Parity violation in the 0.734-eV neutron resonance in ^{139}La

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The degree of parity mixing in the 0.734-eV neutron resonance in ^{139}La was measured in a two-sample transmission experiment. An unpolarized neutron beam was weakly polarized in the longitudinal direction at energies near the resonance by transmission through a La_2O_3 sample. The beam was passed through a spin flipper and then through a second sample of La_2O_3. The difference in transmission for the two spin directions was then measured to determine the longitudinal asymmetry. We obtain $9.2\pm1.7\%$ *s*-wave mixing into this *p*-wave resonance, which is consistent with earlier measurements using polarized beams in single transmission experiments. Because parity mixing is an attribute of the weak force, the experiment demonstrates the remarkable enhancement in the weak force in neutron resonances—an effect large enough to allow polarization of a neutron beam. Experiments of this class are described which should permit the first systematic study of the manifestation of the weak force in complex nuclei.

INTRODUCTION

The interaction potential between a neutron and a nucleus may contain a term proportional to the helicity $\boldsymbol{\sigma}\cdot\mathbf{k}$ where $\boldsymbol{\sigma}$ and $\mathbf{k}$ are the spin direction and the momentum vector, respectively, for the neutron. This term changes sign under inversion of coordinates and therefore does not conserve parity. Because parity nonconservation (*P* violation) is an attribute of the weak force and not of the strong force, the detection of *P* violation in neutron-nucleus interactions indicates the presence of the weak force.

Careful experiments using thermal neutrons have detected[1] the $\boldsymbol{\sigma}\cdot\mathbf{k}$ term in neutron-nucleus reactions. However conditions are most favorable for detection of *P* violation in low-energy *p*-wave resonances of compound nuclei owing to enhancements of the *P*-violating effects by several orders of magnitude. Parity violation may be measured by comparing the transmission of a longitudinally polarized neutron beam in a parity-mixed neutron resonance for the two spin directions. The cross section $\sigma^{\pm}$ can be written[2]

$$\sigma^{\pm}=\sigma_p(1\pm fQ)+\sigma_{\mathrm{pot}}\ , \tag{1}$$

where σ_p in the energy-dependent Breit-Wigner resonance shape for the *p*-wave resonance, f is the neutron polarization, Q is the longitudinal asymmetry, and σ_{pot} is the approximately energy-independent *s*-wave potential scattering. The longitudinal asymmetry Q can be written

$$Q=\frac{2\langle\phi_s|U|\phi_p\rangle}{(E_p-E_s)}\left[\frac{\Gamma_n^s}{\Gamma_n^p}\right]^{1/2}, \tag{2}$$

where U is the operator mixing the wave function ϕ_p of the *p*-wave resonance with that ϕ_s of a nearby *s*-wave resonance, E_p and E_s are the resonance energies, and Γ_n^s and Γ_n^p are the resonance neutron widths. We may further estimate the ratio of the compound nuclear matrix element to the single-particle matrix element as[2]

$$\langle\phi_s|U|\phi_p\rangle=\langle\psi_s|U|\psi_p\rangle\left[\frac{D_{\mathrm{com}}}{D_{\mathrm{sp}}}\right]^{1/2}, \tag{3}$$

where the ψ are the single-particle wave functions and the D are the spacing of compound and single-particle resonances. Inserting appropriate values for the ratio of spacings, the ratio of widths, and the separations yields an enhancement of *P* violation by several orders of magnitude in compound resonances over that observed in experiments involving low-lying nuclear states.

This enhancement has been well established experimentally by the Dubna group,[3] which has detected *P* violation in four low-energy *p*-wave resonances by transmission measurements using a neutron beam polarized over a broad energy range. The largest effect seen is in the 0.734-eV resonance in ^{139}La where $Q=0.073\pm0.005$ was detected, yielding a value for the matrix element of 1.28 ± 0.12 meV. At the National Laboratory for High Energy Physics (KEK) in a similar experiment[4] involving both detection of resonance capture gamma rays and transmitted neutrons, a substantially different value of $Q=0.104\pm0.003$ was found.

