Unusual Isospin-Breaking and Isospin-Mixing Effects in the $A = 35$ Mirror Nuclei

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(Received 10 November 2003; published 2 April 2004)

Excited states have been studied in ^{35}Ar following the ^{16}O(^{24}Mg, $1\alpha 1n$)^{35}Ar fusion-evaporation reaction at 60 MeV using the Ge-detector array GASP. A comparison with the mirror nucleus ^{35}Cl shows two remarkable features: (i) A surprisingly large energy difference for the $13/2^-$ states, in which the hitherto overlooked electromagnetic spin-orbit term is shown to play a major role, and (ii) a very different decay pattern for the $7/2^-$ states, which provides direct evidence of isospin mixing.

DOI: 10.1103/PhysRevLett.92.132502 PACS numbers: 23.20.Lv, 21.60.Cs, 27.30.+t

The isospin T is a good quantum number under the fundamental assumptions of charge symmetry and charge independence of the strong force, which imply that the proton and neutron can be viewed as two different states of the same particle, the nucleon. However, it has long been expected [1] and recently been shown [2] that a small part of the nucleon-nucleon interaction adds to the Coulomb force in violating the isospin symmetry. Isospin breaking effects can be studied in pairs of mirror nuclei, in which the number of protons and neutrons are interchanged. They lead to shifts between the excitation energies of a mirror pair, the so-called mirror energy differences (MED), which are known to be precise and challenging probes of nuclear structure.

The experimental studies have focused on nuclei in the $1f_{7/2}$ shell [3–9]. The region between ^{40}Ca and ^{56}Ni is one of the best understood theoretically, and high quality wave functions are available. This greatly simplifies the task of explaining quantitatively the MED [10,11]. One striking outcome of these studies is the importance of nuclear charge symmetry breaking effects that turn out to be as important as the Coulomb force [2].

In principle, experimental studies of $N \sim Z$ nuclei below ^{40}Ca benefit from larger production cross sections, and are thus more easily accessible for in-beam studies. On the contrary, the understanding of mirror nuclei in the *sd* shell represents a more challenging task. The well understood positive parity states produce expressionless MED patterns, while the truly interesting negative-parity states demand cross shell ($sd - pf$) calculations. These are within reach of present shell-model capabilities, but not yet of detailed quantitative use. This should stimulate the study of $N \approx Z$ nuclei in the mass $A \sim 30$–40 region, about which not much is known through modern γ-ray spectroscopic studies [12].

In this Letter we present novel results on ^{35}Ar [13–15]. A comparison with the $T_z = +1/2$ mirror nucleus ^{35}Cl [12,16,17] reveals two remarkable features: (i) A very large MED value for the $13/2^-$ states and (ii) a dramatic difference in decay patterns of the $7/2^-$ states. A similar MED value for the yrast $13/2^-$ states has been reported in the $A = 39$ mirror nuclei [18] but remains unexplained. The interpretation presented here involves the *electromagnetic* spin-orbit interaction, which is shown to have an appreciable effect on the MED.

The experiment was performed at the Legnaro National Laboratory, where the heavy-ion fusion-evaporation reaction ^{24}Mg + ^{40}Ca was studied at a beam energy of 60 MeV [19]. The 0.5 mg/cm^2 thick, enriched ^{40}Ca target was backed by 7 mg/cm^2 tantalum to stop the recoils. However, oxygen was present in the target, giving rise to the reaction ^{24}Mg + ^{16}O. The $A = 35$ mirror nuclei ^{35}Ar and ^{35}Cl were produced in the latter reaction via the evaporation of one α particle and one neutron ($1\alpha 1n$ channel) and one α particle and one proton ($1\alpha 1p$ channel), respectively. The γ rays were detected with the GASP array [20] in its standard configuration. For the detection of light charged particles, the charged-particle detector ISIS [21] was used, which comprised 40 ΔE-E Si telescopes. The NeutronRing replaced six of the 80 bismuth germanium oxide (BGO) elements at the most forward angles. The event trigger required one Ge detector, one BGO detector, and one neutron detector, or two Ge detectors and one BGO detector firing.

The events were sorted offline into E_γ projections and E_γ-E_γ matrices in coincidence with the evaporated particles corresponding to the reaction channels of interest. The previously known 1751 keV transition in ^{35}Ar [13] is clearly seen in the $1\alpha 1n$ gated projection shown in Fig. 1(a). In addition to transitions in ^{35}Ar, other strong peaks are seen in the spectrum originating from ^{58}Cu [22], which is the $1\alpha 1p 1n$ channel from reactions on ^{40}Ca. Transitions from ^{58}Cu occur in Fig. 1(a) when the proton escaped detection.

