^{9}Be(^{3}He, $\vec{p}$)^{11}B polarization and implications for time-reversal invariance

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We have measured the polarization of protons from the ^{9}Be(^{3}He,$\vec{p}$)^{11}B reaction between 35° and 50° at an incident bombarding energy of 13.6 MeV to check claims of time-reversal noninvariance. We find complete disagreement with other polarization measurements for the same energy and angular range, but our results are in agreement with earlier measurements of the analyzing power in the inverse reaction initiated with polarized protons. Consequently we maintain that this reaction and its inverse exhibit no evidence for a violation of time-reversal invariance.

[NUCLEAR REACTIONS ^{9}Be(^{3}He,$\vec{p}$)^{11}B; $E=13.6$ MeV; measured $P(\theta)$, $\theta(\text{lab})=35°, 40°, 45°, 50°$.]

Attendees of the Fifth International Polarization Symposium were surprised to hear the results of an experiment designed to test time-reversal invariance (TRI).[1] The experiment compared proton analyzing powers, A, in the ^{9}Be($\vec{p}$, ^{3}He)^{7}Li and ^{11}B($\vec{p}$, ^{3}He)^{9}Be reactions, with proton polarization values, P, in the inverse reactions, ^{7}Li(^{3}He, $\vec{p}$)^{9}Be and ^{9}Be(^{3}He, $\vec{p}$)^{11}B, respectively. In each pair of reactions, TRI requires[2] that $P=A$ at the same center-of-mass energy, $E_{\text{c.m.}}$, and angle θ. However, Ref. 1 reported differences between P and A in both reactions. In the ^{9}Be(^{3}He, p)^{11}B reaction at $E_{\text{c.m.}}=10.2$ MeV and $\theta=45°$, for example, they report that the polarization[3] is about 2.5 times the analyzing power. We felt compelled to corroborate the experiment because of the profound implications of such a large time-reversal noninvariance effect.

The proton analyzing powers for the ^{11}B($\vec{p}$, ^{3}He)-^{9}Be reaction were measured by Conzett in a single-scattering experiment with a thin ^{11}B target and a beam of 22.4-MeV polarized protons.[1] The analyzing power measurement consisted of detecting the number of particles scattered to the left (L) and to the right (R) as a function of scattering angle, θ. The ratio $(L-R)/(L+R)$ is the product of the beam polarizaton, which was known, and the analyzing power, $A(\theta)$, which was to be determined.[4]

The inverse of the ^{11}B($\vec{p}$, ^{3}He)^{9}Be reaction for 22.4-MeV protons is obtained by reversing all the nuclear spins and the particle momenta. This transformation leads to the ^{9}Be(^{3}He, $\vec{p}$)^{11}B reaction, where the incident unpolarized ^{3}He beam has 13.6-MeV energy ($E_{\text{c.m.}}=10.2$ MeV) and the polarization, $P(\theta)$, of the outgoing protons is to be determined. We measured this polarization by scattering the protons from a secondary target of known analyzing power which, along with left and right detectors, forms a polarimeter (see Fig. 1). In this experiment, $(L-R)/(L+R)$ is the product of the polarimeter analyzing power and the polarization, $P(\theta)$, which is being determined. When $P(\theta)$ and $A(\theta)$ are measured in this way, TRI requires[2] that $P(\theta)=A(\theta)$.

We used a 14.3-MeV beam of ^{3}He^{++} ions from the Los Alamos Tandem Accelerator Facility to produce protons in the primary target, a 4.7-mg/cm^{2}-thick metallic foil of ^{9}Be. The energy loss in the foil was 1.4 MeV, giving an average beam energy of 13.6 MeV. Two sets of four current-measuring slits with

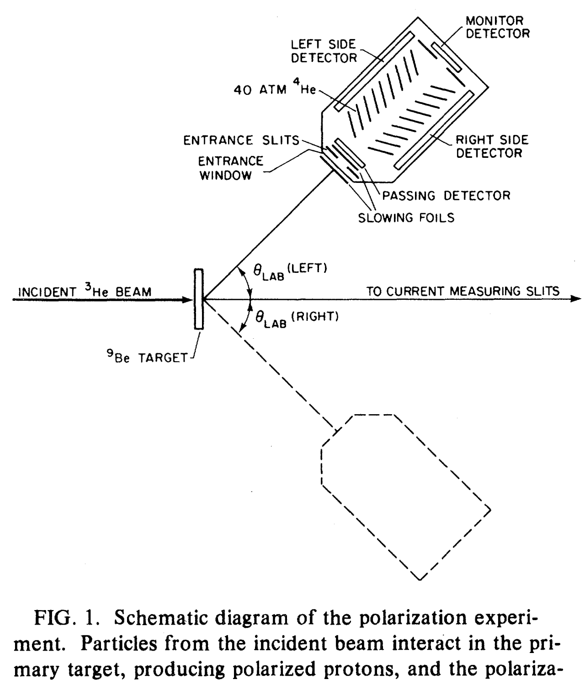

FIG. 1. Schematic diagram of the polarization experiment. Particles from the incident beam interact in the primary target, producing polarized protons, and the polarization is measured as a function of angle by scattering the protons from helium and measuring the left-right asymmetry. Moving the polarimeter to the right side of the beam allows us to eliminate effects due to differences in detector efficiencies.

