UPPER LIMIT OF T NONCONSERVATION IN THE REACTIONS $^{24}Mg + \alpha \rightleftarrows {}^{27}Al + p$

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Time-reversal invariance has been tested via detailed balance in the compound-nuclear reactions $^{24}Mg + \alpha \rightleftarrows {}^{27}Al + p$. The relative differential cross sections agree within the experimental uncertainties, leading to an estimated upper limit for the ratio of the T-nonconserving to the T-conserving reaction amplitudes of $(2\text{-}4) \times 10^{-3}$. The same upper limit is found for the nuclear matrix elements which are odd with respect to time reversal.

Continuing our previous experiments for a search of T-nonconserving effects in compound-nuclear reactions[1] we have studied the reactions $^{24}Mg + \alpha \rightleftarrows {}^{27}Al + p$ under more favorable conditions. We recall briefly the idea of the experiment:

A most sensitive test[2] of time-reversal invariance by detailed balance should be provided by a reaction proceeding via a compound nucleus which is excited in the region of strongly overlapping levels. The interference of many coherently excited resonanced then gives rise to statistical fluctuations of the cross section as a function of energy. In the presence of a time-reversal–odd force the reaction amplitude can be split into a T-conserving and a small T-nonconserving part which are assumed to fluctuate independently of each other.[3] This implies that the T-odd part of the amplitude should be enhanced relative to the T-even one at a minimum of the cross section where the time-reversal–even amplitude is reduced. The most favorable case, of course, will be a reaction where only one single spin channel contributes to the cross section. This is true for the two reactions $^{24}Mg + \alpha \rightleftarrows {}^{27}Al + p$ at $\theta = 0°$ and $\theta = 180°$. The experiment consisted in the measurement of excitation functions at an angle $\theta_{c.m.} = 172.6°$, where the admixture of further amplitudes was estimated to be less than 10%.

The α particles and protons were accelerated by the Heidelberg tandem Van de Graaff. Great effort was made to minimize the background in the spectra. The very carefully prepared targets (15 mm in diameter) consisted of isotopically enriched magnesium (99.96% ^{24}Mg, 33 $\mu g/cm^2$) evaporated onto thin carbon foils and of self-supporting aluminum (35 $\mu g/cm^2$), respectively. The α particles were detected with silicon surface-barrier counters, the protons with lithium-drifted silicon counters, both of them cooled to about −40°C. In the (α, p) measurement, 8- and 9-μ-thick aluminum foils were placed in front of the counters in order to shift α particles to the low-energy end of the spectrum. All other experimental arrangements were the same as in the previous measurements.[1]

The cross sections in both reactions were taken at a very high maximum at $E_p \sim 10.3$ MeV and $E_\alpha \sim 13.45$ MeV and at two other energies, viz. a rather wide minimum at $E_p \sim 10.55$ MeV and $E_\alpha \sim 13.73$ MeV and a second maximum at $E_p \sim 11.3$ MeV and $E_\alpha \sim 14.6$ MeV. In order to avoid the measurement of absolute values, the cross sections of the two reactions were normalized in the high maximum (Fig. 1) and then compared with each other in the minimum and in the second maximum. Since the energy spread in the entrance channel of the (α, p) reaction due to target thickness and beam spread is much larger (about 12 keV) than in the (p, α) reaction, an equal energy resolution in the (p, α) reaction was simulated by averaging later over each six points measured in 2-keV steps. The full lines in Figs. 1 and 2 represent the averaged (p, α) cross sections so obtained.

