1 Fundamental Symmetries in the Nucleus

1.1 Parity-Mixing Measurements

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

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This is a final summary of the results of the TRIPLE collaboration studies of parity violation.

The relative strength of the weak parity nonconserving (PNC) part of the nucleon-nucleon force compared with the strong parity conserving (PC) interaction is about 10^{-7}. Resonances formed with low-energy polarized neutrons show strong PNC effects due to mixing of nuclear levels of the same spin and opposite parity. In heavy nuclei the combination of statistical and kinematic enhancements amplify the PNC effects by 10^4 to 10^6 in the helicity dependence of the low-energy neutron cross section.

To study the neutron-nucleus effective weak interaction the TRIPLE collaboration used the high-flux epithermal neutron beam at the Manuel Lujan Neutron Scattering Center (MLNSC) at the Los Alamos Neutron Scattering Center (LANSCE). Our analysis is statistical – the PNC matrix elements are considered random variables. The statistical analysis yields root-mean-squared PNC matrix elements *without* the need to know the details of the individual wave functions.

We developed a large-area, high-polarization proton target for polarizing the neutron beam, a neutron detector for transmission experiments with large samples, and a large solid angle pure CsI detector for capture experiments with isotopic samples. We also developed a multi-level analysis program that includes all known resonances (in order to determine the shape of the background) and that properly incorporates the effects of the asymmetric beam energy resolution function and Doppler broadening on the resonance shape. All of the data have been reanalyzed with this improved approach. The results for each nuclide studied are given below, as well as references for the papers that present the results for individual nuclides. First the overall results are summarized.

In ^{232}Th all 10 statistically significant PNC effects below 250 eV have the same sign. This "sign correlation" led to a great deal of theoretical activity, but no clear conclusion

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as to the origin of the effect. Above 250 eV a complete analysis cannot be performed since the resolution is not sufficient to resolve the weak p-wave resonances. However, by combining all of the data and focusing on regions of interference minima (between large s-wave resonances) one can observe PNC effects in the energy region above 250 eV. In the energy range 250 to 2000 eV we observe two effects with the same sign as the ten effects at lower energy and four with the opposite sign [Sha00]. These six effects are only a very small fraction of the PNC effects that would be observed with much better resolution.

Excluding ^{232}Th, our data yield longitudinal asymmetries which have 36 positive values and 23 negative values (the sign of the 0.7 eV resonance in ^{139}La is taken as positive). This suggests that the sign correlation observed in ^{232}Th is specific to that nuclide, and is not a general feature of the weak nucleon-nucleus interaction. The localization in energy of the sign effect in ^{232}Th, as well as the evidence for statistical behavior elsewhere, supports local doorway state models.

An overall perspective on parity violation in neutron resonances is presented in a recent article in Reviews of Modern Physics [Mit99], where parity violation in the compound nucleus is considered as an example of the breaking of a discrete symmetry in a chaotic system. A comprehensive review [Mit01] has been published in Physics Reports. In this latter review all of the TRIPLE experimental results are presented in one place. We conclude that the rms PNC matrix elements are qualitatively consistent with theoretical expectations, and that the individual weak spreading widths are consistent with an overall constant or slowly varying mass dependence, but that there are local fluctuations in the values of the weak spreading width.

Results for Individual Nuclides

The results are given for each nuclide studied. Measurements were performed on natural targets for the transmission measurements and on separated isotopes for the capture measurements. Statistically significant parity violation asymmetries are defined here as 3σ effects.

Results near A = 230

^{238}**U** – The uranium target was measured in transmission. Since the target was depleted to 0.2% ^{235}U, the target is essentially pure ^{238}U. Analysis of 24 p-wave resonances yields 5 statistically significant PNC effects [Cra98].

^{232}**Th** – Thorium was measured in transmission; natural thorium is essentially monoisotopic. Analysis of 24 p-wave resonances below 250 eV yields 10 statistically significant PNC effects, all of which have the same sign [Ste98]. This strengthens the evidence for the non-statistical sign-correlation effect. Above 250 eV there are a number of PNC effects of both signs [Sha00]. The thorium data also were used to determine the magnitude of the off-resonance PNC effect. A value of $(0.5\pm1.6) \times 10^{-6}$ was obtained [Mit00].