an opening of 3.2×3.2 mm^2 and separated by 1.3 m kept the beam centered on the foil in the center of the supercube[5] target chamber. We took runs with the polarimeter left and right of the beam axis and averaged the results in the manner described in Ref. 4.

The helium polarimeter[6] was developed and calibrated in previous experiments for incident proton energies from 6 to 16 MeV. It is depicted schematically in Fig. 1 and described in detail in Ref. 6. Physically, it is a cylindrical aluminum chamber 10 cm long and 10 cm in diameter. The polarimeter contains ^{4}He gas at 40 atm pressure, and along the axis it presents a 5-cm path length of "active" region (or secondary target) for analyzing the polarization of protons. Copper vanes 0.25 mm thick define the angle for protons scattered by helium in the active region. Protons scattered by 60° to the left or to the right are detected by two 5-cm-long by 1-cm-high silicon detectors, each 1000 μm thick.

The entrance window to the polarimeter is a 40-mg/cm^2-thick stainless steel foil. Just inside the window, a 0.8-mm-thick Ta collimator containing a 4.1-mm-square aperture defines the solid angle subtended by the polarimeter. This limiting aperture was located 7.6 cm from the primary target yielding an angular acceptance of $\pm 1.5°$. Particles entering the polarimeter were registered by a 500-μm-thick silicon transmission "passing" detector that resolved the proton groups associated with the ground state and 2.1-MeV first excited state of ^{11}B. Protons entering the polarimeter pass through the window, the aperture, and the passing detector and enter the active region. Protons not scattered by ^{4}He travel to the back of the polarimeter and enter another silicon detector that monitors the proton energy. This energy determination provides a connection with earlier calibration curves for the polarimeter.[6]

Protons from the ^{9}Be(^{3}He, $\vec{p}$)^{11}B reaction struck the polarimeter with an energy of about 22 MeV. Two 287-mg/cm^2-thick tantalum foils, one in front of the window and one behind it, slowed the protons to about 15 MeV, yielding energies at the monitor between 7.3 and 9.5 MeV. From below 7 to above 10 MeV the analyzing power is very nearly independent of energy (see Fig. 3 of Ref. 6) and has a value of -0.63 ± 0.02.

To confirm the analyzing power of the polarimeter and check our experimental setup with high-energy protons from a solid target, we used the ^{12}C$(t,p)^{14}$C reaction. Conservation of parity requires that $P = A$ for this reaction[7] since it involves nuclei for which the total angular momenta and parities, J^π, are $\frac{1}{2}^+ + 0^+ \rightarrow \frac{1}{2}^+ + 0^+$.

First we measured the triton analyzing power as a function of angle with 17-MeV polarized tritons[8] incident on a 1.9-mg/cm^2-thick carbon target (see the curve of Fig. 2). Then we repeated the measurements at 50° with a 4.9-mg/cm^2-thick target and

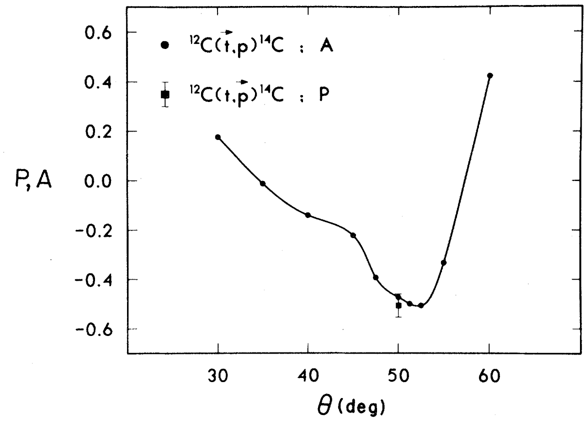

FIG. 2. Measured polarization (square point) and analyzing power (dots and curve) for the ^{12}C$(t,p)^{14}$C reaction at 17.0 MeV. The two quantities are known to be equal from parity conservation. We measured the polarization point to check the analyzing power of the helium-filled polarimeter and to confirm our calculations showing that instrumental effects were not significant for a solid primary target in our geometery.

found no change. Finally we measured the proton polarization in the same reaction, this time using the double scattering apparatus, the thicker target, and an unpolarized triton beam. We reduced the proton energy at the polarimeter monitor detector to 8.9 MeV by placing only one of the 287-mg/cm^2-thick tantalum foils in front of the polarimeter. The result, $P = -0.51 \pm 0.05$ (also shown in Fig. 2) is in agreement with the measured analyzing power, $A = -0.47 \pm 0.02$.

