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Evidence of Time-Symmetry Violation in the Interaction of Nuclear Particles

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

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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 c.m. energies. The Q values are large implying considerable mass, energy, and momentum rearrangement. The measurements of proton polarizations in (^{3}He,$p_{\rm pol}$) 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 ($p_{\rm pol}$,^{3}He) were measured at the Berkeley polarized-beam facility of the 88-in. cyclotron.[5] The ^{3}He detection was effected with two pairs of nominal (20-μm, 200-μm) 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 rf 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. 1(a). Backgrounds associated with the ground-state peaks are small, and the P and A values with and without background subtraction are not significantly different.

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] (called PL1). The

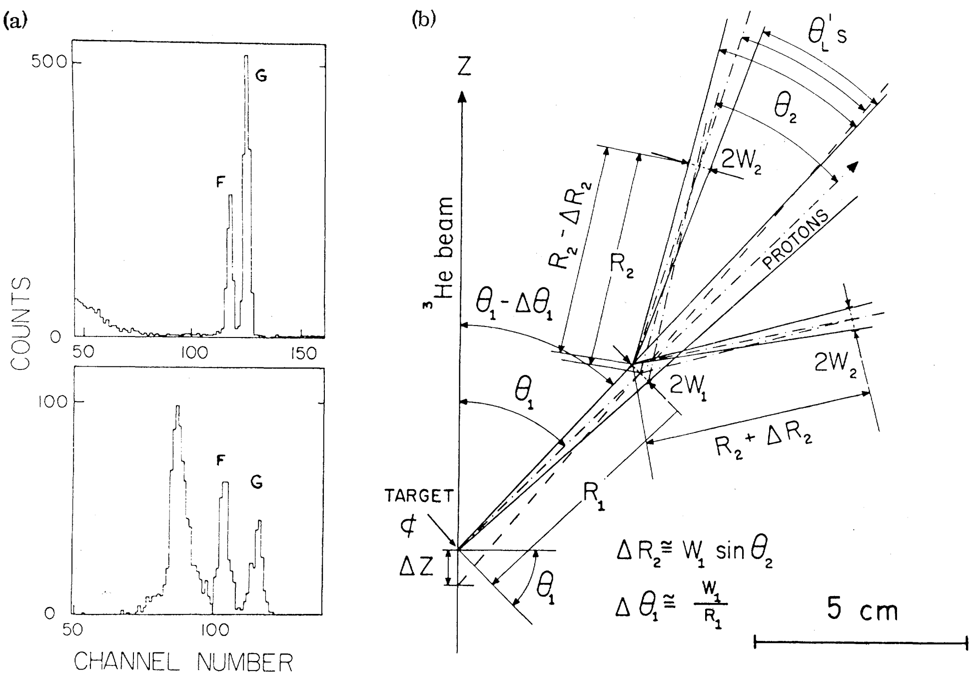

FIG. 1. (a) Sample of experimental spectra. Top: ^{3}He spectrum at 33° from the reaction ^{9}Be($p_{\rm pol}$, ^{3}He)^{7}Li, showing perfect separation of ground (G) and first excited state (F) of ^{7}Li: $\Delta E = 0.47$ MeV. The scale of abscissas is 62 keV/channel. Bottom: ^{9}Be(^{3}He, p)^{11}B polarimeter spectrum at 45° (Laval polarimeter). Each complete measurement consists of a minimum of eight spectra. The measurements at 42° consist of a total of 48 spectra. The measurements at 44° consist of 32 spectra. These spectra also show perfect separation of ground (G) and first excited state (F): $\Delta E = 2.1$ MeV. The abscissa scale is 152 keV/channel. (b) Geometrical layout of the Laval silicon polarimeters. The angles are indicated by θ_i, distances by R_i, and slit widths by w_i. Increments are shown as Δ of the corresponding symbols. The drawing is to scale. The polarization analyzer is a silicon solid-state detector (at R_1); its energy pulse $\Delta E_{\rm anal}$ is added to the left and/or right pulses of the side detectors L and R (at R_2) and permits thereby the use of a fairly thick analyzer, with high scattering efficiency and energy resolution. The asymmetry is $\epsilon = (L - R)/(L + R)$, where L and R are number of counts of left and right peaks.

^{7}Li remeasurements (PL2, Table I) were made with a 500-μm Si polarization analyzer in place of the usual 1000-μm analyzer.[3] This permitted better measurements close to $\theta_{\rm c.m.} = 90°$. 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 I, and the P and A values are compared in Fig. 2.

Since the energies ($E_{\rm c.m.} + Q$) and the energy widths were not identical for the P and A measurements, an excitation function $A(E_p, \theta_L = 37°)$ was measured in the reaction ^{9}Be($p_{\rm pol}$, ^{3}He)^{11}B at an angle near the peak of $A(\theta)$. 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.

