LA-UR- 96-2744

Title:

Study of Parity Nonconservation with Epithermal Neutrons

CONF-960690--11

Author(s):

Susan J. Seestrom, J.D. Bowman, B.E. Crawford, P.P.J. Delheij, T. Haseyama, J.N. Knudson, L.Y. Lowie, A. Masaike, Y. Matsuda, G.E. Mitchell, N. R. Roberson, S. Penttila, YuP. Popov, H. Postma, E.I. Sharapov, S. Stephenson, Y.F. Yen, V. Yuan (Los Alamos National Laboratory, P-23)

Submitted to:

5th International Conference on Applications of Nuclear Techniques "Neutrons in Research and Industry", June 9-15, 1996

Los Alamos
NATIONAL LABORATORY

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Study of Parity Nonconservation with Epithermal Neutrons

S. J. Seestrom[1], J. D. Bowman[1], B. E. Crawford[2,3], P.P.J. Delheij[7], T. Haseyama[8], J.N. Knudson[1], L. Y. Lowie[3,4], A. Masaike[8], Y. Matsuda,[8] G.E. Mitchell[3,4], N. R. . Roberson[2,3], S. Penttila[1], Yu.P. Popov[5], H. Postma[6] E. I. Sharapov[5], S. Stephenson[3,4], Y. F. Yen[1], V. Yuan[1]

[1]Los Alamos National Laboratory
Los Alamos, NM 87545 USA

[2]Duke University
Durham, NC 27708 USA

[3]Triangle Universities Nuclear Laboratory
Durham, NC 27708 USA

[4]North Carolina State University
Raleigh, NC 27965 USA

[5]Joint Institute for Nuclear Research
141980, Dubna, Russia

[6]University of Delft
Delft, The Netherlands

[7]TRIUMF
Vancouver, British Columbia, Canada V6t 2A3

[8]Physics Department, Kyoto University
Kyoto 606-01, Japan

ABSTRACT

I describe a new generation of experiments studying the weak interaction between nucleons. Measurements of the effect of this interaction are few in number and the significance of the observed effects are generally small. It is well known that the weak interaction violates parity. This was first experimentally established by C. S. Wu through measurement of an asymmetry of electrons emitted in the beta-decay of polarized ^{60}Co. The measured asymmetry was large because beta decay is a weak interaction process. For a process in which the strong interaction can contribute, we expect much smaller asymmetries, of order 10^{-7}.

1 INTRODUCTION

In the work I will describe here we study the effects of the weak interaction through the signal of the parity violation associated with that interaction. There are two basic classes of experiment used to detect parity violation. The first relies on the measurement of a cross section or width that would vanish if parity were conserved. One example of this type of experiment in nuclear physics is the decay of an unnatural parity state to a 0^+ nucleus and an α-particle. Such measurements have been made for two nuclei: $^{16}O(2^-) \Rightarrow ^{12} C(g.s.) + \alpha$ [Ref. 1] and $^{20}Ne(1^+) \Rightarrow ^{16} O(g.s.) + \alpha$ [Ref. 2]. Parity-violating widths as small as $10^{-10} eV$ have been measured in these experiments. The interpretation of these results requires a detailed knowledge of the nuclear structure which is generally not available.

The second class of experiments involves a measurement of pseudo-scalar observables that are odd under parity inversion. These involve correlations between spin and linear angular momenta, for example circular polarization of γ-rays $(\sigma_\gamma \cdot k_\gamma)$ or longitudinal analyzing power $(\sigma_p \cdot k_p)$. One set of such measurements has involved measuring γ decays from parity-mixed doublets in light nuclei. The observable is the γ-ray circular polarization P_γ or, if the excited state has been produced with polarization, the γ-ray asymmetry A_γ. Measurements of P_γ in ^{18}F yielded a results[3–5] consistent with zero, as did experiments in ^{21}Ne [Ref. 6]. The Seattle group was able[7] to produce the 110 keV level of ^{19}F in a polarized state and subsequently measured an asymmetry of the decay γ rays. The nuclear structure of the levels involved must be known in order to relate these measurements to the underlying interaction. In the case of ^{18}F and ^{19}F the nuclear matrix elements are calibrated by beta decay of the mirror nuclei.

