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Publication Date
1981-10-01

LBL-13411
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Submitted for Publication

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October 1981

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

EVIDENCE OF TIME SYMMETRY VIOLATION IN THE INTERACTION OF NUCLEAR PARTICLES

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Abstract

Measurements of the proton polarization in the $^{7}\mathrm{Li}(^{3}\mathrm{He},\vec{p})^{9}\mathrm{Be}$ and $^{9}\mathrm{Be}(^{3}\mathrm{He},\vec{p})^{11}\mathrm{B}$ reactions and of the analyzing powers of the inverse reactions, initiated by polarized protons at the same CM energies, show significant differences which imply the failure of the polarization-analyzing power theorem and, "prima facie", of time-reversal invariance in these reactions.

This work was supported by the Nuclear Sciences Division of the U.S. Department of Energy under contract No. W-7405-ENG-48, and by the National Research Council of Canada, the Ministry of Education of Québec, and the Bundesministerium für Forschung and Technologie of Germany.

We report here on the first test specifically designed to compare the polarization (P) in a nuclear reaction with the analyzing power (A) in the inverse reaction$^{1)}$. We find substantial P-A differences. The clear implication is that time-reversal invariance (TRI) is broken in some component of the nuclear interaction, since the P-A equality follows directly from TRI$^{2)}$.

The reactions chosen for the P-A comparison were the two-nucleon transfers ^{7}Li(^{3}He,p)^{9}Be and ^{9}Be(^{3}He,p)^{11}B, with 14 MeV incident ^{3}He ions, and their inverses studied at the same CM energies. The Q-values are large implying considerable mass, energy and momentum rearrangement. The measurements of proton polarizations in (^{3}He,$\vec{p}$) reactions were mostly performed at the Van de Graaff Laboratory of Université Laval, using a facility based on Si-polarimeters$^{3)}$ and results have been already published$^{4)}$. The analyzing powers in ($\vec{p}$,^{3}He) were measured at the Berkeley polarized beam facility of the 88" cyclotron$^{5)}$. The ^{3}He detection was effected with two pairs of nominal (20μ, 200μ) Si-detector telescopes and particle identification. The calibration of the particle identifier spectra was performed with the reaction ^{4}He(p,^{3}He)^{2}H. The proton polarization was reversed several times per second with R.F. transitions. For both the P and A measurements, symmetric left-right geometry was used. This symmetry, along with spin-reversal, effectively eliminates systematic errors in the A measurements, and it makes the P measurements insensitive to small transverse displacements of the beam on the target. References 3-6 contain further details of the experimental techniques.

Experimental spectra in both the P and A measurements are shown in Fig. 1a. Backgrounds associated with the ground-state peaks are small, and the P and A values with and without background subtraction are not significantly different. As an example, Table 1 lists the measured polarimeter asymmetries for the P determinations at $\theta_L = 42^o$.

Because of, (a) the substantial P-A differences in our first measurements and, (b) the significance of this result, we repeated and extended the measurements of A, and we made completely independent checks on the measurements of P. The latter checks were made both at Laval and at Berkeley, with different polarimeters at the two locations. The tests at Laval were twofold. Firstly, some points were remeasured with ^{7}Li and ^{9}Be targets of the same thicknesses as those of the original measurements$^{4)}$, PL1. The ^{7}Li remeasurements (PL2, Table II) were made with a 500μ Si polarization analyzer in place of the usual 1000μ analyzer$^{3)}$. This permitted better measurements close to $\theta_{C.M.} = 90^o$. Secondly, measurements were made with significantly thinner targets in order to determine the dependence of the polarization on the energy interval spanned in the target. This was necessary because these energy widths were not identical for the P and A measurements. The conditions for the various measurements are listed in Table II, and the P and A values are compared in Fig.2. Clear and substantial P-A differences are seen.

Since the ($E_{C.M.} + Q$) energies and the energy widths were not identical for the P and A measurements, an excitation function A(E_p, $\theta_L = 37^\circ$) was measured in the ^{9}Be($\vec{p}$,^{3}He)^{11}B reaction at an angle near the peak of the A(θ) angular distribution of Fig.2. This excitation function is shown in Fig.3. Over an energy span of some 800 keV, about 400 keV on either side of the original energy, we find a smooth variation of A(E_p). There are no sharp increases in A(E_p) that could move its value into agreement with P under a small shift in the energy.

