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Isospin symmetry breaking at high spin in the mirror nuclei ^{35}Ar and ^{35}Cl

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High-spin states in ^{35}Ar and ^{35}Cl have been populated in the ^{24}Mg(^{16}O, αn) and ^{24}Mg(^{16}O, αp) reactions, respectively, at a beam energy of 70 MeV. The comparison between the level schemes of these mirror nuclei shows a striking asymmetry in the population yield of high-spin analog states of positive parity, which indicates different intensities of $E1$ transitions connecting positive- and negative-parity structures in both nuclei. Large energy differences are observed between analog states of negative parity with configurations of dominant pure single-particle character. This results from the comparison with large-scale shell-model calculations in the $s_{1/2}d_{3/2}f_{7/2}p_{3/2}$ valence space. It is shown that important contributions to the energy differences arise from the multipole Coulomb and the relativistic electromagnetic spin-orbit interactions.

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I. INTRODUCTION

Nuclei located on or close to the $N = Z$ line have been the object of considerable interest during the past few years. This region, in fact, is the only place where it is possible to find answers to fundamental problems in nuclear physics, such as the role of proton-neutron pairing or isospin symmetry of the nuclear interaction. One of the consequences of this symmetry is that the level schemes of mirror nuclei (obtained by interchanging neutrons and protons) should be identical. In particular, the isospin selection rules impose that $E1$ transitions between analog states should have the same strength. In the study of mirror nuclei, the signatures of isospin symmetry breaking are, therefore, the differences between the excitation energy of analog states, called mirror energy differences (MEDs), and the different strengths of analog $E1$ transitions.

In recent years, the large increases in sensitivity and resolving power resulting from the advent of large γ-ray arrays coupled to light-particle detectors have allowed the study of $N \sim Z$ nuclei up to high spin and the extension of the investigation up to medium-heavy masses. Interesting results have been obtained in the $f_{7/2}$ shell where mirror nuclei have been extensively studied, both from the experimental and the theoretical side. Nuclei near the middle of the shell present rotational bands and the energy differences between isobaric states in mirror nuclei constitute a very delicate probe of the nuclear structure. In particular, it has been shown that the MEDs are sensitive to nucleon alignment and that one can deduce which type of nucleons align at the backbending in rotational bands [1,2]. Moreover, shell-model calculations in the full *fp* shell, which reproduce the MEDs with very good accuracy, give information on the evolution of the nuclear radius along the yrast bands [3] and it has been pointed out recently [4] that the role of isospin-nonconserving (INC) *nuclear* forces could be as important as that of the Coulomb field in the observed MEDs between mirror nuclei in the $f_{7/2}$ shell.

The extension of these investigations to other mass regions is very important for checking the limits of validity of isospin symmetry for different masses and to explore the importance of the different INC contributions. An interesting region is the upper *sd* shell where, recently, data on analog states in the mirror pairs $A = 31$, 35, and 39 have become available [5–7], revealing in all cases very large MED values for the $13/2^-$ state. In Ref. [6] it has been argued that important contributions to these MEDs should arise from the electromagnetic spin-orbit (EMSO) interaction, which manifests in particular states where a single nucleon, a proton in one nucleus and a neutron in the mirror, is excited from the *sd* to the *fp* shell. It is thus important to extend these level schemes to high-spin states, where these types of configurations are expected.

In this work recent results obtained for the mirror *sd*-shell nuclei of mass $A = 35$ at high spin are reported. Preliminary results have been presented in Ref. [8].