Another member of the second class of experiments is the measurement of longitudinal analyzing powers. Such measurements have been made in the $p+p$ system at a number of incident proton energies.[8–10] The control of systematic errors in these experiments at the level of 10^{-7} is very difficult. In some cases corrections are made to the data that are as large as the remaining effects. The most significant measurement of a non-zero, parity-violating analyzing power[9] was made at $E_p = 45$ MeV and is $A_L = (-1.5 \pm 0.22)10^{-7}$.

In contrast to the 10^{-7} asymmetries measured in pp scattering, very large asymmetries have been measured in $n + A$ at low energies. Alfimenkov,[11] measured transmission of a polarized epithermal neutron beam through a number of samples. They saw very large asymmetries for certain compound nucleus levels. The largest of these was $P_T = 7.3\%$ for a resonance at 0.73 eV in ^{139}La. This is an amazingly large effect of the parity-violating weak interaction in nuclear physics. Before I describe the subsequent work that has utilized the compound nucleus as an amplifier for the weak interaction, I will present a brief review of the physics of the compound nucleus.

2 COMPOUND NUCLEUS

An epithermal neutron incident on a nucleus will excite states at an excitation energy of 6 to 8 MeV in the compound nucleus. At this excitation energy the level spacings are of order 10's of eV as compared to 100's of keV near the ground state. Two processes can occur: potential scattering, in which the neutron is scattered from the overall nuclear potential, and resonance scattering, in which the neutron excites a specific state in the compound nucleus. The potential scattering appears as a more or less energy independent *background* underlying the compound nucleus resonances.

The scattering is characterized by the orbital angular momentum of the neutron, $l = 0$ (s-wave) or $l = 1$ (p-wave). At energies below a few hundred eV the s-wave partial width is much greater than the p-wave width. For reactions on spin 0 targets, the s-waves result in compound nuclear states with angular momentum $J = 1/2$; the p-waves can couple to form either $J = 1/2$ or $J = 3/2$.

We can see that the compound nucleus is a system of a closely spaced levels, of both positive and negative parity. What happens in the presence of a parity non-conserving weak interaction? The positive and negative parity levels will be mixed; the mixing can be described in perturbation theory since the weak interaction causing the mixing is much weaker than the strong interaction that formed the initial eigenstates. The mixing amplitude is proportional to the matrix element of the weak interaction between s and p states divided by the energy difference between the two states. The effect thus becomes larger when the level spacing decreases.

Bunakov and Gudkov[12] have derived an expression for the cross section asymmetry P introduced by the parity-violating mixing of s- and p-wave levels. Their expression is:

$$P = 2\frac{\langle \phi_s \mid H_w \mid \phi_p \rangle}{(E_p - E_s)} \frac{\gamma_s^n}{\gamma_p^n}. \qquad (1)$$

Here E_p and E_s are the energies of the p- and s-wave states, H_w is the weak Hamiltonian, and γ_s^n and γ_p^n are the s- and p-wave partial width amplitudes. The energy denominator results in a *dynamical* enhancement, which is of order 10^3 times larger for these compound nuclear states than for single particle states near the ground state. The ratio of partial width amplitudes γ_s^n/γ_p^n is of order 100. This is the so-called *structural* enhancement. The combination of these two effects results in enhancements of order 10^5 larger than are found in parity-mixing of low-lying single-particle levels.

From the above discussion, we see that there are very large, several percent, effects due to parity violation in the compound nucleus. I have presented arguments that make the magnitude of these effects plausible. Experimentally, the parity violation is measured by looking at pseudo-scalar observables. The vectors available to form pseudo-scalar products are the neutron momentum k_n, the neutron spin σ_n, the target spin I_t, the photon spin σ_γ, and the photon momentum k_γ. Using these one can measure neutron spin rotation, neutron helicity $(\sigma_n \cdot k_n)$ dependence of both total cross section and capture cross section, $(\sigma_n \cdot k_\gamma)$ dependence of the capture cross section, and circular polarization of capture γ-rays. In this paper I will discuss only neutron helicity dependence measured for the total cross section and for the neutron capture cross section.

3 TRIPLE Measurements at LANSCE

The schematic layout of a transmission measurement of the helicity dependence of the total cross section is shown in Fig. 1b. The elements of the experiment are an intense source of neutrons, a spin filter to polarize the neutron beam, a spin flipper to periodically reverse the neutron spin, a target, and a detector to count the neutrons that are transmitted through the target. The signal of parity violation is simply a difference in counting rate between neutrons with spin parallel and anti-parallel to the beam direction.