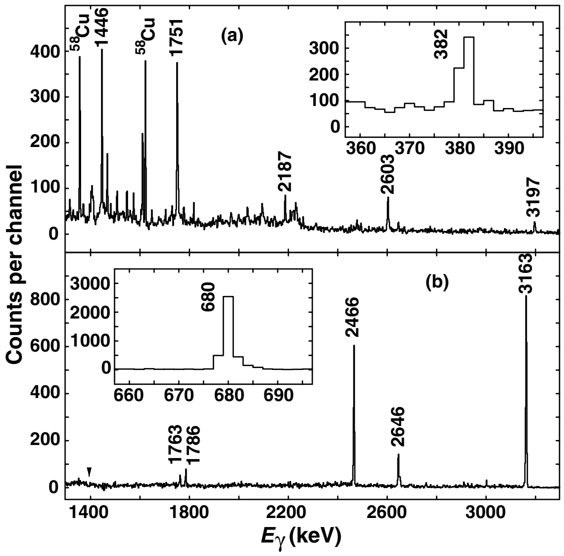

FIG. 1. (a) The $1\alpha 1n$-gated projection. Transitions belonging to ^{35}Ar are marked at 1446, 1751, 2603, and 3197 keV, and in the low-energy inset at 382 keV. (b) A spectrum gated on the 2244 keV transition in ^{35}Cl in coincidence with one α particle and one proton.

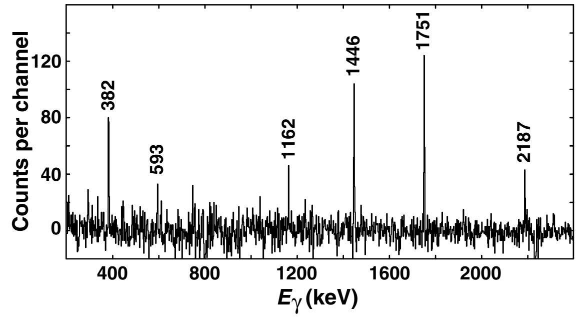

FIG. 2. Sum of spectra in coincidence with one α particle and one of the 382, 1446, 1751, and 2187 keV transitions in ^{35}Ar.

Because of the lack of statistics in the $1\alpha 1n$-gated E_γ-E_γ matrix, the $\gamma\gamma$ analysis of ^{35}Ar was performed in coincidence with one detected α particle and zero detected protons. The γ-ray spectrum in coincidence with the 1751 keV transition reveals clear peaks at 382, 1446, and 2187 keV, which are seen in the $1\alpha 1n$-gated projection in Fig. 1(a) as well. Figure 2 shows the sum of spectra in coincidence with the 382, 1446, 1751, or 2187 keV transitions. Additional lines are visible at 593 and 1162 keV. The resulting level scheme of ^{35}Ar is shown on the left hand side of Fig. 3. A careful inspection of individual and summed coincidence spectra in conjunction with the $1\alpha 1n$-gated projection provides signs for the tentative placements of the 852, 1025, and 1756 keV transitions. The 2603 keV transition marked in Fig. 1(a) corresponds to the decay of the known 2601 keV state to the ground state, and the line at 3197 keV is considered as the decay from the known 3193(10) keV state to the ground state. It does not appear in the $2\alpha 1n$- and $1\alpha 1p1n$-gated projections; i.e., it has to belong to a $1\alpha 1n$ reaction channel. It also matches the summed energies of the 1751 and 1446 keV transitions in ^{35}Ar. For comparison, known transitions in ^{35}Cl are shown in Fig. 1(b), which is a spectrum in coincidence with one α particle, one proton, and the 2244 keV $11/2^- \rightarrow 7/2^-$ γ-ray transition. The relevant part of the level scheme of ^{35}Cl is shown on the right hand side of Fig. 3. Spins and parities are known for the levels in ^{35}Cl [12,16,17]. In case of ^{35}Ar the spin and parity assignments are based on the known $3/2^+$ ground state, on mirror symmetry arguments, and on the ratios of yields $R_{35\text{–}81}$. These are ratios of efficiency-corrected γ-ray intensities measured at the most forward or most backward rings of GASP ($\overline{\theta} = 35°$ with respect to the beam axis) vs the three central rings ($\overline{\theta} = 81°$). Stretched quadrupole transitions have $R_{35\text{–}81} \approx 1.2$, whereas for stretched $\Delta J = 1$ transitions $R_{35\text{–}81} \approx 0.7$. Table I shows $R_{35\text{–}81}$ together with level energies, γ-ray transition energies, relative γ-ray intensities, and spins and parities of initial and final states for the $A = 35$ mirror nuclei. The relative intensities were determined from particle-gated projections [cf. Fig. 1(a)] and suitable coincidence spectra; e.g., the sum of the spectra in coincidence with the 382 and 2187 keV transitions in ^{35}Ar were used to confirm the relative intensities of the 593, 1446, and 3197 keV lines.