All of the data were recorded on line using a MODCOMP computer and CAMAC based interface. Particles registered in the left and right detectors are stored in the computer if they occur in coincidence with pulses in the passing detector (see Fig. 1). Pulses from the left and right detectors each initiate a start signal for a time-to-amplitude converter (TAC) after passing through a timing filter amplifier and triggering a constant fraction discriminator. Pulses from the passing detector are delayed to provide a stop signal to each TAC. For each coincidence signal, we recorded the passing detector energy, the left or right detector energy, and the left or right TAC amplitude. The TAC spectrum consists of a "true" coincidence peak with a width of 2 ns (full width at half maximum) superimposed on a 200-ns-wide random background. In addition to on-line sorting, the raw events were stored on magnetic tape for off-line resorting and reassigning of energy and timing windows. As a continuous check that the electronics and data acquisition system were working properly, we inserted pulser signals at a rate of 2 Hz into the left, right, and passing detector preamplifiers throughout the experiment. We observed no instrumental asymmetries larger than ±0.005 caused by the electronics dead time. Typical beam currents of 1 μA (doubly charged ^{3}He) were used in this experiment, resulting in a total singles counting rate of 10 kHz or less in the passing detector. The true counting rate was one or two per minute.

Typical spectra are shown in Fig. 3. To be recorded as a true event, the L or R count must fall within the energy window of the ground state protons in the passing detector, within the true timing peak of the TAC, and within the energy window of the left or right detector. Accidental background events were recorded by assigning a TAC spectrum window that excluded the true peak and was 20 times wider. Dividing the accidental spectra by 20 thus yields the small backgrounds illustrated as histograms in Figs. 3(d) and 3(e). Accidental background counting rates were about 5% of the true counting rate.

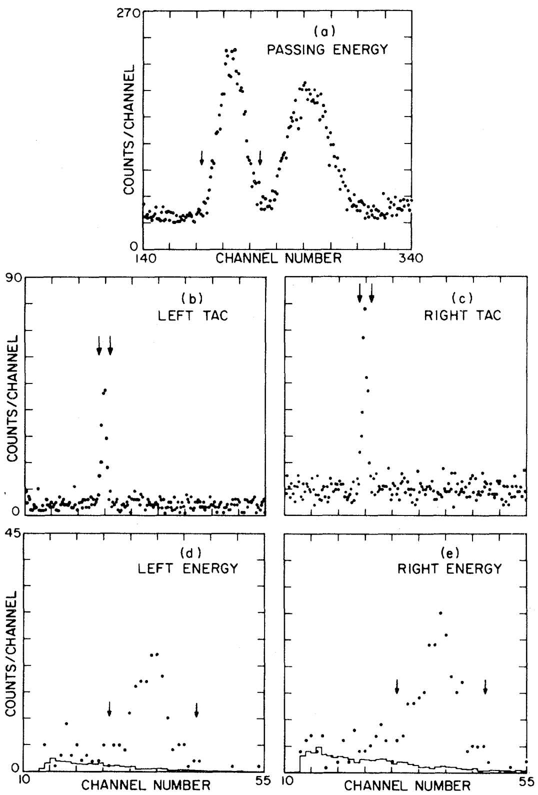

FIG. 3. Typical spectra from the ^{9}Be(^{3}He, $\vec{p}$)^{11}B proton polarization measurement with the polarimeter on the left side of the beam axis as shown in Fig. 1. Part (a) shows the pulse height spectrum of protons from the polarimeter passing detector. Parts (b) and (c) show left and right TAC spectra. Parts (d) and (e) show the final left and right energy spectra with solid circles representing true events and the histogram representing the accidental background. The gating conditions described in the text are indicated by the region of each spectrum between arrows.

