6-1996

Observation of a large parity nonconserving analyzing power in Xe

J J. Szymanski
Indiana University - Bloomington

W M. Snow
Indiana University - Bloomington

J D. Bowman
Los Alamos National Laboratory

See next page for additional authors

Szymanski, J. J., Snow, W. M., Bowman, J. D., Cain, B., Crawford, B. E., Delheij, P. P. J., Hartman, R. D., Haseyama, T., Keith, C. D., Knudsen, J. N., Komives, A., Leuschner, M., Lowie, L. Y., Masaike, A., Matsuda, Y., Mitchell, G. E., Penttila, S. I., Postma, H., Rich, D., Roberson, N. R., Seestrom, S. J., Sharapov, E. I., Stephenson, S., Yen, Y.-F., & Yuan, V. W. (1996). Observation of a large parity nonconserving analyzing power in Xe. Physical Review C, 53(6), R2576–R2580. http://dx.doi.org/10.1103/PhysRevC.53.R2576

Observation of a large parity nonconserving analyzing power in Xe

Abstract

A large parity nonconserving longitudinal analyzing power was discovered in polarized-neutron transmission through Xe. An analyzing power of 4.3±0.2% was observed in a p-wave resonance at E_n=3.2 eV. The measurement was performed with a liquid Xe target of natural isotopic abundance that was placed in the polarized epithermal neutron beam, flight path 2, at the Manuel Lujan Neutron Science Center. This apparatus was constructed by the TRIPLE Collaboration, and has been used for studies of parity symmetry in compound nuclear resonances. Part of the motivation of the experiment was to discover a nucleus appropriate for a sensitive test of time-reversal invariance in polarized-neutron transmission. The large analyzing power of the observed resonance may make it possible to design a test of time reversal invariance using a polarized-Xe target.

Disciplines

Atomic, Molecular and Optical Physics | Physics

Authors

J J. Szymanski, W M. Snow, J D. Bowman, B Cain, Bret E. Crawford, P P J. Delheij, R D. Hartman, T Haseyama, C D. Keith, J N. Knudsen, A Komives, M Leuschner, L Y. Lowie, A Masaike, Y Matsuda, G E. Mitchell, S I. Penttila, H Postma, D Rich, N R. Roberson, S J. Seestrom, E I. Sharapov, Sharon L. Stephenson, Y-F Yen, and V W. Yuan

Observation of a large parity nonconserving analyzing power in Xe

J. J. Szymanski,[1] W. M. Snow,[1] J. D. Bowman,[2] B. Cain,[1,*] B. E. Crawford,[3] P. P. J. Delheij,[4] R. D. Hartman,[1] T. Haseyama,[5] C. D. Keith,[1] J. N. Knudson,[2] A. Komives,[1], M. Leuschner,[1,†] L. Y. Lowie,[6] A. Masaike,[5], Y. Matsuda,[5] G. E. Mitchell,[6] S. I. Penttilä,[2] H. Postma,[7] D. Rich,[1] N. R. Roberson,[3] S. J. Seestrom,[2] E. I. Sharapov,[8] S. L. Stephenson,[6] Y. F. Yen,[2] and V. W. Yuan[2]

[1]*Department of Physics, Indiana University, Bloomington, Indiana 47405*
[2]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545*
[3]*Duke University, Durham, North Carolina 27706*
and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708
[4]*TRIUMF, Vancouver, British Columbia, Canada V6T 2A3*
[5]*Department of Physics, Faculty of Science, Kyoto University, Kyoto 606-01, Japan*
[6]*North Carolina State University, Raleigh, North Carolina 27695*
and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708
[7]*University of Technology, P.O. Box 5064, 2600 GA Delft, The Netherlands*
[8]*Joint Institute for Nuclear Research, 141980 Dubna, Moscow, Region, Russia*

(Received 25 March 1996)

A large parity nonconserving longitudinal analyzing power was discovered in polarized-neutron transmission through Xe. An analyzing power of 4.3±0.2% was observed in a p-wave resonance at E_n=3.2 eV. The measurement was performed with a liquid Xe target of natural isotopic abundance that was placed in the polarized epithermal neutron beam, flight path 2, at the Manuel Lujan Neutron Science Center. This apparatus was constructed by the TRIPLE Collaboration, and has been used for studies of parity symmetry in compound nuclear resonances. Part of the motivation of the experiment was to discover a nucleus appropriate for a sensitive test of time-reversal invariance in polarized-neutron transmission. The large analyzing power of the observed resonance may make it possible to design a test of time reversal invariance using a polarized-Xe target. [S0556-2813(96)50806-X]