We describe here a third approach to this experiment using the recently commissioned[5] pulsed neutron source associated with the Los Alamos Neutron Scattering Center (LANSCE). LANSCE offers a very substantial intensity advance over existing facilities and should make possible the measurement of matrix elements which are smaller by about 2 orders of magnitude than has presently been achieved. Such sensitivity should make it possible to extend these measurements to sufficiently high energies to measure *P* violation in several resonances per nucleus. In this way a systematic study of the manifestation of the weak force in complex nuclei should be possible. A further objective of this work is to identify resonances favorable for conducting a sensitive search for violation of time-reversal invariance (*T* violation).

THE EXPERIMENT

Although a polarized neutron beam was not available for these experiments at Los Alamos, we took advantage of the high neutron intensity at LANSCE to make practical an experimental method less sensitive than those used at KEK and Dubna. Because according to Eq. (1) the cross section is different for the different beam helicities, the two helicity states will be transmitted differently near a resonance exhibiting parity mixing. Starting with an initially unpolarized neutron beam, the transmitted beam will have a small helicity peaking at the resonance energy. The transmitted neutron beam is then passed through a 180-deg spin flipper and then to a second sample of the same material. The ratio of transmitted neutron intensity through the second sample can be measured for the flipped and unflipped beams. The expected effect is small, requiring high beam intensity. However, systematic errors associated with polarization determination are absent.

The diagram for the experiment is shown in Fig. 1. Neutrons are produced by the spallation process using 800-MeV protons from the Los Alamos Proton Storage Ring (PSR). This facility compresses an 880-μs-long beam pulse from Clinton P. Anderson Meson Physics Facility (LAMPF) to a width of 0.27 μs. An average proton current of 10 μA was used in these experiments with a pulse rate of 12 Hz. This corresponds to about 5×10^{12} protons per pulse of 10^{14} neutrons per pulse. The neutrons are moderated into the eV range where they may be used in neutron time-of-flight spectroscopy.

The neutron beam was collimated to 2.54-cm diam at a distance of 6 m from the moderator and transmitted through a La_2O_3 sample with a lanthanum thickness of 0.0906 atoms/b. This sample is located at the entrance to the first coil of the spin flipper and at a distance of 7 m. The polarization introduced into the beam at this point varies rapidly around the energy of the resonance but has a peak value of approximately 1.3%. This beam then passes through the spin flipper and then through a second La_2O_3 sample with lanthanum thickness of 0.188 atoms/b. Neutrons are detected in a ^{6}Li-glass scintillator of thickness 1.0 cm and diameter 10 cm which is located at a flight path of 11 m. At the peak of the resonance the beam intensity is reduced by a factor of 500 by transmission through the two samples. Concrete shielding isolates the neutron detector from backgrounds produced by the two transmission samples. Background is measured by means of a rhodium foil placed in the beam near the first La_2O_3 sample.

The spin flipper is, we believe, of original design and provides a satisfactory solution to the problem of flipping the neutron spin over a broad range of energies as required in white source experiments. The flipper is shown schematically in Fig. 2 and consists of three coils. Coils *a* and *b* are wound on the outside of a 10-cm-diam pipe with a nonuniform turn density that produces a field that goes to zero between them. The current in coil *A* can be reversed in direction. Coil *c* produces a field transverse to the beam direction which peaks where the longitudinal field is zero. The variation of the fields along the beam axis is approximated by

$$\text{coil } a \quad B_Z=\pm B_0,\ \ Z<-Z_0/2\ ,$$
$$B_Z=\pm B_0\sin(\pi Z/Z_0),\ \ -Z_0/2<Z<0\ ,$$
$$\text{coil } b \quad B_Z=B_0\sin(\pi Z/Z_0),\ \ 0<Z<Z_0/2\ ,$$
$$B_Z=B_0,\ \ Z_0/2<Z<Z_0\ ,$$
$$\text{coil } c \quad B_1=B_0\cos(\pi Z/Z_0),\ \ -Z_0/2<Z<Z_0/2\ ,$$

with $B_0=20$ g and $Z_0=100$ cm. When coils *a* and *b* have their currents in opposite directions, the field felt by the neutrons is shown in the upper line of arrows. However, when the direction of current through coil *a* is reversed, the field direction follows the arrows of the lower curve. The neutron precesses around an axis that adiabatically remains aligned with the field direction. The neutron spin therefore can be changed by reversing the

