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BREAKDOWN OF TIME REVERSAL INVARIANCE IN THE INTERACTION OF NUCLEAR PARTICLES

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Abstract

Measurements of the proton polarization in the $^{7}Li(^{3}He,\vec{p})^{9}Be$ and $^{9}Be(^{3}He,\vec{p})^{11}B$ 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.

References 4 and 5 contain adequate descriptions of the experimental techniques. Comprehensive results for P and A measurements in the $^{7}Li(^{3}He,p)^{9}Be$ and $^{9}Be(^{3}He,p)^{11}B$ reactions and their inverses are shown in Figs. 1 and 2. Because of, (a) the substantial P-A differences in our first results and, (b) the significance of this finding, 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 targets of the same thicknesses as those of the original measurements[4], i.e. 2.7 mg cm^{-2} ^{9}Be and 3.4 mg cm^{-2} ^{7}Li targets. The ^{7}Li remeasurements were performed with a 500μ Si polarization analyzer, whereas the usual operation is with a 1000μ analyzer[3]. This permitted better measurements close to 90^{o} CM. In general all new results, shown in Figs. 1 and 2, are in very good agreement with the older data[4]. Secondly new measurements were performed with significantly thinner targets, 0.65 mg cm^{-2} ^{9}Be, and 1.85 mg cm^{-2} ^{7}Li targets, one fourth and one half, respectively, the thickness of the original targets. Thus a possible energy dependence of the polarization could be ascertained. The new measurements on ^{7}Li do not show any significant difference with respect to the thick target results (Fig.1). The new thin target results on $^{9}Be(^{3}He,\vec{p})^{11}B$ seem to show a trend of increasing the polarization (Fig.2). This leads us to the measurements performed as a test with the Berkeley polarimeters[6]. The technique consisted in a direct measurement of the effective analyzing power of the Si polarimeter using the elastic scattering of protons off carbon, at the proton energy of the reaction and angles to be measured. The ^{9}Be target was 4.6 mg cm^{-2} thick, 60% thicker than the 2.7 mg cm^{-2} Laval target, and seven times thicker than the thin Laval target. The values of the polarization measured at Berkeley are somewhat lower than those obtained at Laval. However this is quite consistent with the apparent energy dependence of the thick and thin target measurements at Laval (i.e. the polarization decreases with increasing energy bite), as shown in Fig.2. In summary, no significant energy dependence was observed with either target, and the $^{9}Be(^{3}He,\vec{p})$ thin target polarization results tend to increase the discrepancy with respect to the analyzing-power measurements of the inverse reaction.

In view of the very large P-A differences measured in these reactions, it is important 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 $p+{}^{3}He$[7)] and $p+{}^{13}C$[8)]; it is necessary to scatter from a non-zero spin nucleus, otherwise parity conservation alone ensures that P=A. We have found[9)] 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. And, it is now known from measurements of the depolarization in p-nucleus elastic scattering that the spin-flip probabilities are very small[10)], which leads to P-A≃0 even if the probabilities are not equal as required by TRI. As shown in ref.8,

$$P-A = (\sigma^{-+} - \sigma^{+-})/\sigma \quad , \qquad (1)$$

where σ^{-+} is the cross section for the scattering of a proton from an initial negative spin-state to a final positive spin-state, and $\sigma = (\sigma^{++}+\sigma^{+-}+\sigma^{-+}+\sigma^{--})/2$. The positive (+y) direction is along $\vec{k}_i \times \vec{k}_f$, and $\sigma^{-+} = \sigma^{+-}$ under TRI. Since the depolarization parameter is given by

$$D = 1-2S \qquad (2)$$

with the (total) spin-flip probability

$$S = (\sigma^{+-}+\sigma^{-+})/2\sigma \quad , \qquad (3)$$

measurements of D provide determinations of S. Now assume, for example, that $\sigma^{+-} = 2\sigma^{-+}$, which would be a clear and substantial breaking of TRI. Then, from Eqs. (1)-(3)

$$|P-A| = (1-D)/3 \ . \qquad (4)$$

From the measurement[11] of $1-D = 0.05 \pm 0.03$ close to the energy and angle of the p-^{3}He experiment[7] and an estimate[9] of $1-D \leq 0.06 \pm 0.02$ at the energy and angle of the p-^{13}C experiment[8], Eq. 4 gives $|P-A| \leq 0.017$ and 0.02, respectively. These values are essentially as small as the experimental errors in these P-A comparisons, so the experiments do not provide tests of TRI.

