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Polarization-analyzing power equality as a test of time-reversal invariance in strong interactions

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The polarization of protons from the $^7Li(^3He,\vec{p})^9Be$ reaction was measured at four laboratory angles between 70° and 85° at a bombarding energy of 14 MeV. The results are in marked disagreement with earlier reported measurements performed under similar conditions. A comparison between our polarization measurements and previous analyzing power measurements for the inverse reaction initiated by polarized protons shows no evidence for violation of time-reversal invariance as claimed.

One of the tools to observe possible T-violating effects in strong interactions is to measure $(P-A)$: the difference between the polarization of the particles produced in a nuclear reaction initiated by unpolarized projectiles (P) and the analyzing power (A) in the exact inverse reaction induced by polarized particles. If the Hamiltonians of the interactions involved are invariant under the time-reversal operation, then the polarization and the analyzing power must be equal.

Three years ago the results of an experiment to test time-reversal invariance (TRI) were reported in which the proton analyzing powers A in the $^9Be(\vec{p},{}^3He)^7Li$ and $^{11}B(\vec{p},{}^3He)^9Be$ reactions were compared with the proton polarizations P in the inverse reactions, $^7Li(^3He,\vec{p})^9Be$ and $^9Be(^3He,\vec{p})^{11}B$, respectively.[1] TRI demands that $P=A$ at the same center-of-mass energy and angle for each pair of reactions. Significant differences were observed (Fig. 1). The magnitude of these discrepancies was too large to be attributed to other than strong interaction processes.

Following this announcement, a group at Los Alamos[2] repeated the measurement of the polarization of protons from the $^9Be(^3He,\vec{p})^{11}B$ reaction between 35° and 50°. Their results were in disagreement with those of Slobodrian *et al.*[1]

We undertook an experiment to measure independently the polarization of the protons from the reaction $^7Li(^3He,\vec{p})^9Be$ at the center-of-mass angles where the largest discrepancies between the polarization and analyzing power had been observed. This experiment, involving the reaction of ^3He with ^7Li in which protons are produced and then elastically scattered by an analyzer, is clearly the more difficult to perform. We have accepted the measurement of A with their small statistical errors as previously reported.[1]

We attempted to address a number of possible causes for the large discrepancies between P and A. First of all, we used carbon rather than silicon as an analyzer of the proton polarization; at the relevant energies carbon has an analyz-

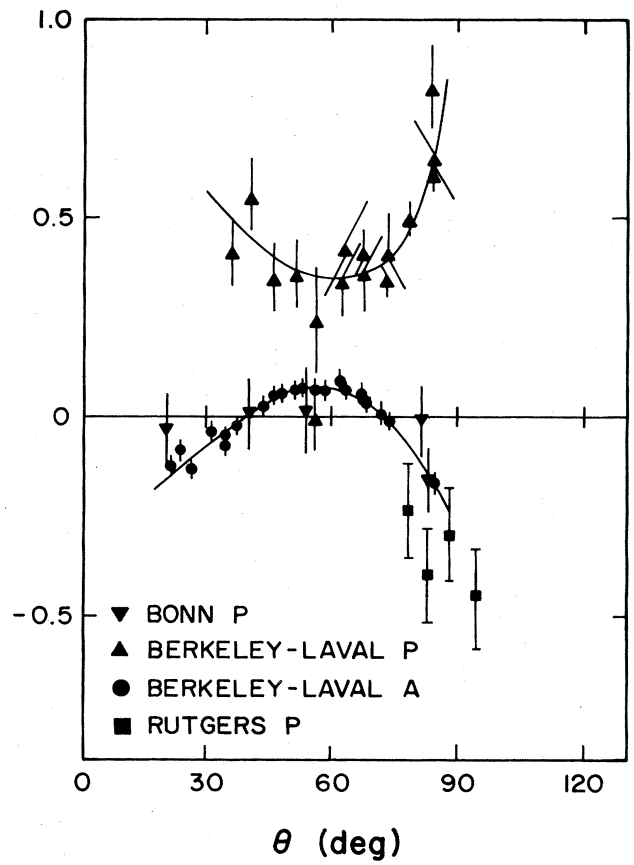

FIG. 1. Polarization (▲) and analyzing power (●) data of Ref. 1, and present polarization (■) measurements for $^7Li(^3He,\vec{p}_0)^9Be$. Results for P from Ref. 7 also plotted (▼).