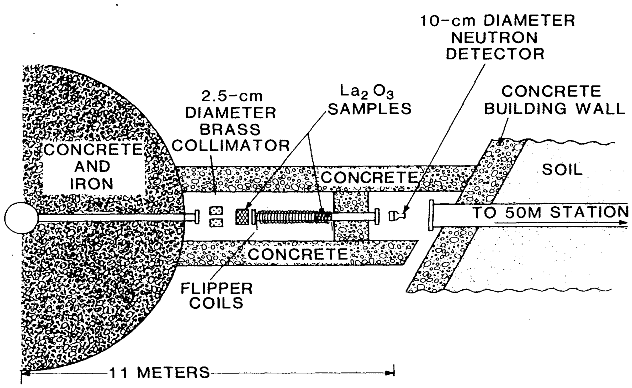

FIG. 1. Plan view of the experiment. Neutrons travel through 7 m of biological shielding and collimation to the first La_2O_3 sample. The beam transmitted through the sample is weakly longitudinally polarized near the 0.734-eV resonance. The beam then traverses three sets of coils, which make up the spin flipper, to the second sample and are detected in a ^{6}Li-glass scintillator.

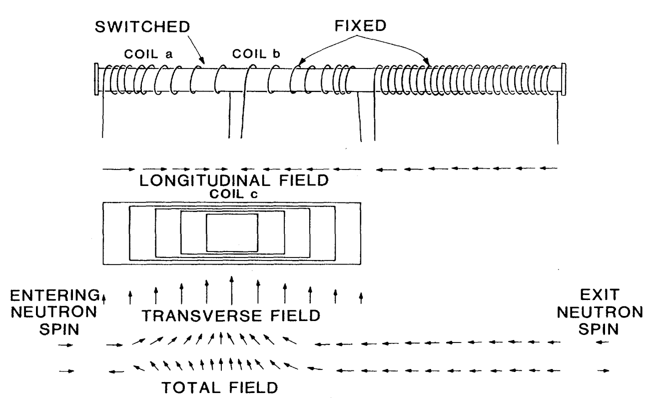

FIG. 2. The spin flipper. A nonuniform longitudinal field produced by two coils is added to a transverse nonuniform field. The total field seen by the neutrons for the flipped and unflipped conditions is indicated by the arrows at the bottom.

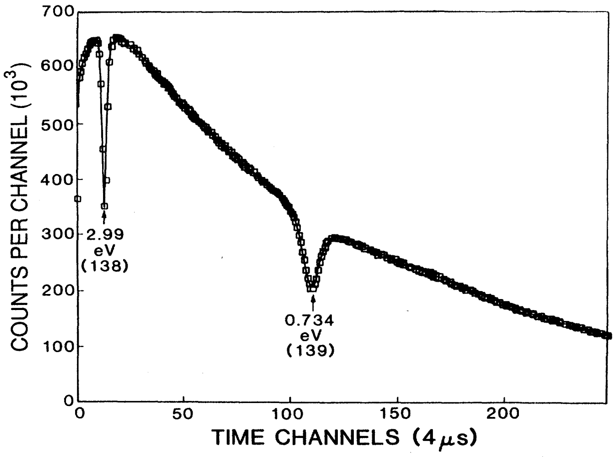

FIG. 3. Two-sample La_2O_3 transmission.

current direction in coil a. At a neutron energy of 1 eV, the flipper is calculated to be 99.9% effective by integration of the equation of motion. The degree of longitudinal polarization is reduced by 0.1% by passing through the flipper. Our calculation shows that for this type of flipper the depolarization, D, is given by the approximate expression $D=0.1/\gamma^2$ valid for $\gamma \geq 2$ where $\pi\gamma$ is the number of radians that the spin precesses in the field B_0 while the neutron travels from $-Z_0/2$ to $+Z_0/2$. The efficiency decreases as the neutron energy increases. At 100 eV the flipper is 90% efficient.