There are 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 nonuniform illumination of the analyzer over the slit width, caused by the angular distribution of the (^{3}He,$p_{\rm pol}$) cross sections. Figure 1(b) 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

$$\epsilon_Z(\theta_1) \simeq \frac{\Delta Z}{R_1}\left(\frac{\sigma'(\theta_2)}{\sigma(\theta_2)}\right)\sin\theta_1 \qquad (1)$$

TABLE I. Experimental conditions. $P(\theta)$ measurements PL1–PL4 were made at Laval, PB1 at Berkeley. $A(\theta)$ measurements AB1 and AB2 were made at Berkeley. For the Laval polarimeters $\langle(\sigma'/\sigma)_2\rangle = -0.24$ and about half that value for the Berkeley polarimeters.

Expt.	$E(^3He)$ [a] (MeV)	Target	Thickness (mg/cm^2)	$E_{c.m.}+Q$ [a] (MeV)	$\Delta E_{c.m.}$ [b] (MeV)	$\Delta\theta_1$ [c] (deg)	$\max(\sigma'/\sigma)_1$ [c] (deg^{-1})
PL1 [d] and PL2	13.5	^7Li	3.4	20.63	0.98	2.2[e]	0.033
	13.6	^9Be	2.7	20.51	0.76	2.2	−0.045
PL3	13.5	^7Li	1.85	20.63	0.53	2.6[e]	0.033
	13.6	^9Be	0.65	20.51	0.18	2.6	−0.045
PL4	13.6	^9Be	2.7	20.51	0.76	1.9[e]	−0.045
PB1	13.7	^9Be	2.7	20.63	0.76	0.86	0 at 40° (lab) −0.045 at 45° (lab)
	E_p [a]			$E_{c.m.}$ [a]			
AB1	22.92	^9Be	0.65	20.61	0.1		
	22.37	^{11}B	0.30	20.49	0.1		
AB2	23.05	^9Be	0.45	20.73	0.1		
	22.37	^{11}B	0.30	20.49	0.1		

[a] Energy at center of target.
[b] Energy width spanned by experiment. For (^{3}He,p) it is dominated by the energy spread due to target thickness. For (p,^{3}He) it is dominated by the beam energy width.
[c] Defined in text ($\Delta\theta_1 = \frac{1}{2}$ angle subtended by analyzer slit, i.e., slit accepts $\theta_1 \pm \Delta\theta_1$).
[d] Ref. 4.
[e] With inclusion of multiple-scattering effects in the analyzer 2.2° is increased to 3.1°, 2.6° to 3.5°, and 1.9° to 2.7°.

and for the nonuniform slit illumination

$$\epsilon_S(\theta_1) \cong -\frac{1}{3}\frac{w_1}{R_1}\frac{w}{R}\frac{\sigma'(\theta_1)}{\sigma(\theta_1)}\left(\frac{\sigma'(\theta_2)}{\sigma(\theta_2)} - 2\sin\theta_2\right). \quad (2)$$

Here $\sigma'(\theta_i) = d\sigma(\theta_i)/d\theta_i$, $w/R = (w_1R_2 + w_2R_1)/R_1R_2$; all remaining symbols are shown in Fig. 1(b). Clearly $(w_1/R_1)(w/R) \cong \Delta\theta_1(\Delta\theta_1 + \Delta\theta_2)$. We have $(\epsilon_S)_{max} \cong 0.0015$.

The asymmetry ϵ_Z at $\theta_i = 45°$ and $\Delta Z = 0.002$ in., 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 $\theta_L = 42°$ 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 in. 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 *effective analyzing power* 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 $A_{eff} = 0.2415$. Also, an overall experimental check was made routinely in the Laval experiments through a measurement of the proton polarization in the reaction ^{2}H(^{3}He, p_{pol})^{4}He. 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}Be(^{3}He,p_{pol})^{11}B polarizations at $\theta_L = 40°$ and 45° were determined by way of a direct comparison with known ^{12}C(p,p_{pol})^{12}C polarizations. At each angle, measurements were made of the asymmetries $\epsilon(^3He, p_{pol})$ and $\epsilon(p, p_{pol})$ for the polarized protons from the respective reactions. The proton energy in the (p,p_{pol}) scattering was selected so that the energy of the protons incident on the polarimeters was the same as those from the (^{3}He,p_{pol}) reaction. The latter polarization was then given simply as

$$P(^3He, p_{pol}) = P(p, p_{pol})\epsilon(^3He, p_{pol})/\epsilon(p, p_{pol}). \quad (3)$$

Since $P = A$ in ^{12}C(p,p)^{12}C scattering from parity conservation alone, values of $A(p_{pol}, p)$ can be used in Eq. (3). Although literature values of $A(\theta)$ in ^{12}C(p_{pol},p)^{12}C scattering are available near the proton energy used,[8] a separate, high-