ing power of 0.61 whereas the value for silicon is only 0.21, making the measurement with the latter more difficult. Another suggestion was that the observed discrepancies might arise from compound-nucleus fluctuations; the projectile energies (and hence the average compound-nucleus excitation energy ranges) for the two inverse reaction targets might not be precisely matched. We measured an excitation function for the ^{7}Li(^{3}He, p$_0$)^{9}Be differential cross section over the relevant experimental energy range in $\sim$100-keV steps and observed no fluctuations.[3] Another suggested cause of difficulty concerns the deuterons produced in the reaction ^{7}Li(^{3}He, $\vec{d}_0$)^{8}Be which could create a serious source of contamination in the reaction of interest here.[4] It turns out that over the angular interval of our measurements, the energy difference between these deuterons and the ground-state protons amounted to at least 2 MeV; nevertheless, we took special precautions to reject these deuterons as described next.

The experiment was carried out using the Rutgers 8 MV FN Tandem Van de Graaff accelerator. A duoplasmatron source produced a 4-μA beam of ^{3}He ions which were then accelerated to 14 MeV. An average current of 200 nA was obtained on target. The target was a 2.8 mg/cm^2 rolled metallic lithium foil with an effective thickness of 3.1 mg/cm^2 when the target normal was set at 25° to the beam axis. The energy loss in the target was 0.924 MeV, giving an average beam energy of 13.5 MeV.

Three sets of current-measuring slits were used to keep the beam accurately centered on target. A beam spot of about 2×2 mm was produced at the center of the target chamber. The first set of slits was located about 2 m from the center of the last quadrupole lens, with an opening of 4×4 mm. The second set of upstream slits was located 76 cm from the first set, and 60 cm from the center of the target chamber. They had an opening of 3×3 mm. A third set of slits was located at the exit of the scattering chamber at a distance of 101 cm from the chamber's center. A slit amplifier system was used to monitor the drift of the beam direction to within ±0.1°.

The polarimeter consisted of a 40 mg/cm^2 thick carbon analyzer foil, two $(\Delta E-E)$ surface barrier detector telescopes, a thick monitor detector, collimation apertures, and aluminum absorber foils. A schematic diagram of the polarimeter and its placement relative to the accelerator beam and primary lithium target is shown in Fig. 2. A 2.5×5.1 mm aperture placed 48.3 mm from the center of the first target defined the acceptance angle of ±2° of the polarimeter. Particles emitted from the lithium target were detected in the telescopes after scattering from the carbon analyzer through 47±8.5° to the left and right of the normal to the analyzer foil, respectively. The acceptance angle of each telescope was defined by an aperture before the E detector. The monitor detector shown in the center of the polarimeter in Fig. 2 allowed us to monitor the condition of the target and spectrum quality during the course of the experiments. Such a spectrum is shown in Fig. 3; note that all particles coming from the ^{7}Li+^{3}He reaction can be seen here without discrimination, and with good statistics. The additional absorber inserted in front of the monitor insured that all particles stopped in this detector. Except for the 47° scattering angle these particles have undergone the same interactions as those entering the two telescopes.

The data were collected with a typical slow coincidence circuit feeding into a CAMAC-based data-acquisition system.

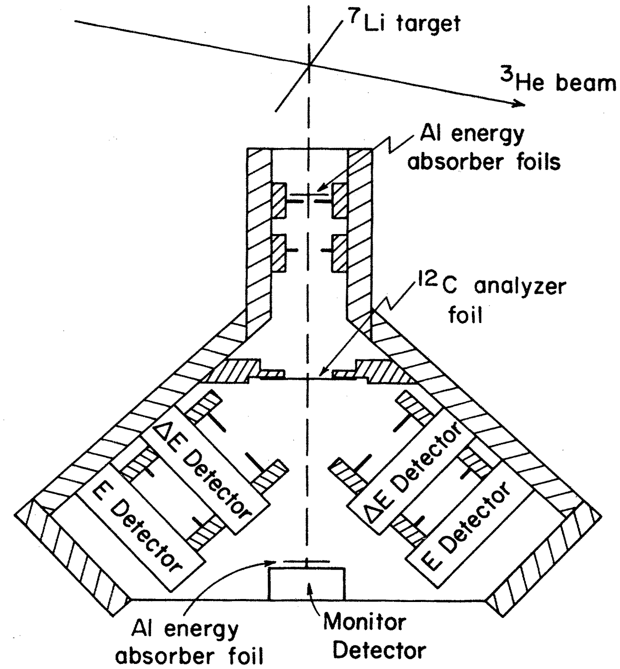

FIG. 2. Rutgers polarimeter showing experimental geometry and placement of Al energy absorber foils and C analyzer foil.