II. EXPERIMENTAL DETAILS

This experiment was performed at Legnaro National Laboratory, where a 400 μg/cm^2 self-supporting target of ^{24}Mg was bombarded by a beam of ^{16}O at 70 MeV, delivered by the XTU-Tandem accelerator. The mirror pair ^{35}Ar-^{35}Cl was produced via the evaporation of one α particle and one neutron and one α particle and one proton, respectively. The γ rays were detected with the GASP spectrometer [9], which consists of an array of 40 Compton-suppressed HPGe detectors and a multiplicity filter of 80 BGO scintillators. The events were collected when at least two Ge detectors and one BGO scintillator fired in coincidence. To have a better identification of the different reaction channels, the γ spectrometer was operated in conjunction with the 4π charged-particle detector ISIS [10] and the neutron ring, which consists of six BC501A scintillators with an overall efficiency of 3–5%, replacing the six BGO elements at the most forward angles. For calibration of the energy spectra standard sources of ^{56}Co and ^{152}Eu have been used. The events were sorted off-line into E_γ-E_γ matrices in coincidence with the evaporated particles corresponding to the reaction channels of interest. To reduce the Doppler broadening of the peaks, an event-by-event kinematical reconstruction of the velocity of the recoiling nuclei was performed.

Prior to our study, information about high-spin states in ^{35}Cl has been reported in Ref. [11]. In that work, levels up to spins $17/2^+$ at 8.8 MeV and $13/2^-$ at 6.1 MeV, for positive and negative parity, respectively, have been studied. In the present work we have added 32 new transitions and 17 new levels, extending the level scheme of ^{35}Cl up to $23/2^+$ at 13.9 MeV for positive parity and up to $31/2^-$ at 22 MeV for negative parity. The complete level scheme has been reported in Ref. [12] and more detailed results will be published elsewhere. In this article we will consider only the states relevant for the comparison with the mirror nucleus ^{35}Ar.

The nucleus ^{35}Ar has been studied recently by Ekman *et al.* [6], who observed up to the $13/2^-$ state at 5.8 MeV. In the present experiment we have added nine new transitions and five new high-spin states, extending the level scheme of ^{35}Ar up to the $23/2^-$ state at 12.3 MeV. The analysis for ^{35}Ar has been done by starting from the identification of possible new transitions in the $1\alpha 1n$ matrix. However, because of the lack of statistics in this matrix, the analysis has been performed by studying the $\gamma\gamma$ coincidences in the 1α matrix. The candidate transitions were confirmed and assigned by observing their presence when gates were put on the $\gamma\gamma$ matrix with the 1α particle condition (where the statistics is higher) and their absence when the same gates were put on the matrices requiring the coincidence with more charged particles. Figure 1 illustrates spectra in coincidence with selected transitions in ^{35}Cl (a) and ^{35}Ar (b), obtained from the $1\alpha 1p$ and 1α matrices, respectively. Note that the transition of 1255 keV in spectrum (b) is contaminated by the strong 1266-keV transition from ^{31}P, populated by the $2\alpha 1p$ reaction. The assignment of the 1255-keV transition to ^{35}Ar was based on its presence in the spectrum obtained from the $1\alpha 1n$ matrix with gates on the 1446- and 1756-keV transitions, as illustrated in the inset.