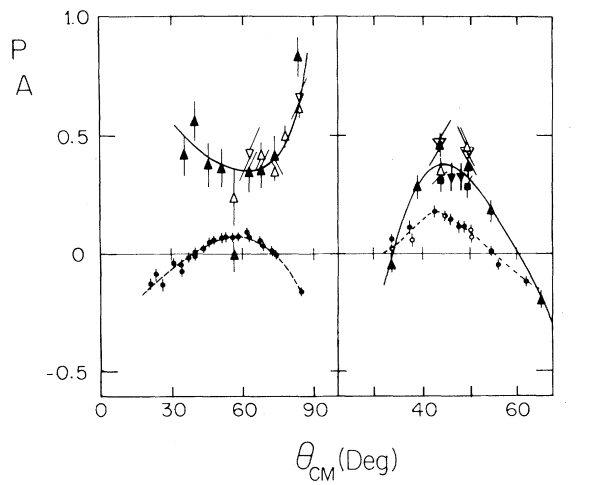

FIG. 2. Left: Comparison of ^{7}Li(^{3}He, p_{pol}) polarizations (triangles) with the analyzing powers in ^{9}Be(p_{pol}, ^{3}He)^{7}Li (dots). Solid and open upright triangles correspond to PL1 and PL2 of Table I. Inverted open triangles correspond to PL3. Dots are from AB2. Right: Comparison of ^{9}Be(^{3}He, p_{pol})^{11}B polarizations (triangles and squares) with analyzing powers in ^{11}B(p_{pol}, ^{3}He)^{9}Be (dots). Open dots are from AB1 of Table I, solid dots from AB2. Upright triangles are from PL1 and PL2 as above. The solid squares are from PB1 (Berkeley polarimeter results). The solid inverted triangles are from PL4, with strict monitoring of the target position. Solid and dashed lines are polynomial fits to the polarization and analyzing powers, respectively. Error bars reflect largely statistical fluctuations and uncertainties in background subtraction.

statistics measurement was made of $A(\theta)$ at this energy, E_p =24.13 MeV. The statistical errors were in the range ΔA =± 0.001 to 0.003, with an additional absolute scale uncertainty of ± 2.1% from the beam-monitoring ^{4}He polarimeter.[5] From Eq. (3), then, the P(^{3}He,p_{pol}) values were given directly from the ratio of the measured asymmetries and the measured $A(p_{pol},p)$ values, and no separate calibration of the polarimeters was required. From Table I and Eq. (2) it is clear that there is no correction for nonuniform illumination of the analyzer at 40°(lab) and at 45° $\Delta A \cong 0.006$, resulting in $\Delta P \cong 0.018$ (Berkeley polarimeters).

Following reports of our preliminary results,[9,10] independent determinations of P in the reaction ^{9}Be(^{3}He,p_{pol})^{11}B have been made by a group at Los Alamos.[11] 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, as measured by the authors of this Letter. 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 reactions ^{7}Li(^{3}He,p)^{9}Be and ^{9}Be(^{3}He,p)^{11}B and A in 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.

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. One of us (F.H.) was supported by a Deutscher Akodemischer Austauschdienst fellowship.

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Nuclear Fluid Dynamics versus Intranuclear Cascade—Possible Evidence for Collective Flow in Central High-Energy Nuclear Collisions

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The predictions of a variety of current theoretical models of high-energy nuclear collisions are compared with recent experimental data for central collisions of ^{20}Ne on ^{238}U at $E_{lab} = 393$ MeV/u. The experimental observation of broad sideward maxima in the angular distributions of low- and medium-energy protons is reproduced by a nuclear fluid-dynamical calculation with final freezeout of the protons. In contrast, the current intranuclear-cascade and simplified collision models predict forward-peaked angular distributions.

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High-energy nuclear collisions offer a unique opportunity to probe nuclear matter at high density and temperature. However, a precise knowledge of the reaction dynamics is required to extract information on the bulk properties of nuclear matter from the experimental data.

It has been pointed out that the large pressure in the high-density, high-temperature matter should cause a collective hydrodynamical sideways flow.[1,2] Quite early experiments[2] reported sideward maxima in the angular distributions of α particles emitted from high-multiplicity selected, i.e., central, collisions. On the other hand, inclusive, i.e., impact-parameter averaged, data[3,4] on light-fragment emission do not show sideward-peaked angular distributions. However, the measured azimuthal correlations between light and heavy fragments[5] exhibit signatures of the hydrodynamical bounce-off effect,[6,7] and so do the two-proton correlations[8] in heavy systems.

From the inclusive data[3] it was in general not possible to differentiate between the existing dynamical models. Possible differences are washed out by the impact-parameter averaging.[9] Hence, recent high-multiplicity selected data[10] for Ne (393 MeV/u) + U → light fragments have received great attention. It is the purpose of the present work to compare the predictions of several distinct model calculations for this reaction and to provide a test of these models by a direct con-