The coincidence served two purposes: simple particle identification through differential energy loss, and reduction of the random background. The upper- and lower-level discriminators, as well as the timing requirements and energy calibration of the entire system were determined by in-

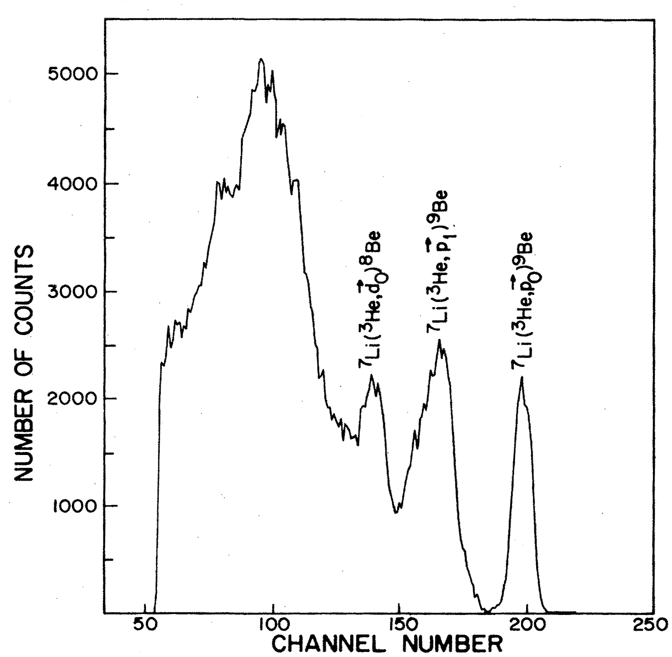

FIG. 3. Typical particle energy spectrum from the monitor detector at 75° (lab). This spectrum is identical to those viewed by the telescope detectors (cf. Fig. 4) except for the scattering angle and particle-type discrimination.

jecting a very low current beam of 16.0-MeV protons directly into the polarimeter set at 0°. The discriminators were adjusted such that particles falling 2 MeV or more below the elastic protons from carbon would not appear in the final spectrum. The energy interval to the inelastic proton group leading to the 4.4 MeV first-excited state of ^{12}C was used for this calibration. The resolving time of 3.0 μsec resulted in a negligible random coincidence rate in view of the extremely low counting rates from the discriminators.

The stability of the data acquisition system was checked with a pulser and resistive divider network that simulated pulses from the $(\Delta E - E)$ detector telescope. The observed drift in the timing over several days was determined to be less than 3% of the resolving time of the circuit. The gain drift of the amplifiers was less than 1% (two channels) or equivalently 200 keV in the total energy spectrum. Since the energy interval between the ground state and first-excited state proton group in the $^7Li(^3He,p)^9Be$ is about 1600 keV, this gain shift did not noticeably affect our results.

As an overall check of the polarimeter, data acquisition system, and beam positioning slits, the polarization of 16-MeV protons elastically scattered from ^{12}C was measured. The procedure for this measurement was identical to that used for the $^7Li(^3He,\vec{p}_0)^9Be$ polarization measurements. The polarization measured in this test, 0.475 ± 0.030, agreed satisfactorily with the published value 0.454 ± 0.010.[5] This indicates that the systematic errors in our measured polarizations are small ($\sim \pm 0.02$) compared to the statistical errors ($\sim \pm 0.15$).

Polarization measurements for the $^7Li(^3He,\vec{p}_0)^9Be$ reaction were carried out at 70°, 75°, 80°, and 85° in the laboratory system. At each energy the thickness of the energy absorbers was chosen so that the average energy of the ground-state proton group at the center of the analyzer foil was 18.1 MeV. In this energy range the analyzing power of carbon is well known.[5] Instrumental asymmetries were minimized by taking data sequentially on opposite sides of the accelerator beam axis. Remaining asymmetries caused by beam misalignment, translation of the target parallel to the beam axis and variations of the cross section across the analyzer foil were not eliminated by this procedure. We did measure the angular variation of the $^7Li(^3He,p_0)^9Be$ cross section and found it to be essentially flat.[6] Using this information, we performed a computer simulation allowing for the finite acceptance angles of the analyzer foil as well as those of the polarimeter telescopes, yielding negligible instrumental asymmetries (less than 0.01); in addition, the polarimeter calibration using carbon as a primary target described above leads us to set a limit of ± 0.02 to the uncertainty in our determination of P, which is very small compared to the quoted statistical errors.