The TRIPLE group is carrying out transmission measurements at the Los Alamos Neutron Scattering Center (LANSCE). Our apparatus has been described in detail in Ref. 13. At LANSCE a proton storage ring is used to compress the 500 μsec beam pulse from the LAMPF accelerator into a pulse of about 250 nsec. The beam extracted from the PSR strikes a tungsten neutron production target that is surrounded by moderating material to produce a flux of low energy neutrons. The shielding around the production target is penetrated by well-collimated neutron flight paths. Our experiment is located on a flight path extending to a detector located at 60m. The long flight path is necessary to obtain sufficient energy resolution to resolve states up to a few hundred electron volts.

The neutron beam is polarized by taking advantage of the fact that the singlet np cross section is much larger than the triplet cross section over a large energy range. When the unpolarized neutron beam passes through a sample of polarized protons one spin state is selectively attenuated.[14] The protons are contained in NH_3 material in which polarization centers have been induced by irradiation. The protons are polarized by the dynamic nuclear polarization technique in a 5 Tesla magnetic field at a temperature of near 1 Kelvin. The microwave pumping

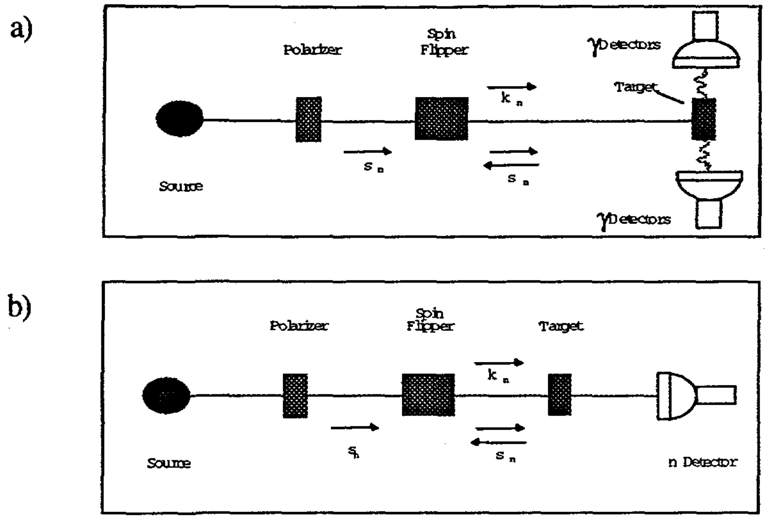

Figure 1: Schematic of experimental layout for capture a) and transmission b) measurements of the helicity dependence of the total cross section

frequency is 140 GHz. The magnetic field is uniform to a part in 10^4 over a diameter of 80 mm. We have achieved proton polarizations of better than 90% , but the neutron polarization has been about 70%. A thicker target could improve the neutron beam polarization obtained.

The relative polarization is monitored run by run using standard NMR techniques. The absolute magnitude of the neutron beam polarization is required to extract the parity-violating asymmetry P from the data. We perform this calibration using the large asymmetry for the 0.73 eV resonance in ^{139}La. We have measured this asymmetry independent of neutron beam polarization by replacing the spin filter with a second Lanthanum sample. The parity violation in the 0.73 eV resonance is used to both polarize and analyze the beam. Using this technique we measured[15] the asymmetry for the 0.73 eV resonance to be $P = 9.7 \pm 0.3\%$.

Following the polarizer is a magnetic spin flipper to allow a fast reversal of neutron spin. The transmission sample is mounted in the downstream end of the spin flipper inside a sample cryostat that allows us to cool the samples to 70 Kelvin to reduce the Doppler-broadening of the neutron line shapes. We have instrumented spin transport all the way to 60 meters so that we can study PV in neutron capture with a detector located in the 60m detector building.

We have two different detector systems. The first is a ^{10}-B loaded liquid scintillator detector[16] for use in transmission. The second is a segmented capture gamma-ray detector made of CsI(pure) material.[17]

The large neutron flux at LANSCE has enabled us to perform measurements over a large range of neutron energies. For samples that are available in sufficient quantity, 0.5-1.0 Kg, transmission measurements are the most efficient. Figure 2 shows an example of the quality of data we are now able to obtain. Raw asymmetry and transmission spectra are shown for ^{238}U. One can see a number of strong s-wave resonances, as well as shallower dips due to p-waves. In the asymmetry spectrum in the upper part of the figure one can clearly see a large positive asymmetry near 63.5 eV, as well as a large negative effect near 45 eV.