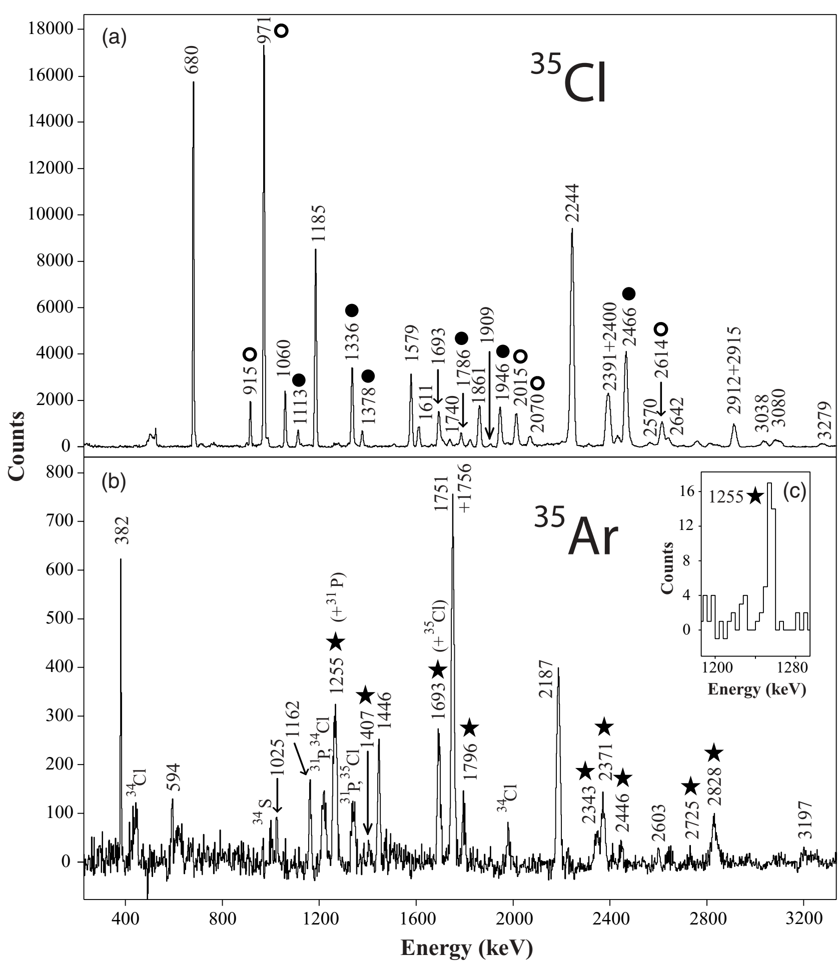

FIG. 1. (a) Spectrum obtained from the $1\alpha 1p$ matrix in coincidence with the 3163-keV transition in ^{35}Cl. The transitions between the high-spin positive-parity states are marked with open circles; the transitions linking these states with the negative-parity states are marked with full circles (see text for discussion). (b) Spectrum obtained from the 1α matrix in coincidence with the 1446- and 382-keV transitions in ^{35}Ar. The new transitions are marked with stars. The inset shows part of the γ spectrum obtained from the $1\alpha 1n$ matrix in coincidence with the 1446- and 1756-keV transitions of ^{35}Ar.