Results near A = 110

^{93}**Nb** – Natural niobium (100% ^{93}Nb) was measured in transmission. Analysis of 18 p-wave resonances yields no PNC effects [Sha99]. From the absence of effects we obtain an upper limit for the rms matrix element and thus an upper limit for the weak spreading width. The value is anomalously low.

^{103}**Rh** – Natural rhodium (100% ^{103}Rh) was measured in transmission. Analysis of 32 *p*-wave resonances gives 4 PNC effects [Smi99].

Palladium

Natural palladium consists of several isotopes. We performed parity violation measurements on natural palladium in transmission and also studied parity violation on enriched ^{106}Pd and ^{108}Pd targets with the capture detector. In order to aid in the isotopic identification of the resonances we also studied the spectroscopy of enriched ^{104}Pd and ^{110}Pd targets with the capture detector.

^{104}**Pd** – Analysis of 3 *p*-wave resonances yields 1 PNC effect.

^{105}**Pd** – Analysis of the transmission data (23 *p*-wave resonances) yields 3 PNC effects.

^{106}**Pd** – An enriched ^{106}Pd target was studied with the capture detector. Analysis of 21 *p*-wave resonances yields 2 PNC effects.

^{108}**Pd** – An enriched ^{108}Pd target was studied with the capture detector. Analysis of 21 *p*-wave resonances indicates no PNC effects.

Results for ^{106}Pd and ^{108}Pd were published earlier [Cra99]. Recently results have been published on the neutron spectroscopy [Smi02a] and on the PNC effects in the palladium isotopes [Smi02b].

Silver

Natural silver is 51.8% ^{107}Ag and 48.2% ^{109}Ag. Natural targets were studied in transmission. In order to aid in the isotopic identification, an enriched ^{107}Ag target was studied with the capture detector.

^{107}**Ag** – Natural silver was measured in transmission. A group at IRMM, Geel, Belgium, studied the same enriched target mentioned above in order to determine resonance spins. Analysis of 15 *p*-wave resonances yields 8 PNC effects [Low99].

^{109}**Ag** – Natural silver was measured in transmission. The combination of the transmission and capture measurements identified many new resonances in ^{109}Ag. Neutron capture was studied with an enriched ^{109}Ag target at IRMM in order to determine resonance spins. Analysis of 9 *p*-wave resonances yields 4 PNC effects [Low99].

^{113}**Cd** – An enriched ^{113}Cd target was studied with a preliminary version of the capture detector. Analysis of 23 *p*-wave resonances gives 2 PNC effects [See98].

^{115}**In** – Natural indium (95.7% ^{115}In and 4.3% ^{113}In) was studied in transmission. An enriched ^{115}In target was also studied with the capture detector. In addition IRMM studied an enriched ^{115}In target and determined many resonance spins. Analysis of 36 *p*-wave resonances yields 9 PNC effects [Ste00].

^{117}**Sn** – An enriched ^{117}Sn target was studied with the capture detector. Analysis of 28 *p*-wave resonances gives 4 PNC effects [Smi01].

Antimony

Natural antimony is 57.25% ^{121}Sb and 42.75% ^{123}Sb. Natural targets were studied in transmission. In order to aid in isotopic identification, an enriched ^{121}Sb target was studied with the capture detector.

^{121}**Sb** – Natural antimony was measured in transmission. Analysis of 17 *p*-wave resonances yields 5 PNC effects in ^{121}Sb [Mat01].

^{123}**Sb** – Natural antimony was measured in transmission. Analysis of 5 *p*-wave resonances yields 1 PNC effect in ^{123}Sb [Mat01].

^{127}**I** – Natural iodine (100% ^{127}I) was measured in transmission. Analysis of 20 *p*-wave resonances yields 8 PNC effects [Mat01].

^{133}**Cs** – Natural cesium (100% ^{133}Cs) was measured in transmission. Although the level density is high and the enhancement factors large, analysis of 22 *p*-wave resonances yields only 1 PNC effect [Sha99]. The weak spreading width for ^{133}Cs is the smallest that we have measured.

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1.2 Quantum Chaos in Nuclei

1.2.1 Chaos and Symmetry Breaking in the s-d Shell

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Statistical studies of nuclear eigenvalues and transitions have provided much of our understanding of chaotic behavior in nuclei. Because the symmetries of the system play a vital role in these analyses, such studies have the potential to provide new and unique insights into the role of broken symmetries. We studied the approximate symmetry isospin in N = Z = odd nuclei. For these nuclei the states of different isospin coexist at all excitation energies, thus enhancing the effects of symmetry breaking.

