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Systematics of Isospin Mixing in Proton Elastic Scattering from Light Nuclei*

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The effects of isospin mixing observed by isospin-forbidden resonant proton scattering from the stable, self-conjugate, even-even nuclei exhibit a simple dependence on target mass number A. Furthermore, for $A=8n+4$, n integral, the mixing is systematically a factor of 5 larger than for $A=8n$. The relation between this behavior and the trends of other relevant nuclear properties is discussed.

The total isospin quantum number T of a nuclear state would be unique if the nuclear Hamiltonian were identical for neutrons and protons.[1] Isospin mixing in nuclear states can be determined by measuring deviations from isospin conservation rules. In this Letter we show that isospin mixing in light nuclei, as evidenced by the reduced widths γ_p^2 in proton isospin-forbidden elastic scattering from the self-conjugate ($N=Z$) nuclei with Z even, shows a very simple dependence on target mass number A. Moreover, we find that γ_p^2 is systematically about a factor of 5 larger for the $A=8n+4$ targets (^{12}C, ^{20}Ne, ^{28}Si, ^{36}Ar) than for $A=8n$ targets (^{8}Be, ^{16}O, ^{24}Mg, ^{32}S, ^{40}Ca). Indications of this periodic behavior had been noted previously[2,3] on the basis of less complete data. The isospin-forbidden α decays of excited $T=2$ states of the same nuclei exhibit a periodic behavior to a limited extent.[4]

Proton elastic scattering from self-conjugate target nuclei through $T=\frac{3}{2}$ resonances is isospin forbidden; it can occur by isovector ($\Delta T=1$) or isotensor ($\Delta T=2$) interactions. We measured elastic-scattering excitation functions at four backward angles over the lowest $T=\frac{3}{2}$ resonances for ^{24}Mg, ^{28}Si, and ^{32}S targets, using methods described previously.[2,5] Typical target thicknesses corresponded to a mean energy loss of 300 eV, and the high-resolution system[6] produced an incident beam spread with full width at half-maximum of ~ 650 eV. Representative excitation functions are shown in Fig. 1. Polarized-beam data with thicker targets and a beam resolution of about 1.5 keV were also accumulated near each resonance.

For each target nucleus the high-resolution excitation functions were analyzed[5] in terms of spin-flip and spin-nonflip helicity amplitudes.[7] With the use of the polarized-beam data only two real parameters were required to fit the off-resonance data at each angle. The $T=\frac{3}{2}$ resonance was ascribed a Breit-Wigner energy dependence with the resonance energy, the width Γ, and the proton elastic-scattering partial width Γ_p as parameters. The ratio Γ_p/Γ was constrained to be

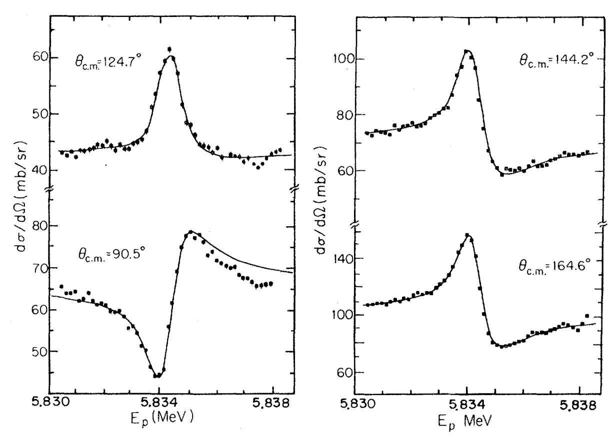

FIG. 1. High-resolution excitation functions over the lowest $T=\frac{3}{2}$ resonance observed in $^{28}Si(p,p)^{28}Si$. The target was enriched SiO (mean energy loss 250 eV) on a C foil. The solid lines are fits for total width $\Gamma=360$ eV, $\Gamma_p/\Gamma=0.82$, and an energy-resolution function with $\Delta=650$ eV and $\xi=80$ eV, as discussed in the text.

consistent with previous β-delayed–proton experiments[8-11] (Refs. 8 and 9 for ^{24}Mg, Ref. 10 for ^{28}Si, and Ref. 11 for ^{32}S). The energy-resolution function was a Gaussian of full width at half-maximum Δ to describe the incident-beam resolution, convoluted with a Landau energy-straggling function[12] with straggling parameter ξ. The effects of energy straggling in the target are essential to provide a proper fit on the high-energy side of the resonances. Only the nonresonant amplitudes were allowed to vary with angle. The uncertainty in Γ_p was assigned on the basis of the variation of the best-fit value of Γ with angle, and the uncertainties in Δ and the branching ratio Γ_p/Γ. Previous high-resolution data on the lowest $T=\frac{3}{2}$ resonance observed in ^{20}Ne$(p,p)^{20}$Ne (at two angles), for which $\Gamma < 1200$ eV had been estimated,[13] were similarly reanalyzed, resulting in $\Gamma = 750^{+50}_{-250}$ eV for $\Gamma_p/\Gamma = 0.2$ (Ref. 9). Previous determinations of Γ and Γ_p/Γ were used for the nuclei ^{8}Be, ^{12}C, ^{16}O, and ^{36}Ar; high-resolution experiments on ^{12}C and ^{16}O are in progress at Triangle Universities Nuclear Laboratory. The values of Γ_p, and the proton reduced widths γ_p^2 obtained by dividing out the Coulomb penetrabilities[14] (evaluated at a radius of $1.4A^{1/3}$ fm), are given in Table I and shown in Fig. 2(a).