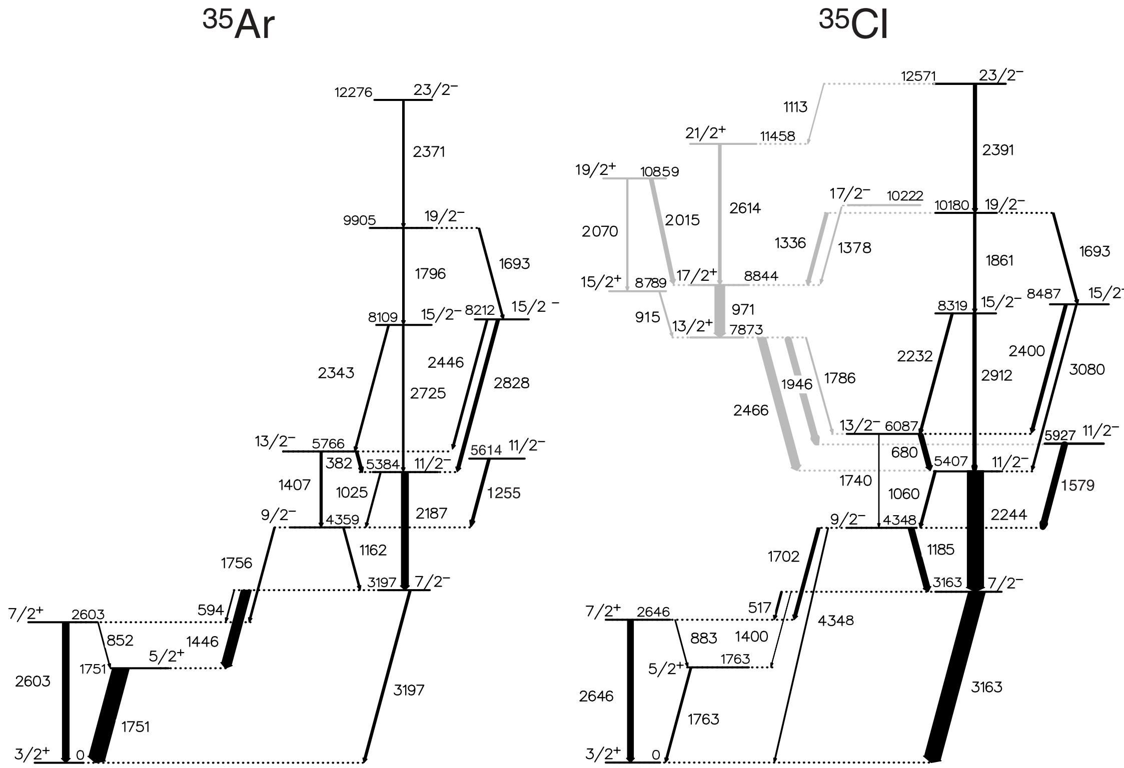

FIG. 2. Proposed level schemes for the $A = 35$ mirror nuclei ^{35}Ar and ^{35}Cl. For the latter only the relevant subset of states is shown.

Spins and parities for the new levels have been assigned on the basis of transition multipolarities deduced from measured ADO ratios [13]. These ratios are calculated according to

$$R_{\mathrm{ADO}} = \frac{I_\gamma(34^\circ) + I_\gamma(146^\circ)}{2I_\gamma(90^\circ)}, \tag{1}$$

where $I_\gamma(\theta^\circ)$ are the γ-ray intensities corrected for efficiency, obtained from spectra registered by the detectors of the GASP array in the rings at corresponding angles, gated on the axis where all the detectors are added together. Stretched quadrupole transitions have $R_{\mathrm{ADO}} \approx 1.3$, whereas $R_{\mathrm{ADO}} \approx 0.8$ for stretched dipole ones.

The complete level scheme of ^{35}Ar resulting from our measurement is shown in Fig. 2, together with the relevant part of the level scheme of its mirror nucleus, ^{35}Cl. Tables I and II show the level energies, the energy and the relative intensity of the γ transitions, the ADO ratios, and the spins and parities of initial and final states for the two mirror nuclei. In ^{35}Cl firm spin and parity assignments were possible on the basis of measured R_{ADO}. For the weaker populated ^{35}Ar nucleus, the spin and parity assignments are based on R_{ADO} values and on mirror symmetry arguments.

III. DISCUSSION

One interesting feature that emerges from the comparison of the two level schemes is a striking asymmetry, namely the absence of the high-spin positive-parity structure in ^{35}Ar (shown in gray for ^{35}Cl in Fig. 2). The positive-parity structure in ^{35}Cl has a population yield comparable with that of the negative-parity structure, whereas in ^{35}Ar it is not observed. As illustrated in Fig. 1, the intense transitions between the positive-parity states in ^{35}Cl and the transitions linking them to the negative-parity states [marked with open and full circles, respectively, in Fig. 1(a)] do not meet the corresponding mirror transitions in ^{35}Ar [Fig. 1(b)]. The fact that the feeding and decay $E1$ transitions (1336, 1946, and 2466 keV) in ^{35}Cl are strong and that they are below the detection limit in ^{35}Ar indicates a remarkable asymmetry between the two mirror nuclei, as in the hypothesis that isospin symmetry $E1$ analog transitions should have the same strength. The different $E1$ strengths in both mirrors could be due to suitable cancellations of the $E1$ matrix elements caused by isospin mixing, as proposed by Ekman *et al.* [6] to explain the asymmetry in the branching ratio of the decay-out of the $7/2^-$ states.

The second interesting feature of the $A = 35$ mirror pair is the very large mirror energy differences, $\mathrm{MED}(J) = E(J, T_z = -1/2) - E(J, T_z = +1/2)$, between analog high-spin negative-parity states. In Ref. [6] the highest spin state observed in ^{35}Ar was the $13/2^-$ state, and the energy difference reported for this spin was MED $= -320$ keV. In the present work we observed large MED values for all the new high-spin yrast states, up to $J^\pi = 23/2^-$, as well as for the yrare $11/2^-_2$ and $15/2^-_2$ states. This is illustrated in Fig. 3, where the MED values for the negative-parity states are plotted as a function of the angular momentum. It is interesting to compare the MED values in $A = 35$ with those obtained recently for other $T_z = \pm 1/2$ mirror nuclei in the upper *sd* shell. As seen in Fig. 3, large MED values are also found for some states in the

TABLE I. The energies of excited states in ^{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.

