TESTS OF TIME-REVERSAL INVARIANCE IN THE REACTIONS $Mg^{24}+d \rightleftarrows Mg^{25}+p$ †

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No evidence for a violation of time-reversal invariance has been found in a study of the inverse reactions $Mg^{24}+d \rightleftarrows Mg^{25}+p$, using 10-MeV deuterons and 15-MeV protons. Relative differential cross sections for the two reactions agree to within an experimental standard deviation of 0.4%. This is tentatively interpreted as implying that the ratio of the T-odd to T-even reaction amplitudes is probably less than 0.4%.

The discovery of Christenson, Cronin, Fitch, and Turley[1] of a violation of CP invariance has, in the light of the CPT theorem, stimulated an examination of time-reversal (T) invariance in other experimental situations. Evidence for a T nonconservation in the decay of the η^0 meson has since been reported.[2] In the viewpoint of Lee[3] such violations, and possible violations in low-energy nuclear reactions,[4] could be attributed to a large breakdown of T invariance in the electromagnetic interaction. These considerations and improvements in nuclear technology, which permit greater precision than obtained in earlier experiments, have motivated the reciprocity test of T invariance reported here.

Previous experimental studies of T invariance reactions have been based on comparisons of polarization and asymmetry in elastic scattering[5] and on comparisons of cross sections in inverse reactions.[6] Typical experimental uncertainties were in the neighborhood of 5%, and the results were interpreted as setting upper limits of several percent on the ratio F of the T-odd to T-even reaction amplitudes. Comparable limits have been set in experiments involving gamma-gamma correlations from oriented nuclei,[7] and improved experiments are in progress.[8,9]

The reciprocity measurements described here involve the inverse (ground state) reactions $Mg^{24}+d \rightleftarrows Mg^{25}+p$, which were chosen primarily for experimental convenience. The study was carried out at the University of Washington tandem accelerator using deuterons of approximately 10 MeV and protons of approximately 15 MeV. For each reaction the ratio of the differential cross sections at two angles was measured using two counters simultaneously. These ratios, at the same c.m. angles, can differ for the (d,p) and (p,d) reactions only if there is a T nonconservation. Such a comparison of cross-section ratios involves considerably smaller systematic errors than a comparison of absolute (d,p) and (p,d) differential cross sections, and there is no apparent reason to believe that it represents a less sensitive test of T.

The (d,p) protons (typically 13 or 15 MeV) were detected in solid-state detectors with polyethylene degraders in front to stop particles heavier than protons. Each of the two proton spectra was displayed in one quadrant of a multichannel pulse-height analyzer. The (p,d) deuterons (typically 8 or 10 MeV) were detected in solid-state $\Delta E-E$ telescopes and were similarly displayed.

The data of this experiment consist of the angular distributions shown in Fig. 1 and of the energy dependence of $R(E)=\sigma(E,\theta_2)/\sigma(E,\theta_1)$ shown in Fig. 2; E is the excitation energy in the Al^{26} system. The angular distribution was taken at $E=20.68$ MeV corresponding to a local maximum in $R(E)$, and $R(E)$ was measured at angles $\theta_1=29.7°$ and $\theta_2=119.2°$ (c.m.) corresponding to maxima in the angular distribution. Angular maxima were chosen in order to reduce the sensitivity of $R(E)$ to errors in the determination of angle and (in preference to minima) to reduce statistical and systematic counting uncertainties. An expanded graph in the insert of Fig. 2 displays particularly accurate data taken near the peak of $R(E)$. The excitation function data constitute the main experimental results. The less accurate angular distributions represent a weaker test of T and serve primarily to guide the choice of θ_1 and θ_2.

The comparison of the angular distributions and excitation functions for the (d,p) and (p,d) reactions will be discussed following a consideration of experimental corrections and uncertainties. The quoted uncertainties are to be interpreted as standard deviations. The most important experimental problems encountered were concerned with solid angles, counter ef-