A primary concern in our experiments has been the study and correction of instrumental asymmetries of the polarimeters in the measurements of P. The Si polarimeter combines the advantage of high scattering efficiency with good energy resolution, but it suffers the disadvantages of rather low effective analyzing-power and rather high sensitivity to small misalignments in comparison with ^{4}He or ^{12}C polarimeters. With our symmetric left-right geometry, there remain two sources of instrumental asymmetry that cannot be eliminated by the interchange of polarimeters in the procedure followed at Laval. One is a shift away from symmetry in the left-right proton scattering angles of the polarimeter due to a displacement of the target along the beam direction from its geometrically proper position, i.e. the center of rotation of the polarimeters. The other is a similar effect, due to non-uniform illumination of the analyzer over the slit width, caused by the angular distribution of the (^{3}He,$\vec{p}$) cross sections. Fig. 1b) shows a detailed drawing of the geometry of one polarimeter. The angular distributions of these systematic asymmetries, to leading order in the relevant parameters are easily established: for a target displacement ΔZ

$$\varepsilon_Z(\theta_1) \cong \frac{\Delta Z}{R_1}\,[\sigma'(\theta_2)/\sigma(\theta_2)]\,\sin\theta_1 \qquad (1)$$

and for the non-uniform slit illumination

$$\varepsilon_S(\theta_1) \cong -\frac{1}{3}\frac{w_1}{R_1}\frac{w}{R}\frac{\sigma'(\theta_1)}{\sigma(\theta_1)}\left[\frac{\sigma'(\theta_2)}{\sigma(\theta_2)} - 2\sin\theta_2\right] \qquad (2)$$

$\sigma'(\theta_i) = \dfrac{d\sigma(\theta_i)}{d\theta_i}$, $\dfrac{w}{R} = \dfrac{w_1R_2 + w_2R_1}{R_1R_2}$, all remaining symbols are shown in Fig. 1b. Clearly $\dfrac{w_1}{R_1}\,\dfrac{w}{R} \cong \Delta\theta_1(\Delta\theta_1 + \Delta\theta_2)$.

The asymmetry ε_Z at $\theta_i = 45^\circ$ and $\Delta Z = 0.002''$, for example, is approximately 0.005 for the Laval geometry and 0.003 for that of Berkeley. For the measurements of experiment PL4, on ^{9}Be at $\theta_L = 42^\circ$ and 44°, extreme care was exercised in monitoring the target position. Two transits sighting at right angles were used, with one aligned along the beam direction. The target was centered to ±0.001" and thus ε_Z is quite small. The conversion from measured asymmetries to polarizations is accomplished with a computer program which includes all finite geometry corrections calculated not with (2) but exactly, and uses an <u>effective analyzing power</u> for the polarimeters[3,4)]. The latter is a good approximation: in tests subdividing the analyzer detector thickness into ten slices, one obtains an average $A = 0.2413$, to be compared with $A_{eff} = 0.2415$. Table III shows analyzing powers and polarizations at 42° and 44°. Also, an overall experimental check was made routinely in the Laval experiments through a measurement of the proton polarization in ^{2}H(^{3}He,$\vec{p}$)^{4}He reaction.

The agreement with completely independent measurements$^{7)}$ was always within the errors of the separate results.

At Berkeley, a completely different control experiment was possible with the availability of higher energy protons. That is, in experiment PB1 the $^{9}\mathrm{Be}(^{3}\mathrm{He},\vec{p})^{11}\mathrm{B}$ polarizations at $\theta_L = 40^{\circ}$ and 45° were determined by way of a direct comparison with known $^{12}\mathrm{C}(p,\vec{p})^{12}\mathrm{C}$ polarizations. At each angle, measurements were made of the asymmetries $\varepsilon(^{3}\mathrm{He},\vec{p})$ and $\varepsilon(p,\vec{p})$ for the polarized protons from the respective reactions. The proton energy in the $(p,\vec{p})$ scattering was selected so that the energy of the protons incident on the polarimeters was the same as those from the $(^{3}\mathrm{He},\vec{p})$ reaction. The latter polarization was then given simply as

$$P(^{3}\mathrm{He},\vec{p}) = P(p,\vec{p}) \quad \varepsilon(^{3}\mathrm{He},\vec{p})/\varepsilon(p,\vec{p}) \tag{3}$$