As expected, the level energies of the $A = 35$ mirror nuclei displayed in Fig. 3 are very similar. However, there are two obvious differences. The first concerns the γ-ray energies of the topmost $13/2^- \rightarrow 11/2^-$ transitions, which differ by as much as 300 keV. This difference translates directly into a dramatic decrease of the MED at $J^\pi = 13/2^-$, which is shown in Fig. 4. The filled symbols represent energy differences of the $A = 35$ mirror pair, while open circles show the results for negative-parity yrast states in the $A = 39$ system [18]. The second remarkable difference comes from the decay pattern of the $7/2^-$ states. In ^{35}Ar the 1446 keV $E1$ branch clearly dominates the 3197 keV $M2$ decay, while the corresponding 1400 keV $E1$ decay is essentially absent in ^{35}Cl [see

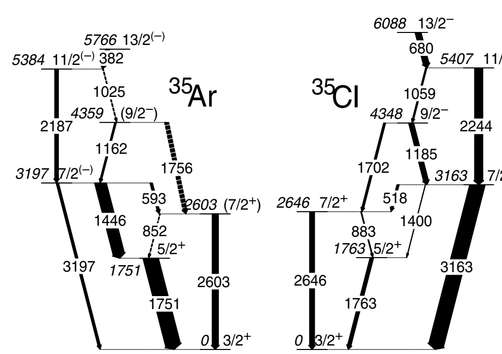

FIG. 3. Proposed level schemes for the $A = 35$ mirror nuclei ^{35}Ar and ^{35}Cl. For the latter only the relevant subset of known states is shown. The energy labels are given in keV and the widths of the arrows are proportional to the relative intensities of the γ rays. Tentative transitions are dashed.

TABLE I. The energies of excited states in ^{35}Ar and ^{35}Cl, the transition energies and relative intensities of the γ rays, angular distribution ratios, and spins and parities of the initial and final states of the γ rays.

E_x	E_γ	I_{rel}	R_{35-81}	J_i^π	J_f^π
^{35}Ar					
1750.7(6)	1750.7(4)	100(7)	1.41(14)	$5/2^+$	$3/2^+$
2603.1(8)	852(1)	4(2)		$(7/2^+)$	$5/2^+$
	2603.0(5)	41(9)	1.01(17)	$(7/2^+)$	$3/2^+$
3196.9(7)	593(1)	12(6)		$7/2^{(-)}$	$(7/2^+)$
	1446.2(2)	76(7)	0.71(9)	$7/2^{(-)}$	$5/2^+$
	3197.0(7)	14(4)	1.45(51)	$7/2^{(-)}$	$3/2^+$
4359.1(13)	1162(1)	11(3)		$(9/2^-)$	$7/2^{(-)}$
	1756(1)	27(4)		$(9/2^-)$	$7/2^+$
5384.3(10)	1025(1)	5(2)		$11/2^{(-)}$	$(9/2^-)$
	2187.4(4)	24(3)	1.60(36)	$11/2^{(-)}$	$7/2^{(-)}$
5765.9(10)	381.6(1)	26(3)	0.69(18)	$13/2^{(-)}$	$11/2^{(-)}$
^{35}Cl					
1763.0(3)	1763.1(2)	22.9(7)	1.43(7)	$5/2^+$	$3/2^+$
2645.6(4)	882.9(1)	4.9(4)		$7/2^+$	$5/2^+$
	2645.5(4)	32.3(10)	1.21(6)	$7/2^+$	$3/2^+$
3162.9(4)	517.7(1)	14.3(8)		$7/2^-$	$7/2^+$
	1399.6(1)[a]	0.30(4)[a]		$7/2^-$	$5/2^+$
	3162.7(4)	100.0(30)	1.43(7)	$7/2^-$	$3/2^+$
4347.8(5)	1185.0(2)	32.9(10)		$9/2^-$	$7/2^-$
	1702.0(3)	13.0(8)		$9/2^-$	$7/2^+$
5407.1(5)	1059.3(2)	9.1(9)		$11/2^-$	$9/2^-$
	2244.2(3)	53.9(17)	1.24(6)	$11/2^-$	$7/2^-$
6087.5(6)	680.4(1)	39.1(12)	0.65(3)	$13/2^-$	$11/2^-$