PACS number(s): 24.80.+y, 11.30.Er, 25.40.Ny, 27.60.+j

Parity nonconserving (PNC) effects have been observed in polarized neutron-nucleus scattering for several nuclear species [1–9]. Weak amplitudes in nuclei are typically 10^{-6}–10^{-7} ($=G_F K_F{}^2$, where G_F is the Fermi constant and K_F is a typical Fermi momentum in a nucleus) of strong interaction amplitudes, but PNC effects in heavy nuclei are enhanced by the small level spacings of compound nuclear resonances and by the mixing of strongly excited s-wave resonances into weakly excited p-wave resonances [10,11]. Many large PNC effects have been observed, including three ~10% effects [1,5,6,9]. This mechanism is expected also to amplify parity-odd, time-reversal (TR) noninvariant effects [10–14].

One of the motivations for searching for a PNC neutron resonance in Xe was to discover a resonance useful for a TR invariance test. Tests of TR invariance in neutron transmission involve searching for terms in the neutron forward scattering amplitude proportional to $\vec{\sigma}_n\cdot(\vec{J}\times\vec{k}_n)$ or $\vec{J}\cdot\vec{k}_n(\vec{\sigma}_n\cdot\vec{J}\times\vec{k}_n)$m [15–18]. In these expressions $\vec{\sigma}_n$ is the neutral spin $\vec{J}$ is the target spin, and $\vec{k}_n$ is the neutron momentum vector. The first expression, the threefold correlation, is both parity-odd and T-odd and can thus be produced by the same mechanisms that produce CP violation in kaon decays. A TR test sensitive to the threefold correlation requires a polarized nuclear target that possesses a neutron resonance with a large PNC effect for the largest possible enhancement.

Unfortunately, the nuclei in which large PNC asymmetries have been discovered so far are not easy to polarize in the required amounts. Efforts in progress to polarize ^{139}La by dynamic nuclear polarization have achieved polarizations <20% in external magnetic fields in excess of 2 T [19]. The high magnetic fields and low temperatures required place stringent design requirements on the polarized target to avoid systematic errors. In particular, the high holding fields and the spin dependence of neutron-nucleus scattering (''nuclear pseudomagnetism'') affect the neutron polarization, producing a major source of systematic error [20].

We were encouraged to search for PNC resonances in Xe because of the interesting possibilities for the production of dense, highly-polarized ^{129}Xe targets. Large quantities of highly-polarized, solid ^{129}Xe with relaxation times of up to several hundred hours have been maintained by optical-pumping techniques [21,22]. The polarization can be produced at higher temperatures and lower external magnetic fields (of order 0.1 T) than those needed for dynamic nuclear polarization. The lower field can be adjusted to cancel the pseudomagnetic effect, thereby suppressing the main source of systematic error.

This paper describes the observation of a large PNC effect in a p-wave resonance in Xe. Subsidiary measurements indicate that the resonance is most likely in ^{131}Xe.

The measurement was carried out at the Manuel Lujan Neutron Science Center (MLNSC). The experiment utilized

*Present address: Department of Physics, Texas A and M University, College Station, TX 77843.

†Present address: Department of Physics, University of New Hampshire, Durham, NH 038245.

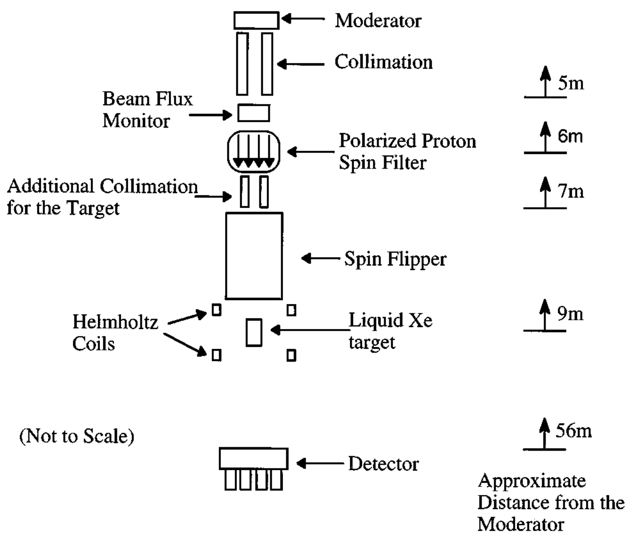

FIG. 1. Layout of the flight path 2 neutron apparatus at MLNSC.