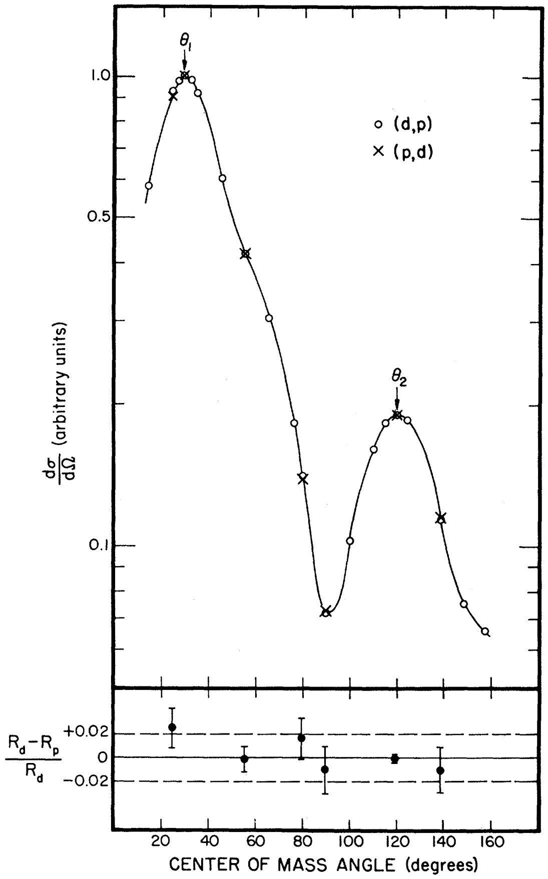

FIG. 1. Angular distributions for the reactions $\mathrm{Mg}^{24}(d,p)\mathrm{Mg}^{25}$ and $\mathrm{Mg}^{25}(p,d)\mathrm{Mg}^{24}$ at an excitation energy of 20.68 MeV in Al^{26}. Maxima in the angular distributions are labeled θ_1 and θ_2; these are the angles used in measuring $R(E)$. The differential cross sections are normalized to unity at θ_1. The differential cross sections at θ_1 are about 6 mb/sr for the (d,p) reaction and about 2 mb/sr for the (p,d) reaction. The solid curve is drawn through the two sets of data to guide the eye. The lower part of the figure shows the fractional differences between R_d, the normalized cross section measured in the (d,p) reaction, and R_p, the normalized cross section measured in the (p,d) reaction.

ficiency, dead-time and pile-up losses, determination of counts in analyzer peaks, target impurities, and beam energy.

(a) Solid angles. – To eliminate changes in the ratio of solid angles as the beam wanders over the fact of the target, the target was oriented with its plane bisecting the angle between the two counters. The same detector apertures and holders were used in the (d,p) and (p,d) experiments so that small mechanical errors would cancel in the ratio comparison; these errors do not appear in the figures or in the later discussion of experimental uncertainties. Remaining solid-angle difficulties lead to a relative uncertainty in R which was typically 0.08%.

(b) Counter efficiency. – The efficiencies of the counters at the energies of interest were determined using a proton-proton and deuteron-deuteron elastic scattering method in which it was possible to compare the number of particles entering the counter with the number appearing in the peak of the detected spectrum. The measured efficiencies were approximately 99.5% for the proton counters and 99.9% for the deuteron counters. The magnitudes of the losses can be understood in terms of nuclear interactions in the counters; the counter at θ_1, detecting more energetic particles, had the lower efficiency. The measured efficiency corrections to R were $(-0.12\pm0.06)\%$ for the (d,p) reaction and $(-0.04\pm0.04)\%$ for the (p,d) reaction.

(c) Dead time and pile up. – To permit corrections for dead-time and pile-up losses, pulses from an electronic pulser, driven at a rate proportional to the incident beam intensity, were fed into each preamplifier in parallel with the detector pulses. The pulser events were routed into the two otherwise empty quadrants of the multichannel analyzer. The measured electronic losses for the pulser peaks were used to correct the apparent number of events in the detector peaks. Typical losses were in the neighborhood of 1%, varying proportionally with beam intensity and differing at the two angles and in the two reactions. They contribute an uncertainty of about 0.05% to R.

(d) Determination of counts in analyzer peaks. – Aside from the corrections of (c), the determination of the number of counts in the ground-state peaks required assignments of background, of boundaries in the number of accepted channels and, for the (p,d) case only, corrections arising from overlap of the ground- and excited-state peaks. The largest correction, which was for the (p,d) background in the counter at θ_2, was typically about 0.9%. Systematic errors in the determination of these corrections are similar for the counters at θ_1 and θ_2 and therefore partially cancel. The uncertainties in the corrections to R were about 0.10% for the (d,p) reaction and 0.15% for the (p,d) reaction. These represented the largest individual systematic uncertainties in the experiment.

