Improved Experimental Test of Detailed Balance and Time Reversibility in the Reactions $^{27}Al + p \rightleftharpoons {}^{24}Mg + \alpha$

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A new test of the principle of detailed balance in the nuclear reactions $^{27}Al(p,\alpha_0)^{24}Mg$ and $^{24}Mg(\alpha,p_0)^{27}Al$ at bombarding energies 7.3 MeV $\le E_p \le$ 7.7 MeV and 10.1 MeV $\le E_\alpha \le$ 10.5 MeV, respectively, is reported. Measured relative differential cross sections agree within the experimental uncertainty $\Delta = \pm 0.51\%$ and hence are consistent with time-reversal invariance. From this result an upper limit $\xi \le 5 \times 10^{-4}$ (80% confidence) is derived for a possible time-reversal–noninvariant amplitude in the reaction.

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Motivated by the CP nonconservation found in the neutral kaon system,[1] several tests of time-reversal invariance[2] in low-energy nuclear physics have been performed in the weak, electromagnetic, and strong interactions and were consistent with time reversibility at the level of $\sim 3 \times 10^{-3}$. More recently, as a result of the development of new techniques, new experimental results from the realm of the weak[3] and electromagnetic[4] interactions, accurate at the level of 10^{-4}, have been reported. We supplement these results by a new upper limit also at the level of 10^{-4} for a time-reversal–noninvariant amplitude in the strong interaction. Other recent searches for direct evidence of time-reversal (T) nonconservation are found in Slobodrian *et al.*,[5] Bhatia *et al.*,[6] and Briscoe *et al.*[7]

We have tested T invariance by searching for a violation of the principle of detailed balance in the reaction $^{27}Al + p \rightleftharpoons {}^{24}Mg + \alpha$. Our renewed interest to improve substantially the result of the previous measurements[8] was based on the then generally held belief that pushing the existing upper limits on T nonconservation down below 10^{-3} by about one order of magnitude would exclude millistrong or electromagnetic interactions as a source of CP (or T) nonconservation in the decay of neutral kaons. This, however, by our present day theoretical knowledge,[9] is a rather optimistic expectation. The new experimental result reported in this Letter most likely excludes only full-strong-interaction T nonconservation.

As in the previous test[8] of detailed balance utilizing the reactions $^{27}Al(p,\alpha_0)^{24}Mg$ and $^{24}Mg(\alpha, p_0)^{27}Al$, we used an electrostatic accelerator to produce the respective proton and alpha-particle beams at energies such that the reaction proceeds via the formation of overlapping compound-nucleus states. For substantial sensitivity with respect to detection of a T-noninvariant amplitude and for a straightforward theoretical interpretation of the result, relative differential cross sections (forward- and backward-reaction rates are normalized at a suitable cross-section maximum and are then compared at a minimum) have been measured at a scattering angle of $\theta \approx 180°$. An extensive description of the experimental apparatus, which was also employed for a test of detailed balance in the same nuclear reaction but at isolated resonances, is given elsewhere.[10] In brief, the 4-MV Dynamitron tandem accelerator at Bochum provided the charged-particle beams with an energy spread $\Delta E/E < 3 \times 10^{-4}$ and an energy stability of $\delta E/E < 2 \times 10^{-5}$ (Ref. 11). The beam entered the scattering chamber through a collimating system, passed an annular detector placed at a mean angle $\langle \theta_{\rm lab} \rangle = 177.6°$, and struck the target before being caught in the Faraday cup. For the detection of α particles and protons Si surface barrier detectors of 100 and 500 μm, respectively, were employed and placed at 177.61° and 177.56°, respectively, in order to have the same mean center of mass angle for both reactions. The change in $\theta_{\rm c.m.}$ within the measured energy interval is $< 8 \times 10^{-4}$ deg and therefore negligible. Furthermore, we used self-supporting ^{27}Al targets (99.9986% ^{27}Al, $\rho x = 26 \pm 2\ \mu g/cm^2$) and various ^{24}Mg targets (99.94% ^{24}Mg, $\rho x = 4$–$7\ \mu g/cm^2$) and wobbled them in order to average over possible inhomogeneities of the target.[12] The mechanical parts of the entire experimental setup were machined to highest precision and their adjustment was periodically checked.

At the level of precision aimed for, we have tried during the measurements to identify and correct different systematic effects, three of which are briefly mentioned. First, great care has been exercised to obtain nearly background-free spectra. Second, a precisely reproducible recycling procedure for the analyzing magnet was established. It enabled us to reproduce the structures of the excitation function within ± 1 keV during a given run and within ±3 keV from run to run. Third, in order to check that scattering and solid angles did not change during the runs, we measured by means of two monitor counters the left-right forward-angle asymmetry and found it to be less than ±0.2 mm at a beam spot of 1–1.5 mm. The total running time amounted to 50 d with the accumulation of 624 alpha-particle and 475 proton spectra.