flight path 2 and the apparatus that the TRIPLE Collaboration has built for PNC measurements in neutron resonances. The apparatus and techniques have been previously documented [23]. The major elements of the apparatus are (see Fig. 1) (1) a beam monitor to normalize the incident neutron flux [24], (2) a longitudinally-polarized-proton spin filter that removes neutrons with spins antiparallel to the proton polarization [25], (3) a spin flipper that allows rapid reversal of the neutron beam polarization [26], (4) the liquid Xe target, and (5) a 55-element ^{10}B-loaded liquid scintillator detector [27].

The beam polarization was reversed regularly to reduce the effect of systematic errors. The accumulated data set was divided into 44 runs, where each run was formed by 20 beam polarization sequences. The beam-polarization sequence contains 8 steps with neutron helicity states $+--+-++-$. This pattern was chosen to eliminate first- and second-order time drifts [26]. Each step takes 10 seconds and contains 200 beam pulses.

A liquid Xe target was used for this measurement to provide an approximately 1.3-interaction-length attenuation to the neutron beam. The vessel containing the liquid Xe was a Cu cylinder measuring 10.2 cm diameter by 13.3 cm long. The neutron beam entered the liquid Xe through Al windows 0.25 cm thick located at each end of the Cu cylinder. The first 24 production runs were acquired with 5 cm collimation located just downstream of the polarizing cryostat and the remaining runs with 8 cm collimation. In both collimation configurations the transverse extent of the beam was well-contained within the liquid Xe. The vessel was filled by condensing 524 liter-atm of natural Xe, with the cooling power provided through Cu cables connected to a liquid nitrogen bath. The Xe temperature was maintained at a constant value with heater wire controlled by a proportional integrator-differentiator circuit. The neutron beam polarization through the Xe target was maintained by a 60 G field parallel to the beam direction produced by a Helmholtz coil pair. The liquid Xe temperature was maintained at 166.5 K, with a typical variation of ± 0.2 K, which corresponds to a vapor pressure of 1080 torr and Xe density of 2.93 g/cm^3. The temperature was measured using diode thermometers and the pressure with a capacitance manometer. The density variations due to temperature fluctuations were negligible.

Neutrons were detected in a ^{10}B-loaded liquid scintillator. The scintillator is subdivided into 55 light-isolated elements [27]. Each element is read out with a photomultiplier tube with a specially-designed base that was capable of handling the typical instantaneous rate of a few MHz per tube. Individual pulses from each element are discriminated to differentiate neutron pulses from single photoelectron noise and reduce the effects of large pulses from $\sim$2 MeV γ's produced in the reaction $n+p \rightarrow d+\gamma$ and $\sim$0.5 MeV γ's from $n+{}^{10}\mathrm{B} \rightarrow {}^{11}\mathrm{B} \rightarrow \alpha + {}^{7}\mathrm{Li}^* \rightarrow {}^{7}\mathrm{Li}+\gamma$. The pulses are then added using an analog summing circuit. The incoming digital pulses are stretched in the analog summer to match the pulse width to the digitization time, which results in each pulse being counted once and only once. The resulting analog voltage is passed through a 1 μs passive filter, and a 12-bit transient digitizer samples the analog voltage at 1 μs intervals. The entire arrangement has a dead time that is characteristic of each individual detector element while utilizing a single transient digitizer channel. Data are taken for 8192 1 μs channels, which corresponds to a low-energy limit of 0.25 eV at the 56 meter location of the detector array.