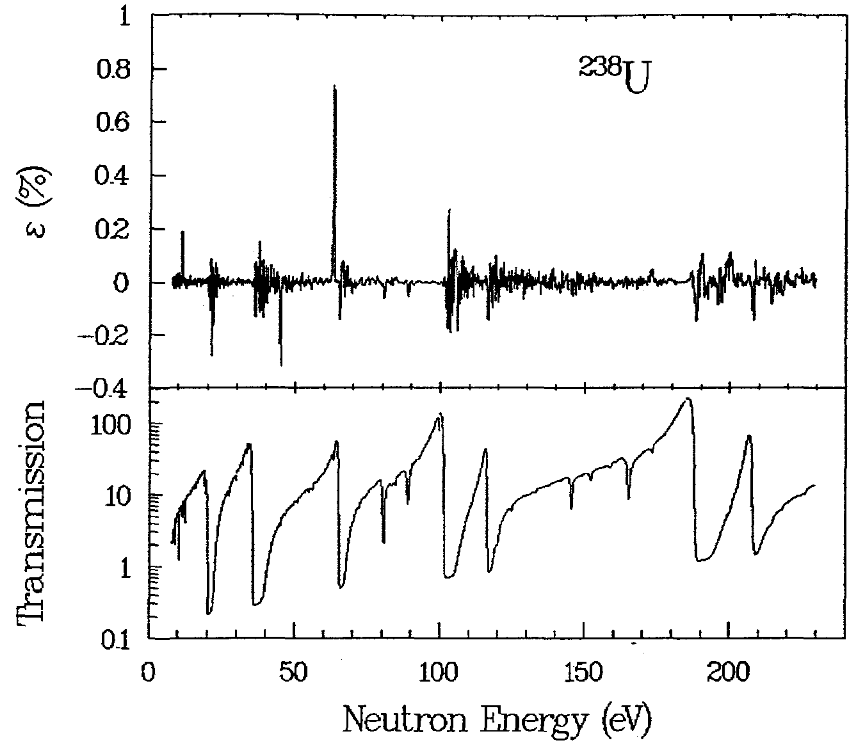

Figure 2: Raw asymmetry and transmission spectra for ^{238}U

3.1 Preliminary Results

Preliminary analysis has been made of the ^{238}U data shown above. We find five resonances that exhibit parity-violating asymmetries of greater than 3 sigma significance; three have positive asymmetries (11.3, 63.5, and 173.2 eV) and two have negative asymmetries (45.2 and 89.2 eV). This data set has much improved statistical significance over our earlier data[18] due to major improvements in the experimental apparatus. It should be noted that analysis of these data have been much facilitated by the measurement of the spins of the resonances at GEEL[19] All five of the resonances that exhibit non-zero asymmetries were determined by the GEEL group to have J=1/2, and in fact there are only two J=1/2 resonances for which we do not see a significant effect.

We have also repeated the earlier measurements[20] on ^{232}Th. Here we find seven significant effects (for resonances at 8.3, 38.2, 47.1, 64.5, 128., 167, and 197 eV), and all seven are positive.

Transmission measurements were also made on a samples of natural Indium, Siver, and Niobium. In 1992 capture measurements were made on an isotopic ^{115}In sample in order to identify the resonances belonging to that isotope.[21] The fitting of these data are in progress, but so far we have identified five significant effects in ^{115}In. We also made measurements on Ag and Nb; nine significant effects were seen in Ag but none were seen in Nb. The lack of any significant effects in Nb might be due to a target that was too thick, resulting in a number of p-waves being *black*.

In addition to the transmission measurements described above, we made capture measurements on an isotopic sample of ^{113}Cd. For isotopically enriched samples, usually available in 100-300 gm quantities, the capture method is the most sensitive. The BaF_2 detectors used were less than optimum and we ran this experiment for only four days of beam. Nonetheless, we measured three significant asymmetries, two positive (102 and 290 eV) and one