A time spectrum measured using a multiscaler with a 4-μs dwell time is shown in Fig. 3 where counts per channel are displayed as a function of neutron flight time to the detector. The two resonances indicated in the figure include the 0.734-eV p-wave resonance of interest, and an s-wave resonance at 2.99 eV in the 0.1% ^{138}La isotope fraction of the natural lanthanum sample.

The experimental procedure was to switch by computer the direction of the current in coil a with dwell periods of 200 PSR pulses (17 s). The multiscaler spectra were stored in separate portions of memory for flipped and unflipped beam and the two spectra were accumulated on line. The time required for changing the state of the experiment was 6 s. The total time for a full cycle was about 0.75 min which compares with a typical measurement time of about 12 h. Eleven such runs were analyzed for our final P-violation result. Half the data were collected with the fields in coils b and c reversed from those described above to eliminate any systematic effects of the magnetic field acting directly on the neutron detector.

ANALYSIS AND RESULTS

The transmission asymmetry R is defined as

$$R=\frac{A(+)-A(-)}{A(+)+A(-)}, \tag{4}$$

$$A(\pm)=\frac{\sum_1 Y_i(\pm)}{\sum_2 Y_i(\pm)+\sum_3 Y_i(\pm)}, \tag{5}$$

where $(+)$ refers to the nonflipped data and $(-)$ to the flipped data, and the integers refer to different energy intervals. Region 1 is near the center of the resonance and the normalization regions 2 and 3 are far from the resonance. The yield in the ith time channel $Y_i(\pm)$ may be written as

$$Y_i(\pm)=F_iE_iP_i\{[1+\tfrac{1}{2}(N_1\pm N_2)^2\bar{\sigma}_i^2Q^2+\cdots]\times e^{-\sigma_i(\bar{N}_1+N_2)}+b\}, \tag{6}$$

where F_i is the neutron flux, E_i is the detector efficiency, P_i is the transmission due to potential scattering, N_1 and N_2 are the polarizer and analyzer target thicknesses, $\bar{\sigma}_i$ is the thermal-averaged neutron resonance cross section, Q is the longitudinal asymmetry in the cross section, and $b/(1+b)$ is the fractional background. The Q^2 terms are small in regions 2 and 3 so that the transmission asymmetry R may be written

$$R=\frac{\sum_1 Y(+)-\sum_1 Y(-)}{\sum_1 Y(+)+\sum_1 Y(-)}.$$

The Q^2 dependent terms in region 1 are small, $\frac{1}{2}(N_1+N_2)^2\bar{\sigma}^2Q^2=10^{-3}$, so R can be expanded keeping only lowest-order terms in Q_2 to give

$$\frac{R}{Q^2}=\frac{N_1N_2\sum\bar{\sigma}_i^2(Y_i-bF_iE_iP_i)}{\sum Y_i}. \tag{7}$$

In order to evaluate this expression, it is necessary to know not only Y_i, but also $\bar{\sigma}_i$ and the product $G_i=F_iE_iP_i$. We determine these quantities by making a least-squares fit to determine parameters describing G and $\bar{\sigma}$ using the energy region 0.633–0.760. We assume for G_i,

$$G_i=G_0\frac{\Delta T}{T_i}\left[1+A_1\frac{1}{\beta_i}+A_2\frac{1}{\beta_i^2}\right],$$

where G_0 is a normalization, ΔT is the time-channel width, T_i is the time of flight, and A_1 and A_2 describe the small remaining variation of G_i with neutron velocity β_i. For $\bar{\sigma}_i$, we take a standard Doppler-broadened Lorentzian shape. We obtain