The neutron time-of-flight transmission spectrum [$T(t)=Y_+(t)+Y_-(t)$, where $Y_+(Y_-)$ is the number of counts detected with $+(-)$ neutron helicity] and the asymmetry in the transmitted intensity [$A(t)=(Y_+(t)-Y_-(t))/(Y_+(t)+Y_-(t))$] in the vicinity of $E_n=3.2$ eV are shown in Fig. 2. The PNC effect in the $E_n=3.2$ eV resonance can be seen in the asymmetry spectrum. The transmission data were corrected for the effects of dead time, electronic noise, and γ-ray background. The line shape of the $E_n=3.2$ eV resonance was then fit to the form

$$Y_\pm(E_n)=N_\pm C(E_n)\exp[-n\sigma_p^{\max}\phi(E_n)(1\pm f_n P)],$$

where $N_\pm$ is the normalization for + and − helicities, $C(E_n)$ describes the energy dependence of the neutron flux, the detector efficiency, and the absorption due to the nonresonant cross section, n is the target thickness, $\sigma_p^{\max}$ is the maximum value of the p-wave resonance cross section, $\phi(E_n)$ is the Doppler-broadened p-wave line shape, f_n is the neutron polarization, and $P=(\sigma_+-\sigma_-)/(\sigma_++\sigma_-)$ is the PNC longitudinal analyzing power of the resonance cross section. The parameters describing the resonance shape, $\phi(E_n)$ and $\sigma_p^{\max}$, are extracted from a fit to the data summed over the 44 runs. The neutron polarization is determined from a subsidiary measurement described below. All other parameters are determined for each of the 44 runs.

The value for the neutron polarization f_n is extracted from calibration runs made with a La target, where the La target is located at the downstream end of the spin flipper, just before the Xe target. The PNC analyzing power for the $E_n=0.734$ eV resonance in ^{139}La is well established to be $P=9.55\pm0.35\%$ [9]. The La measurement calibrates the relation between the proton polarization in the polarizing cryostat to the neutron beam polarization f_n. The typical value is $f_n=73\%$. The proton polarization is monitored during each run using an NMR measurement and a run-by-run correction to f_n is made. A neutron spin-transport calculation showed that the combined fields due to the Xe cryostat Helmholtz coils and

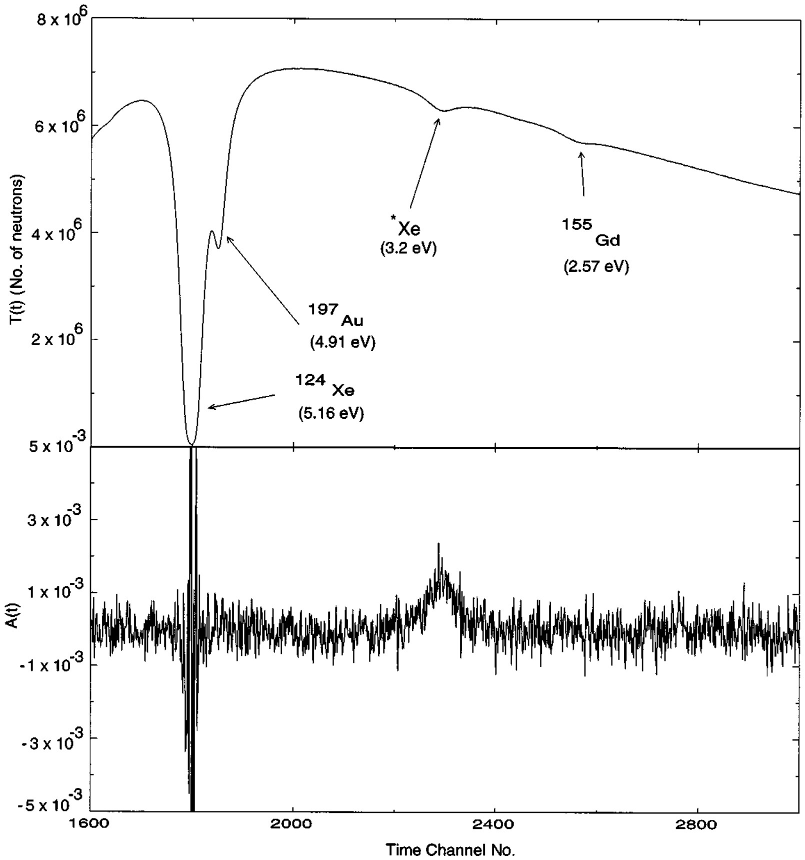

FIG. 2. The transmission spectrum, $T(t)=Y_+(t)+Y_-(t)$ and the asymmetry in the transmitted intensity, $A(t)=(Y_+(t)-Y_-(t))/(Y_+(t)+Y_-(t))$ in the vicinity of E_n=3.2 eV $Y_+(Y_-)$ is the intensity of the transmitted neutron beam with $+(-)$ neutron helicity.