As Fig. 2 illustrates for the minimum, the normalized cross sections of the two reactions agree within the experimental uncertainty; this was also found in the second maximum. The result was obtained previously for a direct reaction by Bodansky et al.[4]

Since only relative yields are compared in the forward and backward reaction, many experimental uncertainties become negligible, e.g., the counter efficiency, the exact target thickness, the solid angle, and the absolute determination of the collected charge. The remaining errors are discussed in the following:

(1) Counting statistics.—To normalize the excitation functions of the reactions $^{24}Mg(\alpha, p)$ and $^{27}Al(p, \alpha)$ to each other at the maximum, only the points lying on the flat plateau (at E_α around 13.44 MeV) were used, so that the result becomes insensitive against a small energy shift of each single point.[5] The uncertain-

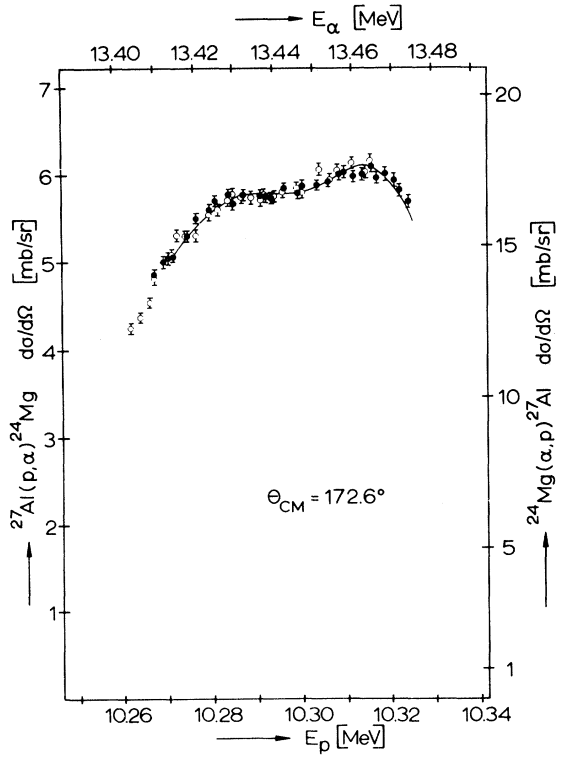

FIG. 1. The maximum of the excitation functions for the reactions ^{24}Mg$(\alpha,p_0)^{27}$Al and ^{27}Al$(p,\alpha_0)^{24}$Mg, where the cross sections have been normalized to each other. The full and open dots correspond to the (α,p) reaction. The solid curve is the (p,α) cross section averaged over 12 keV. The errors result from counting statistics and are considerably smaller in the (p,α) reaction than in the (α,p) reaction.

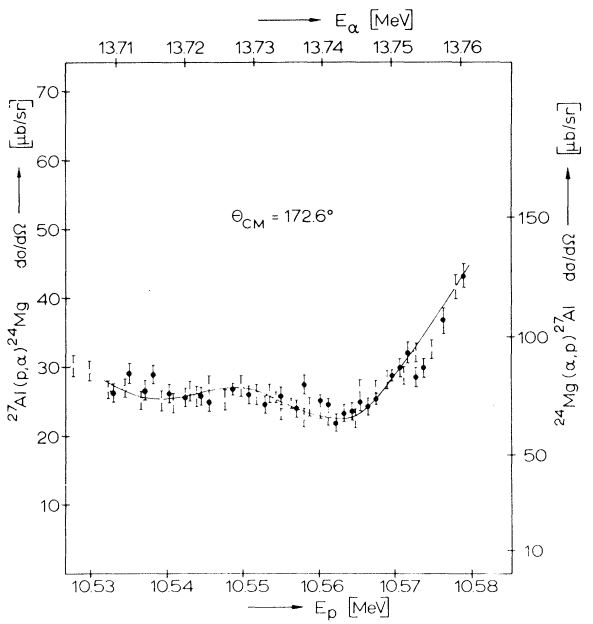

FIG. 2. The excitation functions in the minimum after normalization in the maximum. The solid curve again represents the (p,α) cross section averaged over 12 keV; open and full dots stand for (α,p) cross sections. The statistical errors are shown for each point of the (α,p) reaction; they are slightly smaller in the (p,α) experiment.

ty of the normalization factor given by the counting statistics of all points on the plateau is 0.28 %. In the minimum, the so-normalized cross sections of the two reactions were compared within the relatively flat region 10.54 MeV $\leq E_p \leq$ 10.56 MeV shown in Fig. 2. The statistical uncertainty is 0.8 % in the (α,p) and 0.74 % in the (p,α) reaction. In the second maximum the statistical errors of all points used for the comparison of the two relative cross sections are 0.35 and 0.33 %, respectively.