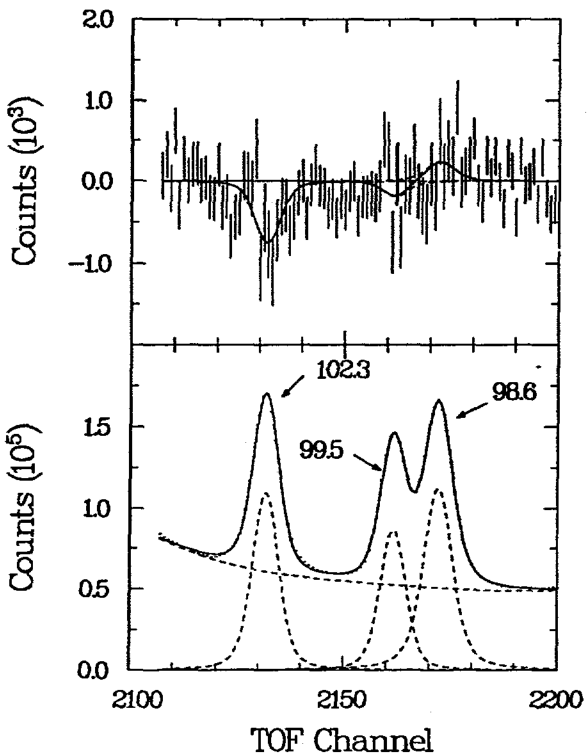

Figure 3: Neutron capture on ^{113}Cd. The upper curve is the difference between spin up and spin down, and lower part is the sum

negative (374 eV). A portion of the spectra near 100 eV for the sum and difference of the two neutron sin states are shown if Figure 3. This is the first time that multiple PV asymmetries have been observed in a single nucleus using the neutron capture reaction.

Figure 4 shows the preliminary results for the value of P extracted for the nuclei discussed above. The solid circles represent the asymmetries of greater than 2σ statistical significance. From this plot one can see that we observe many effects in each nucleus.

4 ANALYSIS

It seems that parity violation is ubiquitous in the compound nucleus; almost each $J = 1/2$ p-wave resonance exhibits parity violation. Although this is in itself interesting, we would like to be able to relate the measured parity violation to the matrix elements of the under-lying weak interaction. An examination of Eqn. 1 shows that this is straightforward in the case of two-state mixing if the parameters E_s, E_p, γ_s, and γ_p are known. In

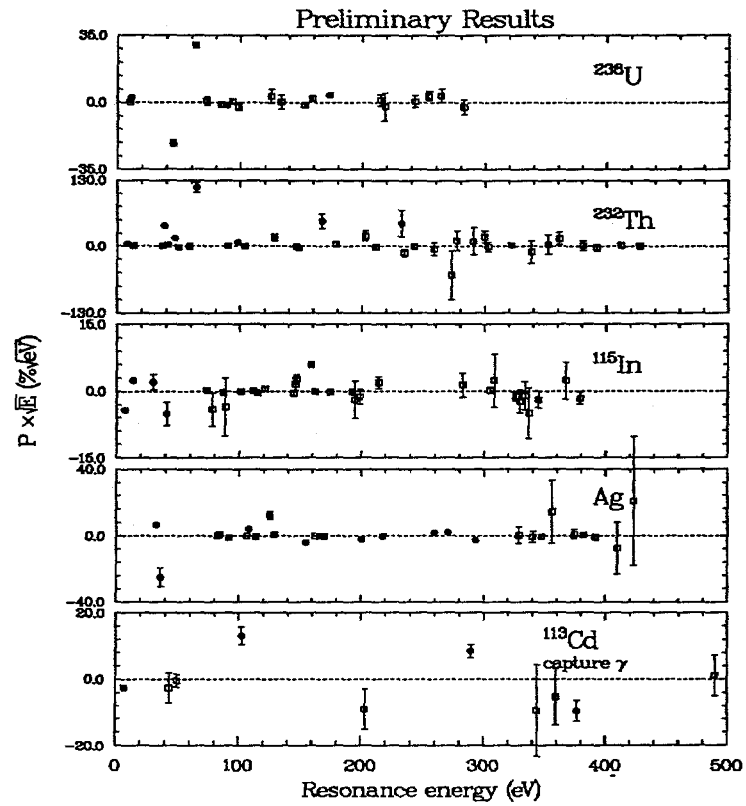

Figure 4: Preliminary asymmetries measured for ^{238}U, ^{232}Th, ^{115}In, AG, and ^{113}Cd. The asymmetries have been multiplied by the square root of the resonance energy to remove the expected energy dependence of the extracted asymmetry

general, however, there are contributions from mixing with a number of s-waves. When there are contributions from many levels the parity violating asymmetry P_i in the i^{th} p-wave is given by:

$$P_i = \sum_j A_{ij} V_{ij}, where A_{ij} = \frac{2}{(E_p - E_s)} \frac{\gamma^n_{sj}}{\gamma^n_{pj}} \tag{2}$$

The subscripts i and j refer to the i^{th} p-wave and the j^{th} s-wave. The measured P_i are therefore linear combinations of many matrix elements V_{ij} and we cannot extract the matrix element between two specific levels.