the spin flipper produce a depolarization of less than 0.5% in the neutron beam as it exits the spin flipper and traverses the Xe target. No correction to the neutron polarization was applied for the neutron flight through the Xe target.

A value for P is determined for each run by combining f_n and the combination f_nP, which is extracted from the fits to $Y_{\pm}(E_n)$. The distribution for P for all of the runs is shown in Fig. 3. A Gaussian fit to the P distribution yields $P=4.3 \pm 0.2\%$.

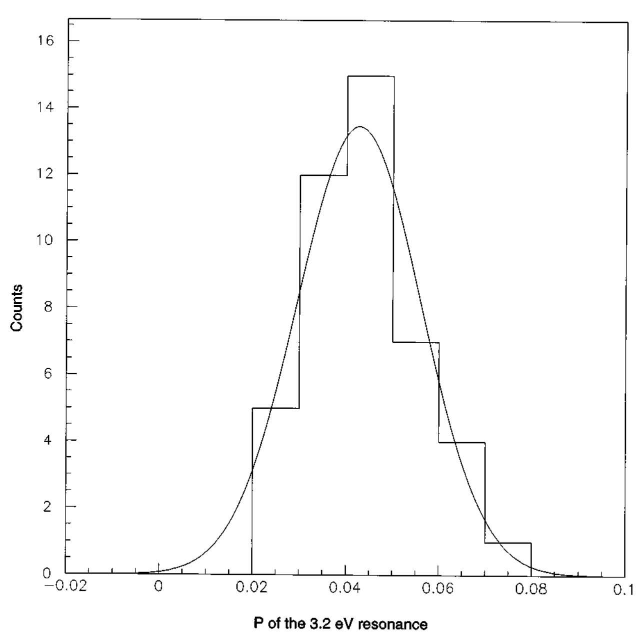

FIG. 3. Distribution of values of P extracted from each individual run. The centroid and width are extracted from this distribution and give the central value of $P$and its error.

An identical analysis was performed for resonances that originate from target and beamline contaminants. Due to their small concentrations, these resonances have an attenuation length that is similar to Xe p-wave resonances. They therefore provide a measure of possible false asymmetries due to detector sensitivity to the spin-flipper magnetic field and the fitting techniques. The results of the contaminant resonance analysis are shown in Table I. Asymmetries fluctuate about zero with a sensitivity of $\sim 10^{-4}$ of the incoming neutron flux.

The PNC measurements were performed with a natural Xe target. To obtain information about the isotope of origin for the E_n=3.2 eV resonance, a target containing ~1 liter-atm of 80.6% enriched ^{129}Xe gas was placed in the (unpolarized) neutron beam several weeks after the liquid Xe run. The gas was contained within an Al cylinder 2.54 cm in diameter by 33 cm long. After ~5 h of measurement with the enriched gas, the Xe gas was pumped out and the empty cylinder was replaced in the beam for ~1.5 h of further measurement.

TABLE I. Results of the analysis on contaminant resonances.

E_n of resonance	Isotope	Asymmetry
2.57 eV	^{155}Gd	0.3 ± 0.5%
4.91 eV	^{197}Au	0.0 ± 0.1%
60.3 eV	^{197}Au	0.1 ± 0.4%

TABLE II. Isotopic abundance of natural Xe, the enriched Xe gas, predicted integrated cross sections, and nearest known resonances for the isotopes of Xe.

