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POLARIZATION-ASYMMETRY TEST OF TIME-REVERSAL INVARIANCE*

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Time-reversal invariance for strong interactions, in particular for that part of the force which flips the spin of the proton, has been tested by comparing the polarization and asymmetry in the elastic scattering of 32.9-MeV protons from ^{13}C at 60°. By making the measurements for ^{13}C relative to ^{12}C, where spin flip is forbidden except in case of parity nonconservation, we avoid the need to measure either an absolute beam polarization or absolute analyzing power. Our first result is that the polarization and asymmetry are equal to ±2.5%; consequently, we observe no violation of time-reversal invariance.

The discovery of the violation of charge conjugation and space inversion (CP) invariance in the decay of the K_2^0 meson by Christenson et al.[1] has stimulated a whole host of experiments in search of violation under time reversal of the weak, electromagnetic, and strong interactions. The search for time-reversal violation in nuclear reactions has centered on tests of detailed balance by the comparison of cross sections in inverse reactions. Very accurate measurements[2] have been made which have reduced the uncertainty in the cross-section comparisons to about ±0.3%. Handler et al.[3] have tested time-reversal invariance in p-p scattering at 430 MeV by comparing selected triple-scattering parameters.

Another time-reversal test in nuclear reactions is the comparison of polarization and asymmetry in elastic scattering. For particles of spin $\frac{1}{2}$, the polarization P is defined as the scattered-beam polarization when an unpolarized target is bombarded by an unpolarized beam, and the asymmetry A is defined as the experimentally measured left-right asymmetry ϵ when a beam of 100% polarization is scattered by an unpolarized target. All scatterings are at the same angle θ. In the case of a beam which is not 100% polarized, A is related to ϵ by

$$\epsilon = P_0 A = \frac{\text{No. scattered left}}{\text{No. scattered left and right}} - \frac{\text{No. scattered right}}{\text{No. scattered left and right}} \equiv P_0(L-R),$$

where P_0 is the fractional polarization of the incident beam. In order to indicate why a polarization-asymmetry comparison is sensitive to time-reversal invariance, we follow Squires[4] and con-

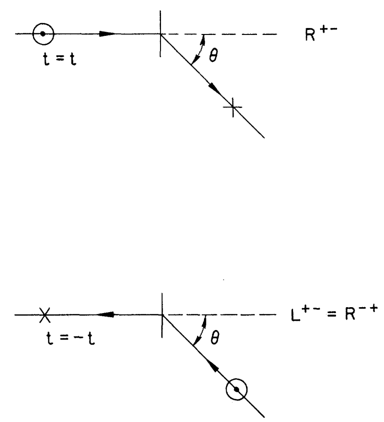

FIG. 1. Schematic diagram showing the influence of the time-reversal operation on a proton spin-flip elastic scattering.

sider the process shown schematically in Fig. 1. A proton with spin up (+) is scattered through an angle θ to the right in such a way that it emerges with its spin down (−). The probability of this process is designated by R^{+-}. Under the time-reversal operation ($t=-t$) R^{+-} becomes L^{+-}. By assuming invariance under rotation about the beam direction, $L^{+-}=R^{-+}$. Therefore, a violation of time-reversal invariance would be signaled by the inequality of R^{+-} and R^{-+}.

If an unpolarized beam is scattered through an angle θ to the right, the polarization of the scattered beam, using the Basel convention, is

$$P=R^{--}+R^{+-}-[R^{++}+R^{-+}],$$

and if a 100% polarized beam, $P_0=1$, is scattered through the same angle from the same target, the asymmetry A is given by

$$A=R^{++}+R^{+-}-[L^{+-}+L^{++}],$$

which from rotational invariance becomes

$$A=R^{++}+R^{+-}-[R^{-+}+R^{--}].$$

We find that

$$A=P+2(R^{-+}-R^{+-}),$$

or that $A=P$ identically if time-reversal invariance holds, and that any departure from this equality indicates violation of time-reversal invariance. We note here that $A\neq P$ on account of parity violation, but this effect is expected[5] to be of the order of 10^{-6} and does not concern us in this paper.

The experiment is simple in principle: One just measures the difference in P and A for the elastic scattering of protons from a suitable target.

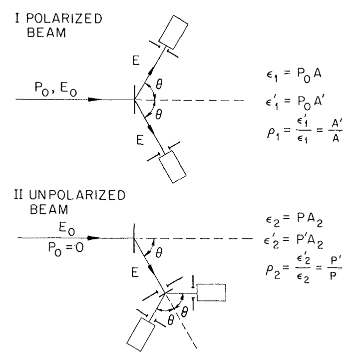

FIG. 2. Schematic diagram of polarization-asymmetry test of time-reversal invariance. The unprimed quantities apply when ^{13}C is the target, while the primed quantities apply when the target is ^{12}C.