The statistical nature of the wave functions involved allows us to extract the root-mean-square (rms) value of V_{ij} for all the levels in a given nucleus. The individual matrix elements can be treated as Gaussian random variables having mean zero and variance M^2. It can be shown[22] that the P_i, normalized by the sum of A_{ij}, are Gaussian variables drawn from the same distribution as V_{ij}. The distribution of measured parity-violating asymmetries can therefore be used to estimate M, the rms parity-violating matrix element. We have performed a preliminary maximum likelihood analysis to extract an estimate of M from both the Thorium and Uranium data sets. The result is $M = 0.58^{+0.50}_{-0.25}$ meV for ^{238}U and $M = 1.39^{+0.55}_{-0.38}$ meV for ^{232}Th.

The nucleon-nucleon (NN) potential can be successfully described by a meson exchange potential. The mesons that must be included are a function of the energy at which the potential is being calculated. At low energies, only the lightest mesons need be included. The meson-exchange picture can be used to describe the weak NN interaction by using the strong meson-nucleon coupling at one vertex and the weak meson-nucleon coupling at the other. Desplanques, Donoghue, and Holstein[23] have estimated the meson coupling constants in the Glashow-Weinberg-Salam model. The PV meson exchange potential allows the nuclear PV measurements to be connected with the underlying quark model interaction.

Johnson, Bowman, and Yoo[24] have developed a theory to relate the mean-square PV matrix element M^2 to the parameters of the PV meson exchange potential. They first make a connection between M^2 and the PV potential $\alpha_p U_2$ of their model (α_p gives the strength). They find that

$$M^2[keV^2] = 2.6\,\alpha_p^2. \tag{3}$$

Nearly all of the PV interaction, as characterized by α_p, is explained by the exchange of π and ρ mesons only. The contributions of the ρ and the π were found to be nearly equal. M^2 was calculated from various theoretical models for the meson coupling constants. All predictions gave a value of M within one standard deviation of the experimental value.[24]