It is immediately obvious from this discussion that tests of TRI using the P-A equality should be made through measurements in a reaction and its inverse where the spin-flip probability is expected or known to be large, and this is so for the reactions reported here[4].

Since spin-exchange forces are well known components of the nucleon-nucleon interaction, we have also examined the, perhaps, most recent test of TRI in p-p scattering[12]. We have found[9] that here, also, no test of TRI was really made. The experiment used a 430-MeV beam of polarized protons, with the polarization vector lying in the scattering plane and oriented at 45^{o} to the beam direction. After scattering once to the left and once to the right at $\theta_L = 30^{o}$, the in-plane polarization orientations for the separate scatterings were compared. We find that the reported result follows directly from invariance with respect to rotation about the beam axis, so TRI was not tested. Again, it follows from the discussion above that tests of TRI in the basic nucleon-nucleon interaction should be made in p-p and/or n-p scattering through comparisons of P and A at energies and angles for which the quantity (1-D) is maximized.

Returning to our results, it is straightforward to conclude that, "prima facie", TRI is violated. However, it is less simple to evaluate the fraction of the transition (T) matrix elements that is violating TRI The spin-space $\overrightarrow{1/2} \otimes \overrightarrow{3/2}$ is exceptionally big and there could be a considerable enhancement of the difference between the observables P and A, although the violation of TRI of the basic interactions may remain modest[13]. It is also possible that off-the-energy shell virtual processes (including multistep processes) contribute also to an enhancement of effects due to basic violations of TRI in strong and electromagnetic interactions. A full determination of the T-matrices for both direct and inverse reactions is indicated, in order to determine the difference between T and T^{inv}, but this means a colossal work in view of the spin space of these reactions.

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. Since such an inequality between P (in a reaction) and A (in its inverse) directly implies a breakdown of TRI, it follows that this is clear evidence that the interaction of nuclear particles is not time-reversal invariant. Clearly, many more experiments are necessary to detail the TRI breaking interactions, and the theoretical consequences that follow from the CPT theorem[14)] are yet to be explored.

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Footnotes and references

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Figure Captions

FIG.1 Comparison of $^{7}Li(^{3}He,\vec{p})^{9}Be$ polarizations of outgoing protons with the analyzing powers in $^{9}Be(\vec{p},{}^{3}He)^{7}Li$. The triangles are polarizations. The dots are analyzing powers at an incident proton energy of 22.9 MeV. Solid triangles are from Ref.4, open triangles are remeasurements (see text), inverted triangles are thin target results. Also shown by arrows are the energy bites of the polarization and analyzing power measurements due to target thickness and beam energy resolution, together with the energy scale. Solid lines are polynomial fits through the data. Incident ^{3}He energies of experiments of Ref.4 were 14.0 MeV. Subsequent experiments were performed reducing the energy to match the energies at the target center.

FIG.2 Comparison of $^{9}Be(^{3}He,\vec{p})^{11}B$ polarizations with analyzing powers in $^{11}B(\vec{p},{}^{3}He)^{9}Be$. The incident proton energy was 22.4 MeV. The triangles are as in Fig.1. The solid squares are the polarization measurements with the 4.6 mg cm^{-2} target at Berkeley. The open dots are analyzing powers measured in an experiment performed in 1979, the solid dots in 1980, at Berkeley. Solid and dashed lines are polynomial fits to the polarization and analyzing power data respectively. Shown by arrows are the energy bites of the polarization and analyzing power measurements, as in Fig. 1.