[a]Taken from Refs. [12,16].

arrow in Fig. 1(b)], and the state decays directly to the ground state through the strong 3163 keV $M2$ transition. The effect is truly striking and has never been observed before in mirror studies.

To understand the origin of the very large $13/2^-$ MED, it is useful to compare with the situation in the pf shell, where three contributions of about equal importance coexist: nuclear charge symmetry breaking multipole (BM), Coulomb multipole (CM), and Coulomb monopole effects (Cm) [2].

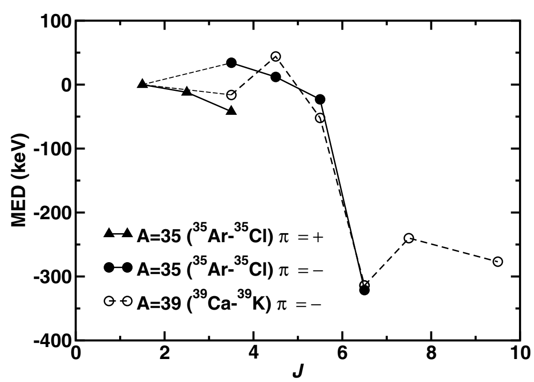

FIG. 4. MED diagram for the $T = 1/2$, $A = 35$, and $A = 39$ mirror nuclei. See text for details.

BM: The energy differences in the $A = 42$ isospin triplet produce direct evidence of charge symmetry breaking. Furthermore, the dominance of $1f_{7/2}$ configurations makes it possible to identify a single matrix element ($1f_{7/2}{}^2$, $J = 2$) as being mostly responsible for the BM contributions to the MED in the $A = 40$–56 region. They are quantitatively crucial but never exceed 30 keV for a given transition. Below $A = 40$ there are no simple arguments to determine the necessary matrix elements, but there are no reasons to expect that they could produce anything close to the observed 300 keV.

CM: These matrix elements are known. They are largest, ≈ 50 keV, in the middle of the $1f_{7/2}$ shell for rotational nuclei in the backbending region, where the Coulomb force sees the alignment of particles. Hence, in the upper sd shell, CM is expected to play a minor role.

Cm: The monopole Coulomb contribution contains three terms: Cm = Cr + Cll + Cls. Cr is basically the classical electrostatic value for a charged sphere. Small differences in the radius of the yrast state of a given spin can lead to appreciable contributions to the MED. In this case, Cr is proportional to differences in the *sum* of neutron and proton orbital occupancies, weighted by the orbits' square radii. Taking the sum ensures that neutron and proton radii are about equal, as requested by experiment [23].

Cll and Cls are single-particle contributions. Their effects are proportional to differences in the *differences* of neutron and proton orbital occupancies. Cll is an $l \cdot l$ term [23], while Cls is the relativistic electromagnetic spin-orbit coupling [24]

$$C_{ls} = (g_s - g_l)\frac{1}{2m_{\rm nucleon}^2 c^2}\left\langle \frac{1}{r}\,\frac{dV_C(r)}{dr}\right\rangle \langle \vec{l} \cdot \vec{s}\rangle,$$

where g_s and g_l are the free gyromagnetic factors. This effect has not been considered before. In the pf shell, Cll is large (125 keV increase for the $2p_{3/2}$-$1f_{7/2}$ proton splitting in ^{41}Ca). For the negative-parity states in the upper sd shell, however, Cls becomes significant. This is principally because the negative-parity states involve excitations from an orbital with $j = l - s$ to one with $j = l + s$. Specifically, there is a gain of 100 keV for the $1f_{7/2}$ orbit, and the $1d_{3/2}$ orbit loses as much. This should be compared with a gain of some 40 and 15 keV for Cll, respectively.