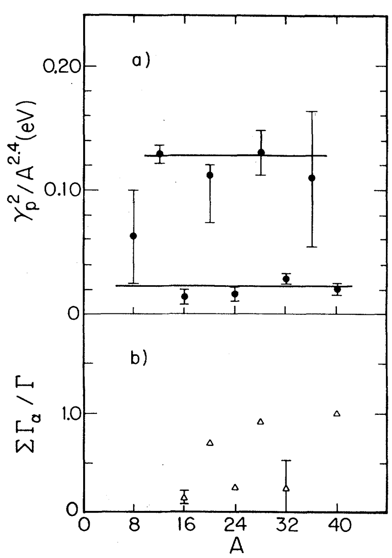

FIG. 2. (a) Proton elastic-scattering reduced widths γ_p^2 (Table I) for T-forbidden $T=\frac{3}{2}$ resonances plotted as $\gamma_p^2/A^{2.4}$ versus the target mass number A for self-conjugate, even-even nuclei. The horizontal lines show the least-squares estimates for $A=8n+4$ targets (upper line) and for $A=8n$ targets (lower line). (b) α-particle summed branching ratios for the T-forbidden decay of the lowest $T=2$ states in self-conjugate, even-even nuclei as a function of parent nucleus mass number A.

The proton reduced widths as a function of A can be fitted by two parallel lines $\gamma_p^2 = c_0 A^b$ for $A=8n$ and $\gamma_p^2 = c_4 A^b$ for $A=8n+4$; thus the difference between the $A=8n$ and $A=8n+4$ nuclei has the same A dependence as the overall trend of γ_p^2. An error-weighted least-squares fit gives $b=2.4$, $c_0 = 0.023 \pm 0.009$ eV, and $c_4 = 0.128 \pm 0.007$ eV. According to the t test for the statistical significance of the difference between two means,[19] the probability that these two values of c describe the same population is $< 10^{-6}$. The form $A^{2.4}$ is closer to the $A^{2.3}$ dependence inferred[5] from isospin mixing calculated in a Fermi-gas model[20] than to the dependence predicted by other models of isospin mixing.[1,2] In general, however, the measured partial widths are much smaller than those suggested by theory.

The α decay from a $T=2$ state in a self-conjugate nucleus to a $T=0$ state in the final nucleus can occur only by $\Delta T=2$ interactions if the α particle has pure isospin $T=0$. In Fig. 2(b) are shown previously determined[4,21-25] $\Delta T=2$ α-decay branching ratios summed over the final states (Refs. 21–25 for $A=16$, 20, 24, 28, and 32, respectively, and Ref. 4 for $A=20$–40). The summed branching ratios may characterize the properties of the excited parent nucleus, rather than the ground state of the daughter nucleus. The α-decay widths Γ_α have not been measured. With the notable exception of ^{40}Ca, the summed branching ratios show oscillations with A which are in phase with the γ_p^2 values for (p,p) scattering.

The very small reduced widths in the (p,p) scattering imply that very small wave-function admixtures are being detected; for $A=20$ γ_p^2 is

TABLE I. Proton partial widths for elastic scattering through T-forbidden resonances of known J^π. The reduced widths γ_p^2 are calculated as described in the text. For ^{40}Ca the analysis did not consider the straggling effects so that the error has been increased over that given in Ref. 2.

A	J^π	Γ_p (eV)	γ_p^2 (eV)	Ref.
8	$(3/2)^-$	30 ± 17	10 ± 6	15
12	$(1/2)^-$	210 ± 11	55 ± 3	16
16	$(5/2)^+$	40 ± 15	12 ± 5	17
20	$(5/2)^+$	150^{+10}_{-50}	165^{+13}_{-65}	13,5
24	$(5/2)^+$	26 ± 9	38 ± 13	5
28	$(5/2)^+$	300 ± 40	435 ± 60	5
32	$(1/2)^+$	110 ± 15	135 ± 20	5
36	$(3/2)^+$	40 ± 20	680 ± 340	18
40	$(3/2)^+$	55 ± 10	165 ± 30	2,5

$\sim 10^{-4}$ of the single-particle limit.[14] The present observations on self-conjugate, even-even, target nuclei show a periodicity in A of 8. We searched for the same periodicity in other relevant, measured nuclear properties—the level densities of $T=\frac{1}{2}$ states near the $T=\frac{3}{2}$ resonances, the excitation energies of the lowest $T=1$ and $T=2$ states in the target nuclei, the target α-particle ground-state spectroscopic strengths,[26] and the internal binding energies of α clusters[27]—but no such periodicity was apparent.[5]

To improve understanding of the γ_p^2 systematics, further measurements of Γ_p for ^{8}Be and ^{36}Ar are desirable. To test whether the isospin mixing is dominated by isospin admixtures in the compound systems, or by target admixtures, systematic examination of higher-isospin states should be made. Measurements of Γ_α for the $T=2$ states would provide more conclusive results than the branching ratios. The explanation of the results presented here poses a challenging theoretical problem.

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