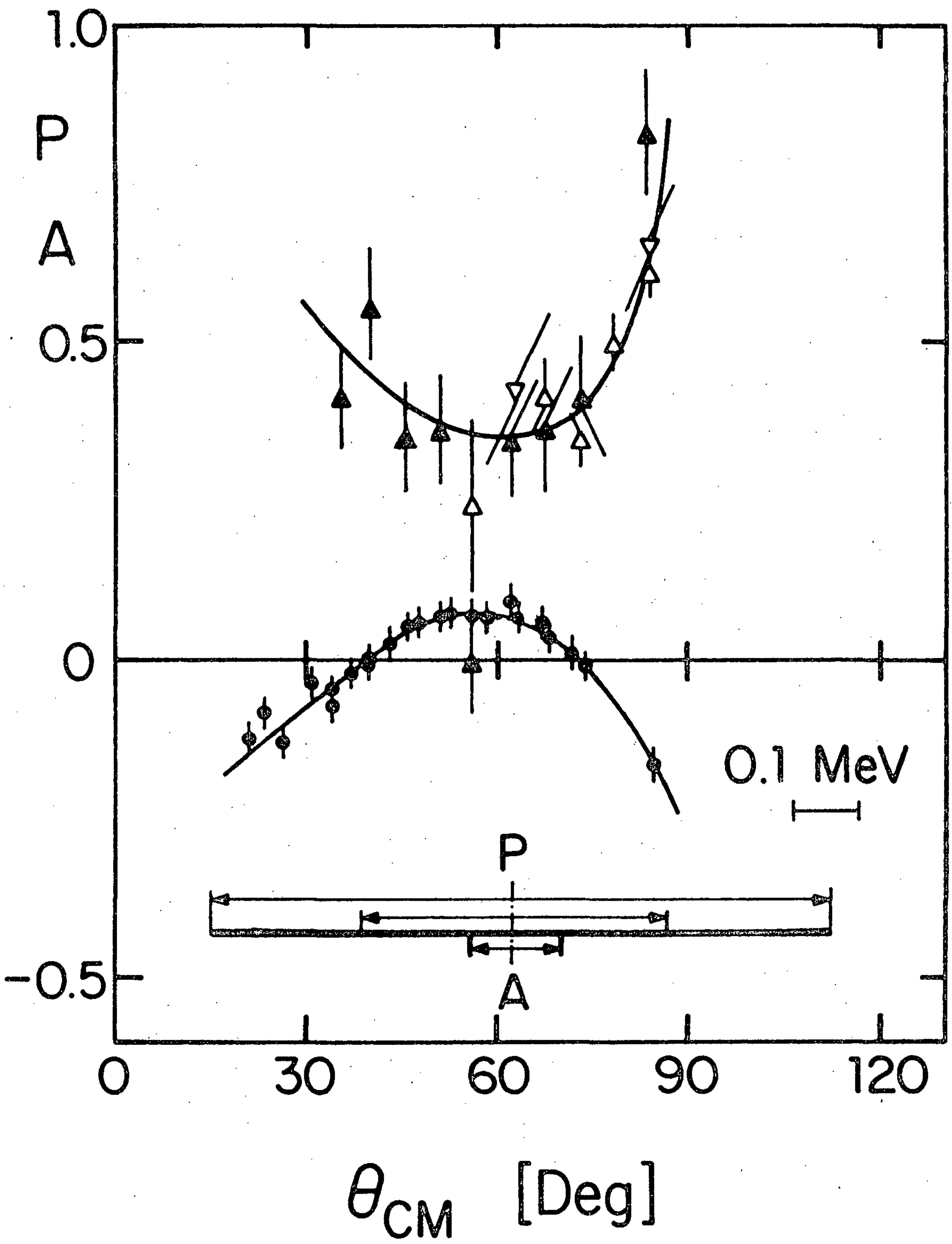

Fig. 1

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