Double-scattering polarization experiments are susceptible to a number of possible instrumental asymmetries that are easily eliminated in analyzing power measurements using polarized beams. Some of these effects are due to the thick targets and large solid angles needed to achieve sufficient counting rates for the double-scattering experiments, and others are a result of nonuniform illumination of the polarimeter. For example, instrumental asymmetries caused by differing efficiencies in the two analyzer detectors are usually eliminated by taking data on both sides of the primary beam axis, as done in this experiment, but changes in the mean scattering angle due to target position misalignment or angular dependence of the differential cross section are not eliminated by this technique. Another noncanceling effect, caused by the large flux of forward-peaked neutrons from the primary reaction, is the higher background rate in the detector nearer to the beam axis. Although we were able to minimize the backgrounds through the use of fast timing, the background asymmetry can be seen clearly in Fig. 3 as higher accidental rates in the right TAC spectrum and corresponding higher backgrounds in the right energy spectrum.

From the dimensional tolerances of the supercube (±0.25 mm), we estimated the possible instrumental asymmetries due to misalignment of the polarimeter rotation axis and to possible beam movement during a set of runs. If these effects combined in the worst way they could yield an instrumental asymmetry as large as ±0.023 giving a systematic error of ±0.04 in the polarization results. Instrumental effects due to background uncertainty, angular dependence of the differential cross section, and the solid-angle correction for our data, including multiple scattering effects, are well within the ±0.04 systematic error.

We measured proton polarization values for the ^{9}Be(^{3}He, $\vec{p}$)^{11}B reaction at laboratory angles of 35°, 40°, 45°, and 50°. The results, which are statistical

TABLE I. Polarization measurements for the ^{9}Be(^{3}He, $\vec{p}$)^{11}B reaction at an incident energy of 13.6 MeV. The uncertainties given are statistical only; a systematic uncertainty of ±0.04 also applies (see discussion in the text).

θ_{lab} (deg)	$\theta_{c.m.}$ (deg)	$P \pm \Delta P$
35	39.1	0.155 ±0.035
40	44.6	0.164 ±0.035
45	50.1	0.037 ±0.035
50	55.5	−0.034 ±0.034

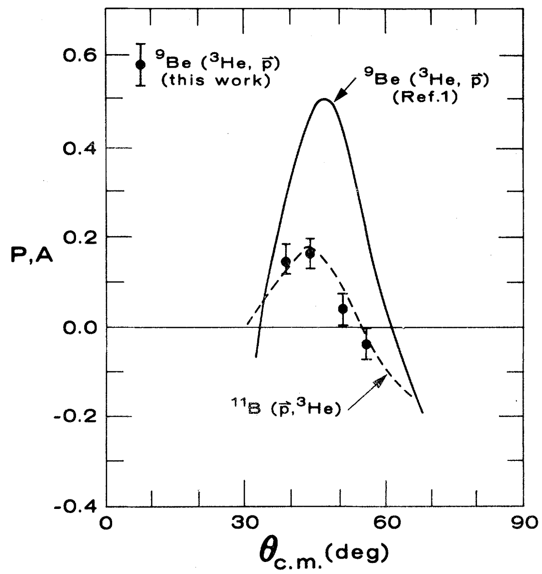

FIG. 4. Time-reversal invariance requires that the polarization and analyzing power values be equal. The points shown are our proton polarization values for the $^{9}Be(^{3}He, \vec{p})^{11}B$ reaction. They disagree with the solid curve representing the same measurements as reported in Ref. 1. The dashed curve represents measured analyzing power values of Ref. 1 for the inverse reaction, $^{11}B(\vec{p}, ^{3}He)^{9}Be$. Our measurements indicate equal values for polarization and analyzing power, and we see no evidence for a violation of time-reversal invariance.

averages of several independent measurements, are given in Table I and are shown in Fig. 4. The polarizations measured by Conzett and Slobodrian[1,3] are represented in Fig. 4 by a solid line, and the analyzing powers are shown as a dashed line. Notice that because our polarization values at 45° and 50° lab are near zero, they are insensitive to the polarimeter analyzing power.

We find complete disagreement between our polarization results and those of Refs. 1 and 3 and no evidence for a violation of time reversal in this experiment. In fact, within our statistical uncertainties, $P = A$ for the $^{9}Be(^{3}He, p)^{11}B$ reaction. After a number of private discussions with Conzett and Slobodrian, the source of the differences in the two sets of polarization data has not been resolved. Instrumental asymmetries, although potentially serious, have been investigated and are believed to be understood by both groups. A significant difference in the two experiments is the use of a silicon polarimeter at Berkeley and Laval versus the helium polarimeter used in our measurements. Both techniques have been used previously in many different applications and the polarimeter calibrations have been checked repeatedly. However, the silicon polarimeter has a much smaller analyzing power (about 0.22 compared with 0.63 for helium) and thus is more sensitive to the instrumental asymmetries discussed above. Resolution of these experimental discrepancies and new, more accurate TRI tests are now of critical importance in the continuing investigation of basic symmetries in nuclear physics.

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