Since $P=A$ in $^{12}\mathrm{C}(p,p)^{12}\mathrm{C}$ scattering from parity conservation alone, values of $A(\vec{p},p)$ can be used in Eq.(3). Although literature values of $A(\theta)$ in $^{12}\mathrm{C}(\vec{p},p)^{12}\mathrm{C}$ scattering are available near the proton energy used$^{8)}$, a separate, high statistics measurement was made of $A(\theta)$ at this energy, $E_p = 24.13$ MeV. The statistical errors were in the range of $\Delta A = \pm 0.001$ to 0.003, with an additional absolute scale uncertainty of ±2.1% from the beam-monitoring $^{4}\mathrm{He}$ polarimeter$^{5)}$. From Eq.(3), then, the $P(^{3}\mathrm{He},\vec{p})$ values were given directly from the ratio of the measured asymmetries and the measured $A(\vec{p},p)$ values, and no separate calibration of the polarimeters was required. From Table II and equation (2) is is clear that there is no correction for non uniform illumination of the analyser at 40° LAB and at 45° $\Delta A \cong 0.006$, resulting in $\Delta P \cong 0.018$ (Berkeley polarimeters). The errors on P were thus determined essentially by the statistics on the measured asymmetries.

In view of the substantial P-A differences measured in these reactions, it is relevant to examine the question of why no significant deviations from P-A = 0 have been seen in the previous comparisons that used elastic scattering. The most accurate of these were made on $p+{}^3He$[9] and $p+{}^{13}C$[10]; it is necessary to scatter from a non-zero spin nucleus, otherwise parity conservation alone ensures that P=A. We have found[11] that neither of these comparisons was accurate enough to provide a significant test of TRI, because the equality between P and A depends on the equality of the two possible spin-flip probabilities. It is now known from measurements of the depolarization in p-nucleus elastic scattering that the spin-flip probabilities are very small[12], which leads to $P-A \simeq 0$ even if the probabilities are not equal as required by TRI. Even though the non-spin-flip components alone provide a test of TRI in a reaction, a more inclusive and significant test using the P-A equality is made through-measurements in a reaction and its inverse where the spin-flip probability is expected and known to be large; and this is so for the reactions reported here[4]

Following reports of our preliminary results[11,13], independent determinations of P in the ${}^9Be({}^3He,\vec{p}){}^{11}B$ reaction have been made by a group at Los Alamos[14]. They report a large discrepancy between their preliminary results and our values, with their measurements of P indicating agreement with A in the inverse reaction. Thus, there is now a clear experimental disagreement to be resolved. At the present, however, our lack of detailed knowledge of their experimental procedures precludes an independent evaluation of their results.

In summary, we have found large differences between P in the ^{7}Li(^{3}He,p)^{9}Be and ^{9}Be(^{3}He,p)^{11}B reactions and A of their inverse processes. From such an inequality between P (in a reaction) and A (in its inverse) it is straightforward to conclude that, prima facie, TRI is violated in these reactions. Clearly, more experiments are necessary to corroborate these results, and we are pursuing them. Certainly, confirmation would stimulate much broader investigations into various reactions in order to provide more detailed knowledge of the time-reversal violation interactions.

We are grateful to R.M. Larimer for her assistance during the course of these experiments at Berkeley. The help of P. Bricault and L. Potvin during the measurements at Laval is gratefully appreciated. Dr. S.S. Dasgupta who assisted us during part of the present work is also heartily thanked. This work was supported by the National Research Council of Canada, the Ministry of Education of Québec, the Nuclear Sciences Division and the U.S. Department of Energy under contract No. W-7405-ENG-48, and the Bundesministerium für Forschung and Technologie of Germany.

Footnotes and references

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1. There have been previous P-A comparisons in reactions, but these have been incidental to the main purpose of the experiments. For example, R.A. Hardekopf *et al.*, Nucl. Phys. A191, 468 (1972), compared their $A(\theta)$ results in $^3H(\vec{p},d)^2H$ with the $P(\theta)$ results of others in $^2H(d,\vec{p})^3H$. The P-A differences that can be noted at E_d = 2 and 3 MeV were ignored and, presumably, were attributed to experimental errors in the $P(\theta)$ measurements.

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