(2) Background corrections.—In the minimum, the relatively high (α,p_1) and (p,α_1) peaks were used to fix the boundary conditions of the (α,p_0) and of the (p,α_0) peaks, respectively. Extensive examination of reaction kinematics made sure that no lines from target impurities were lying under the peaks of the reactions being studied. In the (α,p) case, the background was also estimated by bombarding a pure carbon foil without magnesium evaporated onto it. The uncertainty induced by these corrections was determined to be less than 0.75 % in the (α,p) and 0.5 % in the (p,α) reaction. In the two maxima background corrections were unimportant.

(3) Scattering angle.—Two counters placed symmetrically to 180° were used. In the two reactions the scattering angles differ by 0.1° in the laboratory system. This small change in scattering angle was achieved by putting the target 1.5 mm closer to the two counters in the (α,p) reaction, leaving their position fixed in both experiments. From a measurement of the angular distributions, it follows that the error coming from the uncertainty of the exact target position (±0.3 mm) is 0.24 % in the minimum and negligibly small in the second maximum. Deviations in the relative cross sections caused by a change of the beam position on the target are less than 0.3 % in the minimum and 0.03 % in the second maximum.

(4) Target thickness.—The thickness of the ^{24}Mg target was carefully determined by several methods: by weighing before and after

evaporation, by Rutherford scattering, and by measuring the energy loss of 6-MeV α particles scattered through 160° on the carbon backing after penetrating the Mg layer. The thickness for 14-MeV α particles was found to be 10 ± 1 keV, the error being also an upper limit for the target inhomogenity. Through the averaging procedure mentioned above, this error induces an uncertainty in the (p, α) cross section of 0.25% in the minimum and 0.28% in the second maximum.

(5) Beam current integrator.—The current-integrating system was tested to be stable during the runs to about 0.1%.

All errors listed above are treated as standard deviations and lead to an over-all uncertainty of the relative cross sections in the minimum and in the second maximum of 1.52 and 0.63%, respectively.

With the help of Ericson's theory,[6] an upper limit for the time-reversal-violating part of the reaction amplitude is derived from these experimental deviations. Since the cross section in the minimum is a factor of 31 below the average cross section, an enhancement factor $\nu = 5.57$ is found. In the second maximum, ν is only 1.13, but this disadvantage is canceled by better counting statistics and negligible background problems. We thus conclude that our experimental results yield an upper limit for the ratio of the T-nonconserving to the T-conserving part of the reaction amplitude of 4×10^{-3} with a theoretical confidence of 85%, or 2×10^{-3} with 60% confidence. These confidence limits stem only from the fact that our result is interpreted as an upper limit for the average strength of the fluctuating T-nonconserving amplitude, which has been tested only at two independent points, namely, in the minimum and in the second maximum.

According to Mahaux and Weidenmüller,[7] the intrinsic enhancement factor $(W/\Gamma)^{1/2}$ appearing in Ericson's theory has been put equal to one. Therefore, the relative strength of the matrix elements of the nuclear Hamiltonian H', which is odd with respect to time reversal,[6] is also $(2\text{-}4) \times 10^{-3}$.

To our knowledge, this is at present the best upper limit on T nonconservation in nuclear interactions. Some years ago, Rosen and Brolley[8] obtained about 2% by a comparison of absolute cross sections, while Bodansky et al.[4] previously found an agreement of 0.4% of the relative cross sections in a detailed balance experiment which, however, involves 18 independent spin channels.

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[4]D. Bodansky, W. J. Braithwaite, D. C. Shreve, D. W. Storm, and W. G. Weitkamp, Phys. Rev. Letters 17, 589 (1966).

[5]It turns out, however, that one actually gets the same normalization factor if one uses all the experimental points shown in Fig. 1.

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