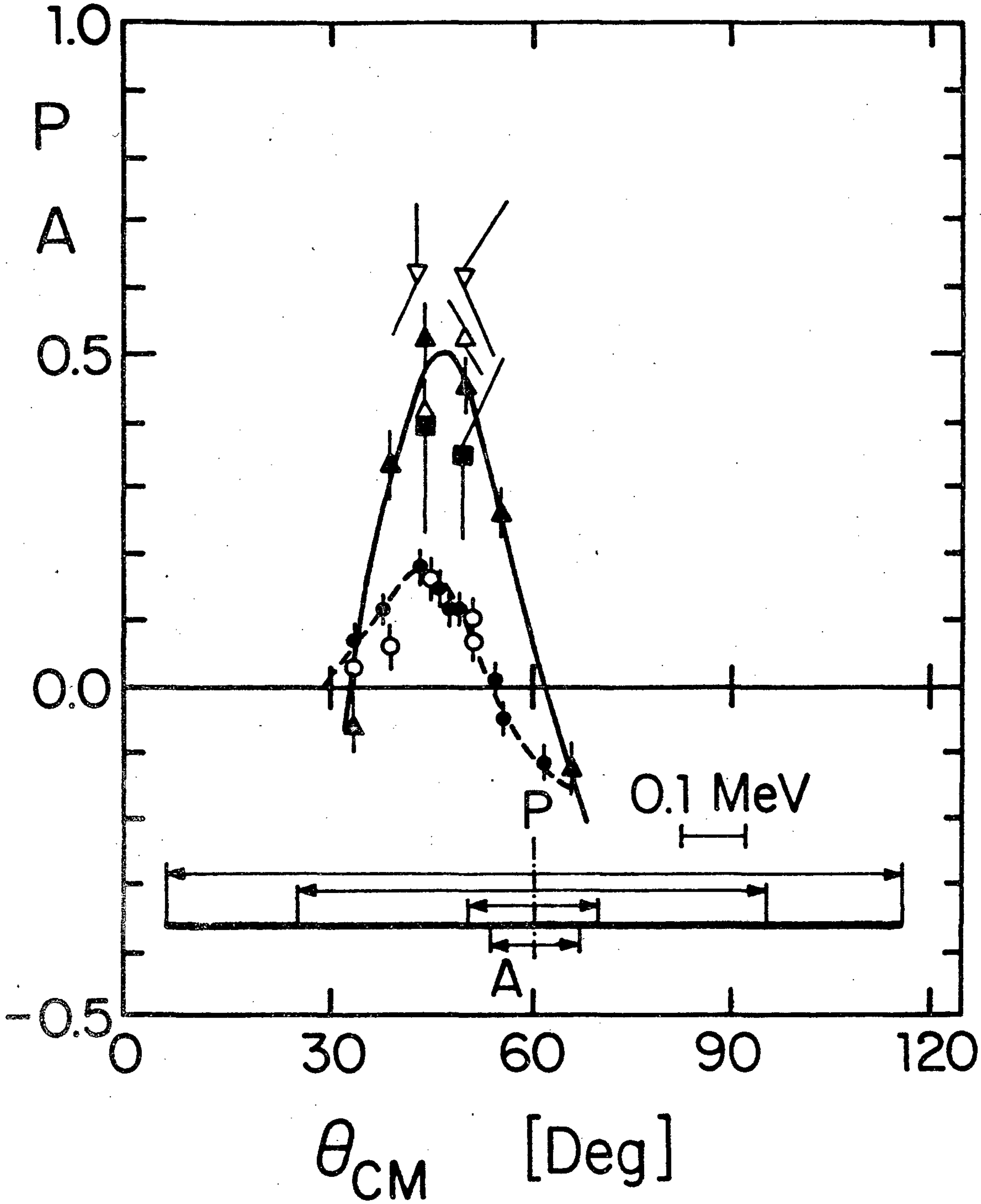

Fig. 2

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