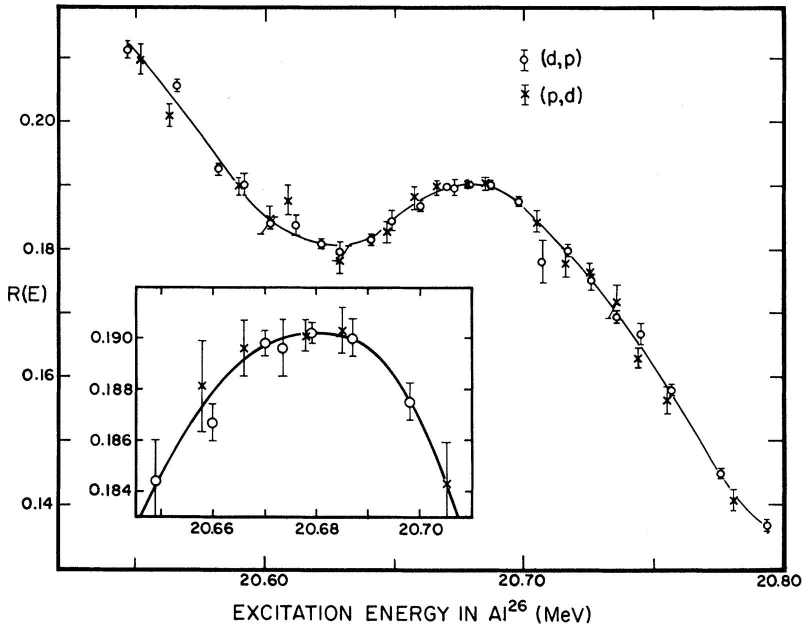

FIG. 2. Excitation function for $R(E)=\sigma(E,\theta_2)/\sigma(E,\theta_1)$ for the reactions $\mathrm{Mg}^{24}(d,p)\mathrm{Mg}^{25}$ and $\mathrm{Mg}^{25}(p,d)\mathrm{Mg}^{24}$ at $\theta_1=29.7°$ and $\theta_2=119.2°$ (c.m.). The data near the peak in the excitation function are presented on an expanded scale in the insert. The errors include both statistical and systematic contributions and are to be interpreted as standard deviations. The solid curves are drawn through the two sets of data to guide the eye.

(e) Target impurities. – The possibility of target impurities contributing significantly to the data was eliminated for the Mg^{25} targets by an examination of reaction kinematics and an elastic scattering study of the impurity content. An upper limit of 0.01% was assigned to possible impurity contributions. Because of less favorable reaction Q values, there were measurable impurity contributions from the Mg^{24} targets. These were examined in detail by comparing the (d,p) spectra from the actual Mg^{24} targets with those from targets of the suspected contaminants. The only impurities making significant contributions were Mg^{25}, Si^{28}, and Cl^{35}. Their combined effect required a correction to R of about $(0.05\pm0.06)\%$, differing slightly for the various Mg^{24} targets which were used.

(f) Beam energy. – Throughout these measurements the deuteron and proton beam-energy spreads, including target thickness effects, were approximately matched at about 5 keV. The energy scales for Fig. 2 were calculated relativistically from the accelerator calibration and the masses of the nuclei involved. The accelerator calibration is based on the $\mathrm{Al}^{27}(p,n)\mathrm{Si}^{27}$ threshold (5.800 MeV[10]) and was determined at the beginning of the last (d,p) and (p,d) excitation function runs. The preliminary energy scales of earlier runs were matched to the later runs by energy shifts ranging from 9 to 16 keV. The total uncertainty in the absolute energy scale of Fig. 2 is 10 keV. However, the important uncertainty, namely the uncertainty in the difference in the energy scales for the (d,p) and (p,d) reactions, is only about 5 keV. It can be seen in Fig. 2 that the two experimental excitation functions agree in energy within this uncertainty.

The data points of Figs. 1 and 2 incorporate the corrections discussed above. The errors assigned to the individual points include both the systematic and statistical uncertainties. Except at the peak of the excitation function of Fig. 2, the corrections and the systematic uncertainties are both small compared with the statistical standard deviations. Typical uncertainties for the angular distributions of Fig. 1 are 0.7% for the (d,p) reaction and 1.6% for the (p,d) reaction. Typical uncertainties for the excitation functions of Fig. 2 are 0.5 and 1.0% for the (d,p) and (p,d) reactions, respectively. Within these uncertainties, both $R(E)$ and the angular distributions are identical for the two reactions.

The most precise comparison was made at the peak of $R(E)$ in Fig. 2 where errors in energy are least significant. The ratios for the single points closest to the peak (see the insert to Fig. 2) are

$$(d,p):\ R = 0.1902 \pm 0.0004,$$

$$(p,d):\ R = 0.1901 \pm 0.0006.$$

The quoted errors include both systematic and statistical contributions. It is concluded that the measured ratios at the peak in $R(E)$ agree to within an over-all experimental uncertainty of 0.4%.

In order to use this result to establish an upper limit on the ratio F of the T-odd to T-even reaction amplitudes, one requires knowledge of the phases between the T-odd and T-even contributions in each spin channel and knowledge of the relative contributions of the different spin channels to the cross section. As no model is yet available which gives these quantities, we assume all relative phases to be equally probable. Then in the best case, where only a single spin channel contributes, the present result implies that F is probably less than about 0.15%. However, there are 18 spin channels. In the unfavorable case where they are all independent and of the same magnitude, the sensitivity of the experiment is reduced by about a factor of $\sqrt{18}$, raising the probable upper limit on F to the neighborhood of 0.6%.

These considerations suggest that a likely upper limit on F is roughly the experimental uncertainty itself. Thus we find no violation of time-reversal invariance in the inverse reactions $\mathrm{Mg}^{24}+d \rightleftarrows \mathrm{Mg}^{25}+p$, and we tentatively assign an upper limit on F of 0.4%. It is hoped that theoretical studies of this reaction, being undertaken by Henley and collaborators, will permit a firmer assignment in the future.

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