Isotope	Natural abundance	Enriched abundance	Predicted integrated cross section (b eV)	Nearby resonances
^{124}Xe	0.10%	0.43%	40	5.16 eV
^{126}Xe	0.09%	0.38%	40	460 eV
^{128}Xe	1.9%	16.91%	2.1	238 eV
^{129}Xe	26.4%	80.59%	0.15	9.5 eV
^{130}Xe	4.1%	1.23%	1.0	430 eV
^{131}Xe	21.2%	0.41%	0.19	14.4 eV
^{132}Xe	26.9%	0.04%	0.15	643 eV
^{134}Xe	10.4%	0.01%	0.38	1001 eV
^{136}Xe	8.9%	0.00%	0.45	–

If the $E_n=3.2$ eV resonance were in ^{129}Xe, then an absorption length [$n\sigma \equiv \ln$(counts target full/counts target empty), with appropriate normalization] due to ^{129}Xe of $n\sigma=(19.2\pm5.0)\times10^{-4}$ would be expected. An absorption length of $n\sigma=(3.5\pm3.8)\times10^{-4}$ was observed, indicating that ^{129}Xe is not the isotope of origin for the $E_n=3.2$ eV resonance. The isotopic abundance of the enriched Xe gas is listed in Table II. The absence of the $E_n=3.2$ eV resonance in this measurement eliminates all Xe isotopes with $A>130$ as the isotope of origin.

The neutron width for a p-wave resonance is limited by the p-wave strength function to be less than $\approx 5\times10^{-9}\langle D_1\rangle$, where $\langle D_1\rangle$ is the average p-wave level spacing. Using the value $\langle D_1\rangle=100$ eV, the quantity $\int\sigma(E)dE=(\pi/2)\sigma_{\text{unitarity}}\Gamma_n$ is limited to $\sim$0.5 b eV. The liquid target transmission spectrum gives $\int\sigma(E)dE=0.04/\alpha$ b eV, where α is the natural abundance for the isotope of origin of the $E_n=3.2$ eV resonance. The fourth column in Table II lists the predicted value of $\int\sigma(E)dE$, based on the known values of α for all the isotopes of Xe. The isotopes with the largest abundance, ^{129}Xe, ^{131}Xe, ^{132}Xe, ^{134}Xe, and ^{136}Xe satisfy the bound, while the other isotopes predict an uncharacteristically large value for the integrated cross section.

The only isotopes with $A>129$ and large natural abundances are ^{131}Xe, ^{132}Xe, ^{134}Xe, and ^{136}Xe. The PNC asymmetry observed in a p-wave resonance is due to mixing with one or more s-wave resonances via the weak interaction. The large value of the PNC asymmetry measured here leads one to suspect that ^{131}Xe is the isotope of origin for the $E_n=3.2$ eV resonance because of the nearby s-wave resonance. A recent measurement of γ-ray spectra from neutron resonances in Xe [28], stimulated by these results, provides direct evidence that the 3.2 eV resonance belongs to the isotope ^{131}Xe.

In summary, the PNC longitudinal analyzing power for the $E_n=3.2$ eV resonance is $P=4.3\pm0.2\%$. A companion measurement provides direct evidence that the isotope of origin for the $E_n=3.2$ eV resonance is most likely ^{131}Xe [28]. ^{131}Xe is polarizable using spin exchange with optically-pumped rubidium and it has recently been shown that ^{131}Xe can be polarized in the solid phase via cross relaxation with polarized ^{129}Xe [22]. However, the spin relaxation time for polarized ^{131}Xe ($J=3/2$) is typically much shorter than that for ^{129}Xe ($J=1/2$), because the higher spin of ^{131}Xe makes it susceptible for depolarization through coupling to electric field gradients. A technique for accumulating polarized ^{131}Xe in sufficient amounts for a TR test in polarized neutron transmission has yet to be demonstrated.

We wish to acknowledge the help of Russ Mortensen and Tom Langston of the LANL technical staff and Moira Wedekind and Norm Jones of the Indiana University Cyclotron Facility staff. The contributions of Ed Schools, an undergraduate student at Indiana University, is also greatly appreciated. Work supported in part by National Science Foundation Grant No. NSF-PHY-93-14783 and Department of Energy Grants No. DE-FG05-88-ER40441 and No. DE-FG05-91-ER40619.