The two latter single-particle effects, Cll and Cls, make the most significant contribution to the MED for single-particle states involving a "pure" single-nucleon excitation (e.g., a pure proton excitation in one nucleus, and a neutron excitation in the mirror). Indeed, it is in such nuclei that the MED can reach several hundred keV. The $T = 1/2, J^\pi = 7/2^-$ states in $A = 33$–39 mirror nuclei provide convincing examples. For $A = 33$ and 37 these MED are about 250 keV, which can be understood as being due to very pure single-particle states obtained by adding a nucleon to the ^{32}S and ^{36}Ar $T = 0, J^\pi = 0^+$ cores. For $A = 35$ and 39 the MED are very small. This is understood from configuration mixing since there is no reason to expect a $7/2^-$ pure single-particle state from coupling a nucleon to the $T = 0$, $J^\pi = 3^+$ "cores" of ^{34}Cl and ^{38}K. This is confirmed by an elementary calculation — allowing only one single particle in the pf shell with the interaction from Ref. [25]. This shows that the unambiguous "single-particle" candidates in the mirror pair are the $J^\pi = 13/2^-$ states, with $1f_{7/2}$ proton (neutron) occupancies very close to 1 (0) for ^{35}Ar—and vice versa for ^{35}Cl. This accounts for the large MED of the $J^\pi = 13/2^-$ states, half of which arises from the Cls + Cll contribution and the other half from Cr, given that the radius of the $1f_{7/2}$ orbit is larger than its sd counterparts. The calculation confirms that for the other negative-parity states the $1f_{7/2}$ occupancies are nearly equal for neutrons and protons (which cancels the Cll and Cls effects) resulting in small MED values.

There is, however, a catch: Assuming $(sd)^n$ and $(sd)^{n-1}(pf)$ configurations for the positive- and negative-parity states, respectively, the effect of Cr on MED should be $\approx$ 150 keV larger for the former since the pf orbits have larger radii. This is not what is observed (see Fig. 4). One solution to the problem could come from strong mixing between $(sd)^{n-n_0}(pf)^{n_0}$ configurations. This tends to equalize the radii of most positive- and negative-parity states. The exceptions are the single-particle states, whose parentage properties would be respected. The conjecture is not far fetched: radii are very sensitive to mixing, as indicated by the spectacular odd-even staggering of the Ca isotope shifts. This can only partially be explained in a restricted $sdpf$ shell-model calculation [26] indicating that stronger mixing is necessary, which is achieved in a full $sdpf$ Monte Carlo shell-model study [27]. It seems clear though that the "new" Cls effect plays a major role in the $A = 30$–40 region.

The explanation for the dramatic difference in decay patterns of the $7/2^-$ states in the $A = 35$ mirror pair that comes naturally to mind is a cancellation of the $E1$ matrix elements due to isospin mixing:

$$|7/2^-\rangle = \alpha|7/2^-, T = 1/2\rangle + \beta|7/2^-, T = 3/2\rangle,$$

$$|5/2^+\rangle = \gamma|5/2^+, T = 1/2\rangle + \delta|5/2^+, T = 3/2\rangle.$$

Using the Wigner Eckart theorem, it is found that the contributions to $E1$ diagonal in T have the same sign for both decays, while the nondiagonal ones have opposite signs. As a consequence, one of the decays is reinforced and the other one is quenched, in this case canceled. Using the known lifetime $\tau = 45.3(6)$ ps [12,16] of the $7/2^-$ state in ^{35}Cl, and the relative intensities of transitions in Table I we have $B(M2; 7/2^- \rightarrow 3/2^+) = 0.25$ W.u. and $B(E1; 7/2^- \rightarrow 5/2^+) = 2 \times 10^{-8}$ W.u. Assuming identical $B(M2)$'s in both members of the mirror system it follows that $B(E1; 7/2^- \rightarrow 5/2^+) = 3 \times 10^{-5}$ W.u. for ^{35}Ar. This means that the contributions diagonal and nondiagonal in T are equal in magnitude and about 1.5×10^{-5} W.u.

To make good use of these results the $(sdpf)^n$ calculations must be supplemented by a reliable estimate of isospin mixing, a major problem which remains to be tackled with modern shell-model techniques.

In summary, the level scheme of the $T_z = -1/2$ nuclei ^{35}Ar has been extended up to the yrast $13/2^-$ state at 5766 keV. It leads to a very large MED providing strong evidence for the need to include the electromagnetic spin-orbit coupling, so far thought to be negligible. The asymmetry in the mirror decay patterns of the $7/2^-$ state is experimentally striking and theoretically challenging.

We thank the accelerator crew and target makers at LNL for the excellent support. This research was supported in part by the Swedish Research Council and the European Commission under Contract No. HPRI-1999-CT-00083.

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