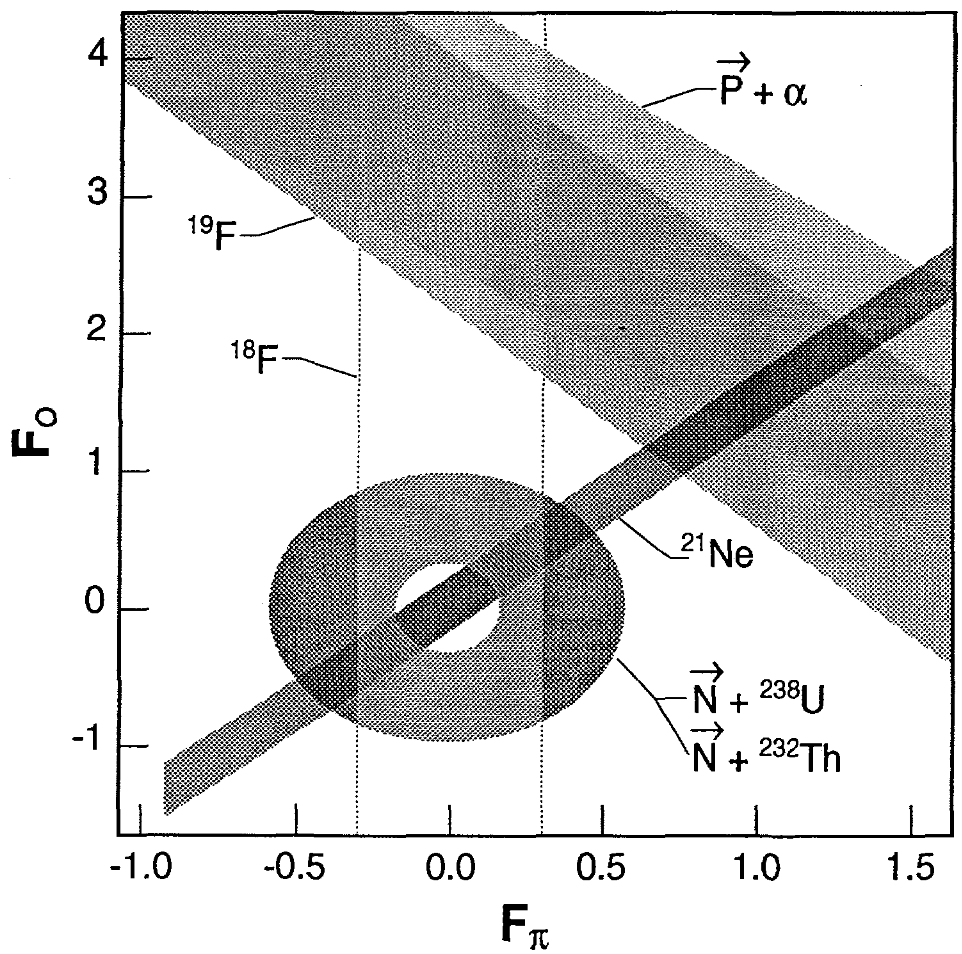

Figure 5: Limits on F_π and F_0, the weak isovector and isoscalar coupling constants obtained from various experiments

Figure 5 shows the limts set on the isoscalar ρ-meson coupling $F_0$and the isovector π-meson coupling F_π by the data on Thorium and Uranium. The data definitely rule out both constants being zero (as expected since non-zero effects were measured). This graph also show limits obtained from parity mixing in the light nuclei ^{19}F, ^{18}F, and ^{21}Ne, of which only ^{19}Ne revealed an effect different from zero. The ^{18}F measurement defines $F_1 = 0$. There is no joint solution that agrees with all three measurements. It should be noted that the ^{21}Ne result is regarded as least certain because of nuclear structure uncertainties in the analysis.

The width in the neutron-data curve will be reduced with the final analysis of the data discussed here. This is in strong contrast to the situation in light nuclei, where there is little prospect for improvement. This initial attempt to related the parity non-conservation observed in the compound nucleus shows promise for obtaining information on the details of the weak interaction between nuclei.

5 SUMMARY

The high intensity, pulsed polarized neutron beam at the Manuel Lujan Neutron Scattering Center has been used to measure parity-violating asymmetries in compound nucleus resonances. Because of the high peak intensity and good time-of-flight resolution, we are able to measure many cases of parity violation in a given nucleus, with accuracy as good or better than 1%. We are able to apply a statistical model to the resulting data set to extract the mean square parity-violating matrix element. Initial attempts have been made to relate the matrix element extract from our data to the coupling constants of the weak meson exchange interaction between nucleons. The final analysis of the data near mass 100 will allow us to look for a mass dependence in the extracted matrix element, which will allow a more stringent test of the model relating M^2 to the meson exchange interaction.

6 REFERENCES

[1] K. Neubeck, H. Schober, H. Waffler, Phys. Rev. C10, 320 (1974).

[2] L. K. Fifield, W. N. Catford, S. H. Chew, E. F. Garman, D. M. Pringle, Nucl. Phys. **A394**, 1 (1983).

[3] C. A. Barnes, *et al.*, Phys. Rev. Lett. **40**, 840 (1978).

[4] G. Ahrens, *et al.*, Nucl. Phys. **A390**, 486 (1982).

[5] P. G. Bizetti, *et al.*, Lett. Nuovo Cimento **29**, 167 (1980).

[6] K. A. Snover, R. Von Lintig, E. G. Adelberger, H. E. Swanson, T. A. Trainor, Phys. Rev. Lett. **41**, 145 (1978).

[7] E. G. Adelberger, H. E. Swanson, M. D. Cooper, W. Tape, T. A. Trainor, Phys. Rev. Lett. **34**, 402 (1975).

[8] V. Yuan, *et al.*, Phys. Rev. Lett. **57**, 1680 (1986).

[9] S. Kistrin, *et al.*, Phys. Rev. Lett. **58**, 1616 (1987).

[10] D. E. Nagle, *et al.*, in *High Energy Physics with Polarized Beams and Targets*, edited by G. H. Thomas, AIP Conference Proceedings No. 51, p. 224.

[11] V. P. Alfimenkov, S. B. Borzakov, Vo Van Thuan, Yu. D. Mareev, L. B. Pikelner, A. S. Khrykin, and E. I. Sharapov, Nucl. Phys. **A398**, 93 (1983).