[1] V. P. Alfimenkov, S. B. Borzakov, Vo Van Thuan, Yu. D. Mareev, L. B. Pikelner, A. S. Khrykin, and R. I. Sharapov, Nucl. Phys. **A398**, 93 (1983).
[2] S. A. Biryukov *et al.*, Yad. Fiz. **45**, 1511 (1987).
[3] Y. Masuda *et al.*, Phys. Rev. C **44**, 2187 (1991).
[4] J. D. Bowman, C. D. Bowman, J. E. Bush, P. P. J. Delheij, C. M. Frankle, C. R. Gould, D. G. Haase, J. Knudson, G. E. Mitchell, S. Penttila, H. Postma, N. R. Roberson, S. J. Seestrom, J. J. Szymanski, V. W. Yuan, and X. Zhu, Phys. Rev. Lett. **65**, 1192 (1990).
[5] 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. Penttilä, H. Postma, N. R. Robersom, S. J. Seestrom, J. J. Szymanski, S. H. Yoo, V. W. Yuan, and X. Zhu, Phys. Rev. Lett. **67**, 564 (1991).
[6] C. M. Frankle *et al.*, Phys. Rev. C **46**, 778 (1992).
[7] C. M. Frankle *et al.*, Phys. Rev. C **46**, 1542 (1992).
[8] X. Zhu *et al.*, Phys. Rev. C **46**, 768 (1992).
[9] V. W. Yuan *et al.*, Phys. Rev. C **44**, 2187 (1991).
[10] V. E. Bunakov and V. P. Gudkov, Nucl. Phys. **A401**, 93 (1983).
[11] V. E. Bunakov and V. P. Gudkov, Z. Phys. A **308**, 363 (1982). For a review see V. P. Gudkov, Phys. Rep. **212**, 77 (1992).
[12] A. Griffiths and P. Vogel, Phys. Rev. C **44**, 1195 (1991).
[13] I. S. Towner and A. C. Hayes, Phys. Rev. C **49**, 2391 (1994).
[14] I. B. Khriplovich, Phys. Rev. C **52**, 1138 (1995).
[15] L. Stodolsky, Phys. Lett. B **172**, 5 (1986).
[16] P. K. Kabir, Phys. Rev. Lett. **60**, 686 (1988).
[17] Y. Masuda, in *Time Reversal Invariance and Parity Violation in Neutron Reactions*, edited by C. R. Gould, J. D. Bowman, and Yu. P. Popov (World Scientific, Singapore, 1994), p. 126.
[18] J. Koster *et al.*, Phys. Lett. B **267**, 23 (1991).
[19] T. Maekawa, Y. Takahashi, H. M. Shimizu, M. Iinuma, A. Masaike, and T. Yabusaki, Nucl. Instrum. Methods A **366**, 115 (1995).
[20] S. K. Lamoreaux and R. Golub, Phys. Rev. D **50**, 5632 (1994).
[21] G. D. Cates, D. Benton, M. Gatzke, W. Happer, K. C. Hasson, and N. R. Newbury, Phys. Rev. Lett. **65**, 2591 (1990).

[22] M. Gatzke, G. D. Cates, B. Driehuys, D. Fox, W. Happer, and B. Saam, Phys. Rev. Lett. **70**, 690 (1993).

[23] 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, R. N. Mortensen, S Penttila, H. Postma S. J. Seestrom, J. J. Szymanski, S. A. Wender, S. H. Yoo, V. W. Yuan, and X. Zhu, Nucl. Instrum. Methods A **326**, 549 (1993).

[24] J. J. Szymanski, J. D. Bowman, P. P. J. Delheij, C. M. Frankle, J. Knudson, S. Penttilä, S. J. Seestrom, S. H. Yoo, V. W. Yuan, and X. Zhu, Nucl. Instrum. Methods A **340**, 195 (1994).

[25] S. Penttilä, J. D. Bowman, P. P. J. Delheij, C. M. Frankle, D. G. Haase, H. Postma, S. J. Seestrom, and Y. F. Yen, in *High Energy Spin Physics, 11th International Symposium*, edited by K. J. Heller and S. L. Smith, AIP Conf. Proc. No. 343 (AIP, New York, 1994), p. 532.

[26] J. D. Bowman, S. I Penttilä and W. B. Tippens, Nucl. Instrum. Methods A **369**, 564 (1996).

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

[28] V. R. Skoy *et al.*, preceding paper, Phys. Rev. C **53**, R2573 (1996).