For the evaluation of the different excitation functions, the (p, α_0) measurements were first normalized to each other at the maximum of the cross section with respect to their height, and accordingly the (α, p_0) measurements. Before these excitation functions of the forward and backward reactions could be compared, the (p, α_0) cross sections were folded[13] in order to take into account the somewhat larger energy spread of the α beam and its energy loss in the target.

The result of this procedure is shown on the left-hand side of Fig. 1. The folded (p, α_0) excitation function is given in the form of a continuous line normalized to the (α, p_0) cross sections marked as open circles with error bars. Since the density of the many measured cross-section points is much too high for all points to be shown, each point is the result of the average of many neighboring points. The absolute cross-section scales given agree within ± 8% (mainly because of the uncertainty of the target thicknesses). For a stringent test of the principle of detailed balance for the relative differential cross sections in the forward and backward reactions, at the cross-section minimum, it is now required that the normalization parameters derived at the cross-section maximum be the same at the minimum. This is indeed the case as is demonstrated in the middle and the right-hand side of Fig. 1, where again, only a mean has been plotted in case of the (α, p_0) reaction. The relative differential cross sections of the (p, α_0) and (α, p_0) reactions agree very well in the nieghborhood of a deep cross-section minimum, the overall uncertainty of the agreement being $\Delta = \pm 0.51\%$. This number incorporates various sources of error arising from counting statistics and background subtraction, bending of the target foils, target thickness, and the total charge collection in the Faraday cup. Hence our result is consistent with T invariance.

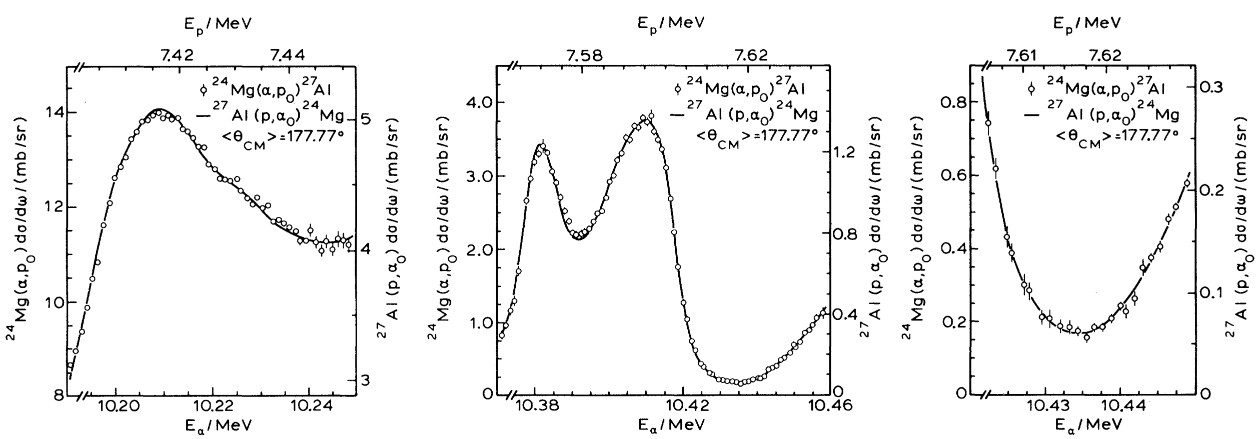

FIG. 1. Left-hand side: Excitation function of the reaction $^{27}Al(p,\alpha_0)^{24}Mg$ folded with an energy spread of $\Delta E = 2$ keV and a mean energy loss $t_E = 4$ keV (solid curve) plotted together with the excitation function of the reaction $^{24}Mg(\alpha, p_0)^{27}Al$ (open circles, not all measured points shown) normalized to the (p, α_0) excitation function. The quantities ΔE and t_E result from a computer search minimizing χ^2. These fit parameters can be determined precisely because of the steep slopes left and right of the maximum. Middle part: a comparison of the forward- and backward-reaction cross sections near and at a deep minimum with same procedure and normalization factor as at the maximum. Right-hand side: The region around the minimum displayed on an enlarged scale. This figure demonstrates the validity of detailed balance for the cross sections measured.

Finally, to determine from the uncertainty Δ an upper limit for a possible T-noninvariant amplitude in the reaction, we follow entirely the theory developed by Ericson[14] and the considerations given to it in Ref. 8. In brief, a measure of detailed balance in the relative cross sections (now for brevity denoted as $\vec{\sigma}$ and $\overleftarrow{\sigma}$) is provided by

$$\Delta = (\vec{\sigma} - \overleftarrow{\sigma})/[(\vec{\sigma} + \overleftarrow{\sigma})/2]. \tag{1}$$

Since at $\theta \approx 180°$ only one spin channel contributes to the reaction, the reaction amplitude can be decomposed into a T-noninvariant and T-invariant part f' and f, respectively. Hence the two inverse cross sections can be expressed as

$$\overleftrightarrow{\sigma} = |f|^2 \pm 2|f|\,|f'|\cos(f,f') + |f'|^2. \tag{2}$$