$$\frac{g\Gamma_n}{\Gamma_\gamma}=7.7\pm0.9\times10^{-7}$$

and (8)

$$\Gamma=0.045\pm0.005 \text{ eV}$$

for $T=295$ K, in agreement with Alfimenkov *et al.*[3] The background parameters G_0, A_1, and A_2 are determined from a large range of energies and are therefore not sensitive to the details of the resonance line shape. In order to determine $\bar{\sigma}_i$ in a parameter-independent manner we use the relation

$$\bar{\sigma}_i=\frac{1}{N_1+N_2}\ln^2\left[\frac{Y_i^D}{G_i^F}-b\right]. \tag{9}$$

We take Y_i^D from the experimental data and G_i^F from the fit. This yields

$$\frac{R}{Q^2}=\frac{\frac{N_1N_2}{(N_1+N_2)^2}\sum_1 (Y_i^D-bG_i^F)\ln^2\left[\frac{Y_i^D}{G_i^F}-b\right]}{\sum_1 Y_i^D} \quad (10)$$

and we obtain $R/Q^2=0.0317$.

The weighted average of the measurements yielded $R=2.7\pm1.0\times10^{-4}$. The Pearson chi-squared test yielded a probability of 0.3 indicating satisfactory dispersion among the measurements. Using the value for R/Q^2 as stated above we find $Q=0.092\pm0.017\%$. The effect of uncertainties in the resonance parameters, sample thicknesses, etc., are negligible compared with the statistical uncertainty.

As a further consistency check we analyzed the *s*-wave resonance at 2.99 eV for *P* violation. This is a prominent resonance in ^{138}La but shows up much less strongly here because the ^{138}La is only 0.1% abundant in the natural sample. An *s*-wave resonance is not expected to exhibit *P* violation owing to the unfavorable barrier penetration.[2] We see no effect at the same level of sensitivity as the 0.734-eV resonance.

Our results of $Q=0.092\pm0.017$ is consistent with the values of 0.097 ± 0.005 and 0.095 ± 0.003 obtained by transmission and capture, respectively, at KEK but agrees less well with the value of 0.073 ± 0.005 reported from Dubna transmission experiments. Unfortunately this experiment lacks the sensitivity to settle the discrepancy between the KEK and Dubna results, which differ by 5 standard deviations.

FUTURE DIRECTIONS

It is remarkable that the *P* violation effect in slow-neutron resonances is so large that it can be put to practical use in polarizing a neutron beam and conducting a measurement such as that described here. This is the first case where the weak interaction has been used to both polarize and analyze a beam. However, the gains in sensitivity from working with a neutron beam polarized by conventional means are so great that further experiments using the technique described here are difficult to justify. For example, using the material lanthanum-magnesium-nitrate (LMN), which contains a high density of hydrogen by hydration, it is possible[6] to obtain a 70% polarized beam over the energy range 0.25–50 000 eV with a beam transmission of 0.10.

If one assumes an average size for the *P*-violation matrix element of 1 mV, our sensitivity estimates indicate that it should be possible to measure the *P*-violation matrix element for several *p*-wave resonances in a single nucleus in a few days. It should be possible therefore to measure the average matrix element, the distribution in sizes, and the distribution of signs of the matrix elements for a particular nucleus. In a relatively short time one might conduct these measurements on a number of nuclei and study systematics.

Because the strong force conserves parity and the weak force does not, a study of *P* violation in excited many-nucleon systems is actually a study of the manifestation of the weak force in these systems. Although the study of the weak force in the nucleon-nucleon system is fairly complete, it is not possible to predict the effects of the weak force in many-nucleon systems. The analogous situation obtains in the study of the strong force. The understanding of the strong force between nucleons does not allow one to accurately predict the properties of many-nucleon systems. The proposed measurements should make possible the first systematic study of effects of weak force in nuclei. Time reversal invariance violation is also predicted[7] to be strongly enhanced in *p*-wave compound nucleus resonances and is an exciting forefront for extension of these measurements using polarized beams and oriented targets.

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