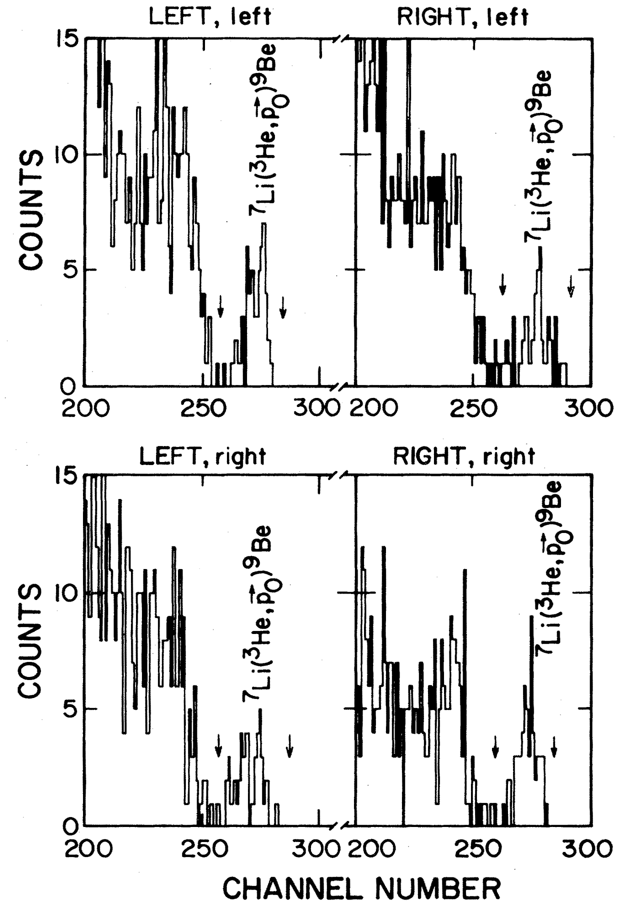

FIG. 4. Typical recorded polarization detector-telescope spectra at 75° laboratory angle. "LEFT," "RIGHT" refer to the polarimeter position relative to the beam; "left," "right" refer to the telescopes at fixed angle of 47° with respect to the center line of the polarimeter. The vertical arrows indicate the limiting channels between which the ground-state proton groups were summed.

Sample telescope spectra typical of a complete polarization measurement are shown in Fig. 4. The vertical arrows indicate the channels between which we summed the counts corresponding to the highest energy proton groups leading to the ground state of ^9Be. The energy calibration was obtained as described earlier, and yielded the energies for the highest energy proton and deuteron groups listed in Table I.

Our results for the polarization measurements in the $^7Li(^3He,\vec{p}_0)^9Be$ reaction are listed in Table II and are also

TABLE I. Energies of the proton and deuteron groups.

$\theta_{lab} = 75°$	Average energy after target (MeV)	Average energy after absorbers (MeV)	Average detected energy after 2nd scattering (MeV)
$^7Li(^3He,p_0)^9Be$	19.6	18.5	16.3
$^7Li(^3He,p_1)^9Be$	18.0	16.9	14.6
$^7Li(^3He,d_0)^9Be$	18.1	16.1	11.8

TABLE II. Results for the polarization measurements in the $^{7}Li(^{3}He,\vec{p}_0)^{9}Be$ reaction.

θ_{lab}(deg)	$\theta_{c.m.}$(deg)	Polarization (P)
70.0	78.1	-0.23 ± 0.12
75.0	83.3	-0.33 ± 0.12
80.0	88.4	-0.28 ± 0.16
85.0	93.5	-0.40 ± 0.12

plotted in Fig. 1; they are in complete disagreement with those reported in Ref. 1. After our measurements were nearly completed, we learned of polarization measurements for the same reaction at laboratory angles between 20° and 75° by Trelle *et al.*[7] The authors used a magnetic spectrograph to separate the ground-state protons before they were scattered by a carbon analyzer foil. Their results are also displayed in Fig. 1, and are seen to be consistent with our measurements within the quoted uncertainties.

We believe that the outcome of our measurements, together with those of Refs. 2 and 7, do not support evidence for time-reversal invariance violation claimed by the Berkeley-Laval collaboration.[1]

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