E_x (keV)	E_γ (keV)	$I_{\rm rel}$	$R_{\rm ADO}$	J_i^π	J_f^π
1763	1763.1(5)	21.2(7)	0.77(3)	$5/2^+$	$3/2^+$
2646	882.9(5)	4.0(1)	0.75(3)	$7/2^+$	$5/2^+$
	2645.7(5)	36.1(4)	1.35(4)	$7/2^+$	$3/2^+$
3163	517.4(5)	11.1(13)		$7/2^-$	$7/2^+$
	1399.9(7)	0.5(2)		$7/2^-$	$5/2^+$
	3163.1(5)	100.0(6)	1.30(2)	$7/2^-$	$3/2^+$
4348	1184.9(5)	44.4(16)	0.54(2)	$9/2^-$	$7/2^-$
	1701.6(5)	23.1(6)	0.76(6)	$9/2^-$	$7/2^+$
	4347.8(8)	5.5(5)		$9/2^-$	$3/2^+$
5407	1059.6(5)	17.1(4)	1.05(4)	$11/2^-_1$	$9/2^-$
	2243.9(5)	89.0(8)	1.26(3)	$11/2^-_1$	$7/2^-$
5927	1578.9(5)	31.8(13)	0.48(1)	$11/2^-_2$	$9/2^-$
6087	680.5(5)	33.0(2)	0.84(2)	$13/2^-$	$11/2^-_1$
	1739.5(5)	2.6(3)	1.38(10)	$13/2^-$	$9/2^-$
7873	1786.2(5)	4.5(2)	1.37(7)	$13/2^+$	$13/2^-$
	1946.2(5)	22.4(12)	0.80(4)	$13/2^+$	$11/2^-_2$
	2466.2(5)	46.2(9)	0.77(2)	$13/2^+$	$11/2^-_1$
8319	2232.7(6)	10.3(5)		$15/2^-_1$	$13/2^-$
	2911.9(8)	18.0(8)	1.35(5)	$15/2^-_1$	$11/2^-_1$
8487	2399.8(8)	14.8(5)		$15/2^-_2$	$13/2^-$
	3080.0(7)	4.7(3)	1.20(12)	$15/2^-_2$	$11/2^-_1$
8789	915.4(4)	7.2(5)	0.69(3)	$15/2^+$	$13/2^+$
8844	971.4(5)	75.3(12)	1.38(3)	$17/2^+$	$13/2^+$
10180	1336.3(5)	23.5(8)	0.75(2)	$19/2^-$	$17/2^+$
	1693.5(5)	19.8(21)	1.44(7)	$19/2^-$	$15/2^-_2$
	1861.3(5)	19.6(13)	1.39(7)	$19/2^-$	$15/2^-_1$
10222	1377.8(10)	5.4(4)	1.32(12)	$17/2^-$	$17/2^+$
10859	2014.7(9)	23.1(12)	0.50(3)	$19/2^+$	$17/2^+$
	2069.8(10)	7.5(5)	1.57(11)	$19/2^+$	$15/2^+$
11458	2614.5(5)	19.0(8)	1.33(4)	$21/2^+$	$17/2^+$
12571	1113.3(5)	4.1(3)	0.86(9)	$23/2^-$	$21/2^+$
	2390.8(5)	16.8(7)	1.34(12)	$23/2^-$	$19/2^-$

TABLE II. Same as Table I for ^{35}Ar.