Our initial studies were of the eigenvalue distribution in ^{26}Al [Shr90]. Although isospin symmetry is broken by only about 3%, this small symmetry breaking has a large effect – in agreement with theoretical expectations. This result is of interest because this was the first explicit proof that a small symmetry breaking (magnitude α) can have a large effect on the statistical distributions, provided that the level spacing D is sufficiently small. That is, the effect depends on the ratio $\lambda = \alpha/\mathrm{D}$. Following our initial measurements there were several theoretical analyses, as well as measurements in "analog" systems that mimic random-matrix theory – microwave resonances in superconducting cavities and acoustic resonances in quartz crystals. We then focused on a series of measurements to establish a complete level scheme for ^{30}P [Gro00]. The resulting eigenvalue distributions are consistent with those for ^{26}Al.

The reason that our studies are the only test of the effect of symmetry breaking on the statistical distribution in a quantum system is the requirement of data of extremely high quality. The eigenvalue set must be both complete (few or no missing levels) and pure (few or no levels with unknown or misassigned quantum numbers); otherwise the measures which employ eigenvalues tend to be severely biased [Shr92]. We have now initiated preliminary measurements on a nuclide with different symmetry breaking characteristics, the N = Z = even nuclide ^{28}Si. In order to expedite the experiment, the initial goal is not complete spectroscopy (and complete transition data), but instead the eigenvalue distributions of the positive parity states. This will significantly reduce the scale of the experiment.

After our initial studies of eigenvalues, we turned our attention to the effect of symmetry breaking on the distributions of electromagnetic transition strengths. Although transition strengths have been widely studied in nuclei, there were no previous direct tests of the effect of symmetry breaking on the distribution of transition strengths and there were no theoretical predictions. However, there were heuristic arguments – all suggested that the

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distributions would remain Porter-Thomas (PT) even in the presence of symmetry breaking. For both ^{26}Al [Ada98] and ^{30}P [Shr00] the reduced transition probability distributions are different from the PT distribution. Our measurements have prompted theorists to examine this question. Barbosa, Guhr and Harney [Bar00] and Hussein and Pato [Hus00] have now studied this general problem within the framework of random-matrix theory and conclude that the distribution is changed from the standard PT distribution. Although there is qualitative agreement between theory and experiment, in the sense that a deviation from the PT distribution is predicted, no detailed analysis of the transition data has yet been performed.

The random-matrix analysis of the eigenvalue distributions in the presence of symmetry breaking appears to describe the data completely. The effect of the breaking of a discrete symmetry on the eigenvalue distribution is thus generic. However, it is not clear that random-matrix theory is sufficient to explain the variety of effects caused by the symmetry breaking on the nuclear electromagnetic transitions. Although the statistics are not conclusive, there are indications that the transition-strength distributions depend on transition properties such as multipolarity or their electric or magnetic character. Clearly these properties are not in the random-matrix formulation. Therefore, the effect of symmetry breaking on the electromagnetic transitions appears to have both a dynamic and a kinematic feature.

This topic is being explored in two major directions. First there is a clear need for a good statistics measurement of the effect of symmetry breaking on the transition strengths. The group at Technical University Darmstadt under Richter measured the effect of symmetry breaking on the eigenvalue distributions with two coupled cavities [Alt98]. They are now planning to measure the effect on the transition strengths with a similar system. This should provide a very good and much more extensive data set. It is anticipated that these data should be explained by random-matrix theory (that is, the kinematical part of the effect).

To explore the dynamical aspects, we propose to consider shell-model calculations – which should come closer to simulating the dynamical effects. In addition to the standard shell-model calculations that conserve isospin, we also consider calculations for which isospin is not conserved in the shell-model Hamiltonian. Within this framework we can determine empirically the effects of the symmetry breaking on the transition-strength distributions. Preliminary analysis of reduced electromagnetic transition probabilities calculated for the nuclides ^{22}Na, ^{26}Al, and ^{34}Cl using the shell-model code OXBASH indicates deviations from the Porter-Thomas distribution when isospin is broken. The magnitude of the deviation appears to depend on the nature of the transition (electric or magnetic, dipole or quadrupole, isoscalar or isovector). This issue is now being explored.

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