Previous polarization-asymmetry comparisons[6] have achieved at best 10% accuracy because both an absolute beam polarization and an absolute analyzing power had to be determined. We reduced this uncertainty by a technique which does not require accurate measurements of these two quantities. The experiment involves the comparison of polarization and asymmetry for elastic scattering near 60° of 32.9-MeV protons from ^{13}C, ground-state spin $\frac{1}{2}$. However, the measurements are made relative to ^{12}C, ground-state spin 0, where there is no spin flip ($R^{+-}=R^{-+}\equiv 0$), and the polarization-asymmetry equality holds regardless of invariance under time reversal. Four measurements are made. They are shown schematically in Fig. 2. The unprimed quantities are used when ^{13}C is the target, the primed quantities when the target is ^{12}C. First, with the polarized beam we measure the asymmetry ϵ_1 and ϵ_1' for each target. The value of the asymmetry depends on the incident beam polarization P_0 in exactly the same way, so that the ratio ρ_1 is dependent only on the ratio of the asymmetries. Second, for the unpolarized-beam measurement, if the scattered energies from ^{12}C and ^{13}C are equal, the analyzing power A_2 of the polarimeter does not appear in the ratio ρ_2 of the measured asymmetries. Then making use of the polarization-asymmetry equality for ^{12}C, the ratio of the polarization and asymmetry in ^{13}C is given by

$$\frac{P}{A}=\frac{\epsilon_1'\epsilon_2}{\epsilon_1\epsilon_2'}=1+\frac{2(R^{+-}-R^{-+})}{A}.$$

These cancellations are strictly correct only to first order. Uncertainties introduced by such effects as the variation of polarization with energy and angle cannot be neglected. It is for this reason that we have chosen the pair of nuclei ^{12}C and ^{13}C on which to make our measurements. From previous measurements[7] on ^{12}C it was apparent that its differential cross section and polarization were especially favorable for the present experiment. Results of more detailed measurements are shown in Fig. 3. The angular distributions for ^{12}C and ^{13}C are quite similar. The flat region in the differential cross section near 60° is advantageous since this feature reduces the systematic asymmetry due to small angular misalignments. Near 60° the polarizations also have broad maxima. Measurements of the elastic polarization at 60° have been made as a function of proton beam energy. All of these detailed subsidiary measurements indicate that it should be possible to reduce the uncertainties in the polarization-asymmetry comparison to less than 1%. We report here a first measurement accurate to 2.5%.

The polarized-beam measurements were made using a proton beam scattered through 25.5° from a 10-MeV-thick calcium target. This technique has been described in detail elsewhere.[8] Because the polarized protons were produced by scattering, there was no variation in P_0 during the course of the experiment. The polarization of the (32.9 ± 0.1)-MeV protons was measured to be 0.312 ± 0.007. This beam was elastically scattered at $\theta_{\rm lab} = 60.0° \pm 0.1°$ from 25-mg/cm^2 targets of ^{12}C and ^{13}C (enriched to 90% ^{13}C). The experimental asymmetries were measured to about ±1%. They were $\epsilon_1'(^{12}\mathrm{C}) = 0.205$ and $\epsilon_1(^{13}\mathrm{C}) = 0.196$. The ratio of these two values, which is equal to the ratio of the asymmetry for ^{12}C scattering to the asymmetry for ^{13}C scattering at $\theta_{\rm lab} = 60°$ and 32.9 MeV, is

$$\rho_1 = A'/A = 1.046 \pm 0.016.$$

For the unpolarized measurements, protons with an energy of 32.9 ± 0.1 MeV were scattered at $\theta_{\rm lab} = 59.9° \pm 0.1°$ from the identical targets used in the polarized-beam measurements. The scattered protons were collimated, transported by a 7.5-cm aperture triplet-quadrupole lens, and brought to a focus about 2.3 m away on a polarization analyzer. This reduced the neutron background from the carbon targets at the analyzer, and was particularly important because of the difference in the (p,n) cross sections for ^{12}C and ^{13}C.