E_x (keV)	E_γ (keV)	$I_{\rm rel}$	$R_{\rm ADO}$	J_i^π	J_f^π
1751	1750.8(5)	100(9)	1.46(24)	$5/2^+$	$3/2^+$
2603	851.8(9)	8(2)		$7/2^+$	$5/2^+$
	2602.6(15)	60(6)	1.37(20)	$7/2^+$	$3/2^+$
3197	593.7(2)	11(2)		$7/2^-$	$7/2^+$
	1446.1(6)	67(5)	0.87(19)	$7/2^-$	$5/2^+$
	3197.0(64)	16(3)	1.71(77)	$7/2^-$	$3/2^+$
4359	1162.0(8)	15(3)	0.95(25)	$9/2^-$	$7/2^-$
	1756.3(14)	17(9)		$9/2^-$	$7/2^+$
5384	1025.2(4)	6(2)		$11/2^-_1$	$9/2^-$
	2186.8(4)	49(3)	1.31(15)	$11/2^-_1$	$7/2^-$
5614	1254.6(8)	15(5)		$(11/2^-_2)$	$9/2^-$
5766	381.5(3)	29(3)	0.81(10)	$13/2^-$	$11/2^-_1$
	1406.9(7)	5(1)	1.30(65)	$13/2^-$	$9/2^-$
8109	2342.6(28)	8(2)		$15/2^-_1$	$13/2^-$
	2725.7(14)	4(1)		$15/2^-_1$	$11/2^-_1$
8212	2446.6(16)	6(2)		$15/2^-_2$	$13/2^-$
	2828.3(7)	28(5)	1.66(56)	$15/2^-_2$	$11/2^-_1$
9905	1693.3(27)	15(3)	1.41(23)	$19/2^-$	$15/2^-_2$
	1796.3(25)	10(3)	1.83(32)	$19/2^-$	$15/2^-_1$
12276	2370.9(25)	15(5)	1.80(40)	$23/2^-$	$19/2^-$

^{39}Ca-^{39}K [7] and ^{31}S-^{31}P [5,14,15] mirror pairs.[1] For $A = 35$ and 39, very similar MED values as a function of spin are seen, with a marked jump at $J^\pi = 13/2^-$, followed by a rather smooth trend at higher angular momentum. In contrast, the MEDs for $A = 31$ show a staggering behavior.

So far, the spin dependence of the MEDs for these nuclei has been discussed at a qualitative level by Ekman *et al.* [6] and Jenkins *et al.* [5] and points to the important role of the EMSO interaction in developing large MED values. For a *quantitative* description of the MEDs between negative-parity states, shell-model calculations can be performed by taking into account both the *sd* and *fp* main shells. However, because the dimension of the matrices to be diagonalized becomes too large if all the shell-model orbits are considered, truncations of the model space are mandatory. Recently, the effective interaction *sdfp* [16] in the reduced valence space $s_{1/2}d_{3/2}f_{7/2}p_{3/2}$ has proven to give a rather good description of the spectroscopy of ^{34}S [17]. This encouraged us to use this model space to compute the MEDs for $A = 35$ and $A = 39$ nuclei. In the case of $A = 31$, this valence space with only three particles outside the core is insufficient to account for high-spin states. As discussed in Ref. [15], the $d_{5/2}$ orbital needs to be opened to have a consistent description of the spectroscopy of mass $A = 31$.

We have calculated the MED values for the mirror nuclei $A = 35$ and $A = 39$ using the code ANTOINE [18] and the *sdfp* interaction. Shifts to the single-particle energies of protons and neutrons are induced by the electromagnetic spin-orbit interaction $E_{\rm EMSO}$ [19,20] and the E_{ll} term deduced in

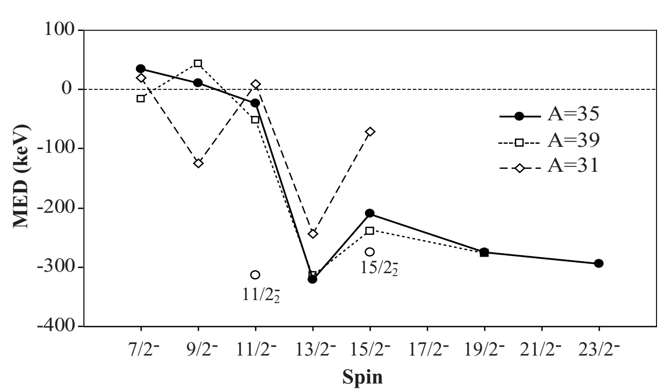

FIG. 3. MED values for negative-parity states in $A = 35$ (present work), $A = 39$ [7], and $A = 31$ [5,14,15] nuclei as a function of the spin. For $A = 35$, MED values are plotted for both yrast (full circles) and yrare (open circles) negative-parity states.