[12] V. E. Bunakov and V. P. Gudkov, Nucl. Phys. **A401**, 93 (1983).

[13] N. R. Roberson, C. D. Bowman, J. D. Bowman, P. P. J. Delheij, C. M. Frankle, C. R. Gould, D. G. Haase, J. N. Knudson, G. E. Mitchell, S. Penttila, H. Postma, S. J. Seestrom, J. J. Szymanski,S. A. Wender, S. H. Yoo,v. Yuan, and X. Zhu, Nucl. Inst. Meth. **A326**, 549 (1993).

[14] S. I. Penttila, J. D. Bowman, P. P. J. Delheij, C. M. Frankle, D. G. Haase, R. Mortensen, H. Postma, S. J. Seestrom, Y.-F. Yen, *Time Reversal Invariance and Parity Violation in Neutron Reactions*, ed. C. R. Gould, J. D. Bowman, Yu. P. Popov (World Scientific, 1994) p.198.

[15] V. W. Yuan, C. D. Bowman, J. D. Bowman, J. E. Bush, P. P. J. Delheij, C. M. Frankle, C. R. Gould, D. G. Haase, J. N. Knudson, G. E. Mitchell, S. Penttila, H. Postma, N. R. Roberson, S. J. Seestrom, J. J. Szymanski, and X. Zhu, Phys. Rev. **C44**, 2187 (1991).

[16] Y.-F. Yen, J. D. Bowman, Y. Matsuda, S. I. Penttila, S. J. Seestrom, H. M. Shimizu, R. W. Strickland, S. Takahashi, S.-H. Yoo, V. W. Yuan, *Time Reversal Invariance and Parity Violation in Neutron Reactions*, ed. C. R. Gould, J. D. Bowman, Yu. P. Popov (World Scientific, 1994) p.210.

[17] C. M. Frankle, J. D. Bowman, S. J. Seestrom, N. R. Roberson, and E. I. Sharapov, *Time Reversal Invariance and Parity Violation in Neutron Reactions*, ed. C. R. Gould, J. D. Bowman, Yu. P. Popov (World Scientific, 1994) p.204.

[18] X. Zhu, J.D. Bowman, C.D. Bowman, J. E. Bush, P.P.J. Delheij, C. M. Frankle, C. R. Gould, D. G. Haase, J. N. Knudson, G. E. Mitchell, S. Penttila, H. Postma, N. R. Roberson, S. J. Seestrom, J. J. Szymanski, V. W. Yuan, Phys. Rev. **C46**, 768 (1992).

[19] F. Corvi, F. Gunsing, K. Athanassopoulos, H. Postma, A. Mauri, *Time Reversal Invariance and Parity Violation in Neutron Reactions*, ed. C. R. Gould, J. D. Bowman, Yu. P. Popov (World Scientific, 1994) p.79.

[20] C. M. Frankle, J. D. Bowman , J.E. Bush, P.P.J. Delheij, C.R. Gould, D. G. Haase, J. N. Knudson, G. E. Mitchell, S. Penttila, H. Postma, N. R. Roberson, S. J. Seestrom, J. J. Szymanski, V. W. Yuan, X. Zhu, Phys. Rev. **C46**, 778 (1992).

[21] C. M. Frankle, J. D. Bowman, P. P. J. Delheij, C. R. Gould, D. G. Haase, J. N. Knduson, G. E. Mitchell, S. S. Patterson, S. Penttila, Yu. P. Popov, N. R. Roberson, S. J. Seestrom, E. I. Sharapov, Y. F. Yen, S. H. Yoo, V. W. Yuan, X. Zhu, Phys. Rev. **C48**, 1601 (1993).

[22] J. D. Bowman, C. D. Bowman, J. E. Bush, P. P. J. Delheij, C. M. Frankle, C. R. Gould, D. G. Haase, J. N. Knudson, G. E. Mitchell, S. Penttila, H. Postma, N. R. Roberson, S. J. Seestrom, J. J. Szymanski, V. W. Yuan, X. Zhu, Phys. Rev. Lett. **65**, 1192 (1990).

[23] B Desplanques, J. F. Donoghue, and B. R. olstein Ann. Phys. **124**, 449, (1980).

[24] M. B. Johnson, J. D. Bowman, and S. H. Yoo, Phys. Rev. Lett. **67**, 310 (1991).