance. Of course, a large value of Δ is not the only factor to be considered in evaluating the merits of a particular experiment. For example, resonances with larger values of Δ often have smaller cross sections. A suitable figure of merit is the quantity $\beta_T = (\Delta / W)^2 d\sigma / d\Omega$. To minimize the time necessary to reach the level of sensitivity W_c, one should measure where β_T is a maximum. The values of β_T for the 41 resonance pairs considered range over 14 orders of magnitude!

For a specific pair of 2^+ resonances in ^{32}S at E_{cm} = 3.1356 and 3.1490 MeV, the values of Δ/W, $d\sigma/d\Omega$, and β_T are shown in Figure 1.2-4. If one assumes that a null value for Δ can be measured at the level of 10^{-2} (the limit obtained by Driller *et al.* [Dri79] in their classic detailed balance experiment), then the implied upper limit for W is of the order of 2 eV. The strong interaction matrix element is of order MeV. The simplest estimate for the upper limit on α_T (the ratio of the strength of the T-violating interaction to the T-conserving interaction) is just the ratio of the two matrix elements: $\sim 10^{-6}$. It is conventional to express symmetry-breaking effects in terms of spreading widths. For time reversal invariance $\Gamma^{TRIV} = 2\pi \langle W^2 \rangle / D$. For this excitation energy in ^{32}S the average level spacing for 2^+ states is about 50 keV. This yields an estimate of an upper limit on Γ^{TRIV} of 5×10^{-4} eV. This is much smaller than obtained from previous measurements.

It appears that the limits on TRI violation obtained from detailed balance tests can be significantly reduced. These results are summarized in a recent paper [Dra94].

Figure 1.2-4 Δ/W, $d\sigma/d\Omega$, and β_T as a function of energy at $\theta_{c.m.} = 180^\circ$ for two resonances in ^{32}S. The arrows at the top indicate the energies of the two resonances.

[Bun89] V.E. Bunakov and H.A. Weidenmüller, Phys. Rev. C **39,** 70 (1989).
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[Dri79] H. Driller *et al.*, Nucl. Phys. **A317**, 300 (1979).
[Mol68] P.A. Moldauer, Phys. Rev. **165**, 1136 (1968).

1.3 Quantum Chaos in Nuclei

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

A.A. Adams, E.G. Bilpuch, G.E. Mitchell, W.E. Ormand[1], J.F. Shriner, Jr.[2]

In an attempt to find alternative signatures for chaos in nuclei, we are examining electromagnetic transition strengths. Several previous analyses with the interacting boson model [Alh92] and the Lipkin-Meshkov-Glick model [Mer93] have suggested that tran-

[1] University of Tennessee, Knoxville, TN and Oak Ridge National Laboratory, Oak Ridge, TN.
[2] Tennessee Technological University, Cookeville, TN.

sition strengths in chaotic regions follow $\chi^2(\nu = 1)$ distributions and that the distribution moves toward $\chi^2(\nu < 1)$ as the dynamics become regular. We are examining a set of ≈ about 85,000 B(M1) and B(E2) values calculated with the shell model code OXBASH for the nuclide ^{22}Na; states with total angular momentum $J \leq 6$ and isospin $T \leq 2$ are included.

The first step in our analysis was to unfold the energy dependence of the eigenvalues. Then we used the method outlined by Alhassid and Novoselsky [Alh92] to normalize the individual B values to their local average. We have grouped the data by spin, by energy, and by transition character. All our results thus far are consistent with $\nu = 1$; Figure 1.3-1 shows the distributions and fit for isoscalar transitions when each set of data is divided into four energy regions. These results suggest that ^{22}Na is chaotic at all energies.

Figure 1.3-1 Distributions of B(M1) and B(E2) values calculated for isoscalar transitions in ^{22}Na. The four plots show the results when the calculated values are divided into four energy regions. Each group is consistent with a $\chi^2(\nu = 1)$ distribution, suggesting that there is no energy dependence in this distribution.

[Alh92] Y. Alhassid and A. Novoselsky, Phys. Rev. C **45**, 1677 (1992).
[Mer93] D.C. Meredith, Phys. Rev. E **47**, 2405 (1993).

1.3.2 Resonances in ^{30}P

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

We have designed, built, and installed a Compton-suppressed spectrometer (see Sect. 5.7.2) for use in the TUNL High Resolution Laboratory. The impetus behind this project was to obtain a nearly complete level scheme in ^{30}P, in order to study the role of chaos and of isospin breaking in this nucleus. In the past year the first data with the new system have been obtained. The first resonance studied was the E_p = 2.2238 MeV resonance, since this was strong in the capture channel and a previous measurement by Reinecke et al. [Rei85] provided a direct comparison with our results. Reinecke had assigned the resonance state J = 2 and T = 1. We have identified 9 primary transitions from the resonance state, which agrees with the results of Reinecke et al. We show the branching ratios obtained from our analysis and compare them with the previous results in Figure 1.3-2; the overall agreement is excellent. Based on our analysis of the branching ratios, and on more detailed analysis of the angular distributions measured by Reinecke, we agree with the J = 2 assignment of Reinecke, and we assign positive parity to the state. However, the isospin is not yet determined.

Several additional resonances in ^{29}Si(p,γ) have been studied, most of them near E_p = 2.5 MeV and a few at low energies. A sample spectrum from the E_p = 1.3286 MeV resonance is shown in Figure 1.3-3. In addition we are reexamining the region E_p = 1 – 2 MeV for previously unobserved resonances.

Figure 1.3-2 Comparison of the branching ratios measured in the present experiment for the E_p = 2.238 MeV resonance in ^{29}Si(p,γ) with the branching ratios measured by Reinecke et al. for this resonance. Reinecke's values are offset slightly in energy so that the two symbols can be distinguished from each other. Error bars are shown for the present measurements.

[1] Tennessee Technological University, Cookeville, TN.

Figure 1.3-3 Gamma-ray spectrum obtained at the E_p = 1.3826 MeV resonance in ^{29}Si(p,γ).

[Rei85] J.P.L. Reinecke et al., Nucl. Phys. **A435**, 333 (1985).