The analyzer was a 49-mg/cm^2 ^{12}C foil. Protons scattered from it were observed at 60° left and right. The peak-to-valley ratio of the elastic peak was always greater than about 60, and the uncertainty in the background subtraction was smaller than the error due to statistics. Two experimental asymmetries were again measured: $\epsilon_2'(^{12}\mathrm{C}) = 0.370$ and $\epsilon_2(^{13}\mathrm{C}) = 0.350$. From the results of our subsidiary measurements, corrections were made for the 0.2-MeV difference in scattered beam energy and difference in angle of 0.1°. We then find the ratio ρ_2 for $\theta_{\rm lab} = 60°$, and for an energy of 32.9 MeV, to be

$$\rho_2 = P'/P = 1.054 \pm 0.017.$$

Now, making use of the equality of the polarization and asymmetry in ^{12}C scattering, our final result: The ratio of the polarization and asymmetry in ^{13}C elastic scattering at $\theta_{\rm lab} = 60°$ and proton energy 32.9 MeV is

$$P/A = 0.992 \pm 0.025.$$

This result represents the most precise polarization-asymmetry comparison to date. It is hoped that with continued efforts, the uncertainty may be reduced still further.

The conclusion of this work is that this scattering process, which is dominated by the strong in-

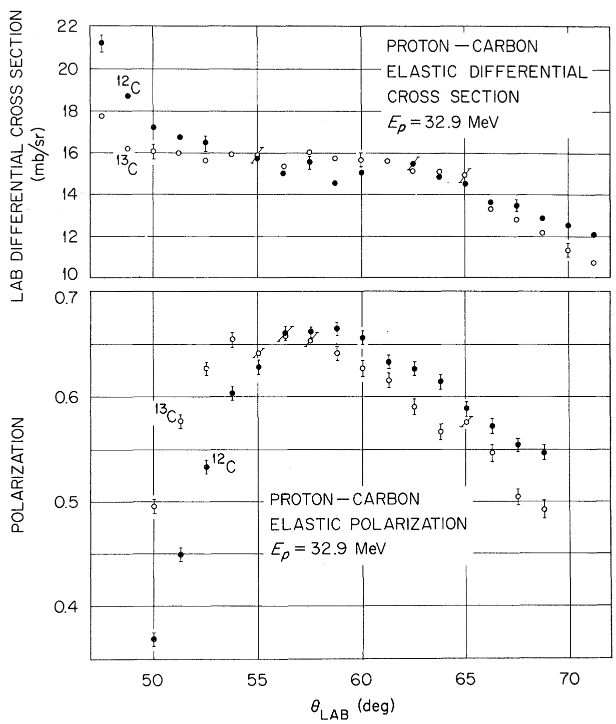

FIG. 3. 32.9-MeV proton elastic-scattering differential cross section and polarization near 60° for ^{12}C and ^{13}C. The error flags represent absolute errors.

teraction, satisfies time-reversal invariance to within the accuracy of the measurements.

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ION-ION POTENTIALS AND THE COMPRESSIBILITY OF NUCLEAR MATTER

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With a schematic model for the nuclear matter we give a unified treatment of the real and imaginary parts of the elastic O^{16}-O^{16} scattering potential. The model connects the parameters of the potential with the density and binding properties of the O^{16}-O^{16} system and reproduces the structure of the excitation function quite well. It is shown that the nuclear compressibility can be obtained from the scattering data, and in the case of the S^{32} compound system there results an effective compressibility (finite quenching of the nuclei) of about 200 MeV.

In ion-ion collisions, as for example in the elastic O^{16}-O^{16} scattering process, the two nuclei penetrate each other if the bombarding energy exceeds the Coulomb barrier (about 12 MeV in the c.m. system for O^{16}-O^{16}). Above 15 MeV (c.m.) the experimental 90° O^{16}-O^{16} differential cross section found by the Yale group[1] is depressed by more than a factor 10 from the Mott cross section and shows a regular resonance structure (see Fig. 3). This obviously suggests that a real scattering potential alone cannot describe such a behavior and that a strong imaginary part has to be present.[1,2] It is the aim of this paper to present some ideas on the origin of the real and imaginary parts of the ion-ion potentials and to compare the results with the experiment.

Before the ions come in contact, the probability for transitions from the O^{16} ground state remains small since the double-closed O^{16} shells have no low-lying excitations. Behind the contact point we expect a competition between two processes: the superposition of the densities of the two nuclei and the rearrangement of the O^{16} shells. Both processes develop in nearly the same time, because the collision time $\tau \approx 5\times 10^{-22}$ sec is of the same order of magnitude as a signigicant nuclear time, e.g., the orbital time of a nucleon in the O^{16} nucleus. In this intermediate region between the limits of an adiabatic and a sudden process we choose the sudden approximation as our starting point. We superpose the nuclear densities to calculate the real part of the potential. The destruction of the O^{16} shells, by