Inserting Eq. (2) into (1), neglecting the $|f'|^2$ terms, taking into account that we are interested in an average T-noninvariant strength $\xi^2 = \langle |f'|^2\rangle / \langle |f|^2\rangle$, where the angular brackets denote an energy average, the fact that the cross-section minimum, in which we test detailed balance, is a factor of ν smaller than the average cross section, and finally that $\mu^{-2} = \langle |f'|^2\rangle / |f'|^2$, we find

$$\Delta = 4\sqrt{\nu}\,\xi\mu\cos(f,f'). \tag{3}$$

The quantity $\mu\cos(f,f')$ is a random quantity which changes as a function of energy like f and f', but its probability distribution is known. We can therefore derive an upper limit for a T-noninvariant amplitude

$$\xi \leq |\Delta/(4\sqrt{\nu})|Z, \tag{4}$$

where Z could be any arbitrary number and the confidence of ξ corresponds to the probability of $|\mu\cos(f,f')| \geq Z^{-1}$.

Obviously, the principle of detailed balance is a useless tool to detect T noninvariance if the relative phase between f and f' is $\varphi = \pm\pi/2$ since $\Delta = 0$ in Eq. (3). This unpleasant accident could in fact occur if one notices that in a suitable basis the matrix elements of H, the T-conserving Hamiltonian, are real and the matrix elements of H', the T-nonconserving Hamiltonian, are purely imaginary. To shed some light on the question of whether this relative phase between H and H' carries over to f and f' we studied a simple schematic model in the spirit of shell-model reaction theory.[15] In that model the S-matrix element between the initial and final states $\psi_E^{(i)}$ and $\psi_E^{(f)}$ has the form

$$S_{if} = -2\pi i \sum_{p,q} V_q^{(f)} D_{pq}^{-1} V_p^{(i)*}, \tag{5}$$

where

$$V_q^{(f)} = \langle \psi_E^{(f)} | H + H' | \varphi_q \rangle \tag{6}$$

and

$$D_{pq} = (E - E_q)\delta_{pq} - W_{pq} + i\pi \textstyle\sum_c V_p^{(c)*} V_q^{(c)}. \tag{7}$$

Here φ_q are bound states with the energies E_q which turn into resonances via the coupling with the continuum channels c as expressed in the last term of Eq. (7). We neglect the real shift of the resonance energies caused by the coupling to the contnuum and define W_{pq} for $p \neq q$ by

$$W_{pq} = \langle \varphi_p | H + H' | \varphi_q \rangle \equiv H_{pq} + iH_{pq}'. \tag{8}$$

Notice that H_{pq} and H_{pq}' are real. Furthermore in W we keep only H', according to Mahaux and Weidenmüller[16] and Moldauer[17]; thus the $V_q^{(c)}$ are real and are moreover assumed to be randomly distributed, which yields $i\pi\sum_c V_p^{(c)} V_q^{(c)} = i\delta_{pq}\Gamma_q/2$. Therefore the matrix D simplifies to

$$D_{pq} = (E - E_q + i\Gamma_q/2)\delta_{pq} + H_{pq} + iH_{pq}'. \tag{9}$$

Now the S matrix for the inverse reaction is

$$S_{fi} = -2\pi i \sum_{p,q} D_{qp}^{-1} V_q^{(f)} V_p^{(i)} \tag{10}$$

and the even and odd amplitudes under time reversal are given by (to first order in W)

$$f \equiv \tfrac{1}{2}(S_{fi} + S_{if}) = -i2\pi \sum_{p,q} \frac{1}{E - E_p + i\Gamma_p/2}\left(H_{pq}\frac{1}{E - E_q + i\Gamma_q/2} + \delta_{pq}\right) V_q^{(f)} V_q^{(i)}, \tag{11}$$

$$f' \equiv \tfrac{1}{2}(S_{if} - S_{fi}) = 2\pi \sum_{p,q} \frac{1}{E - E_p + i\Gamma_p/2} H_{pq}' \frac{1}{E - E_q + i\Gamma_q/2} V_q^{(f)} V_q^{(i)}. \tag{12}$$

We evaluated these expressions numerically using random numbers of typical order of magnitudes for the various physical quantities. This numerical game exhibited a slight preference for $\varphi = \pm\pi/2$ over $\varphi = 0$ or π. Thus the average angle between 0 and $\pi/2$ turned out to be $51° \pm 2°$ in contrast to $45°$ for a uniform distribution of φ. The probability distribution for φ increases (decreases) slightly between 0 and $\pi/2$ ($\pi/2$ and π). This behavior is repeated for negative angles. Thus we conclude that the simple model supports the usual assumption of an equal probability distribution of φ.

Using Eq. (4) we finally obtain an upper limit for a possible T-noninvariant strong-interaction amplitude of

$$\xi \leq 5\times 10^{-4} \text{ (80\% confidence)}. \tag{13}$$

This result represents a factor of 6 improvement over the previous experiment[8] in which detailed balance has been tested in an entirely different energy regime. It is now the most precise measurement in the realm of the strong interaction, comparable in precision with the most precise weak[3] and electromagnetic[4] interaction experiments and sharing with them the fact of being consistent with T invariance, contrary to another recent strong-interaction test.[5]

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