[1]For the $A = 31$ nuclei, MED values were reported previously by Jenkins *et al.* [5] up to the $13/2^-$ state. We have added the MED value at the yrast $15/2^-$ state, based on the ^{31}P level scheme recently established by Ionescu-Bujor *et al.* [15], in which the state at 10218 keV assigned as $13/2^-_3$ in Ref. [5] was identified as the yrast $15/2^-$. Accordingly, we propose the same spin assignment for the analog state at 10146 keV in ^{31}S [5].

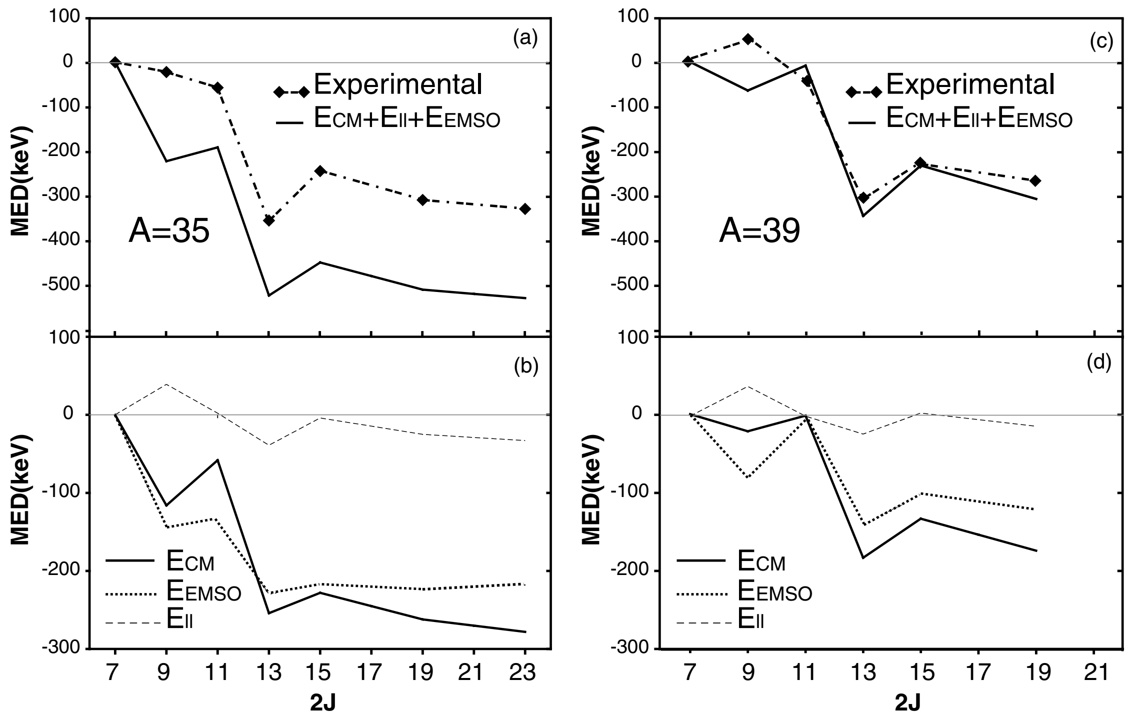

FIG. 4. Experimental MED values for the negative-parity states in (a) ^{35}Ar-^{35}Cl and (c) ^{39}Ca-^{39}K mirror nuclei compared to the theoretical values. The different theoretical contributions (see text) are shown in (b) for $A = 35$ and (d) for $A = 39$. The MED values are referred to the $J^\pi = 7/2^-$ state.

Ref. [21]. The contribution of the EMSO interaction is given by [22]

$$E_{\text{EMSO}} \approx (g_s - g_l)\frac{1}{2m_N^2c^2}\left(-\frac{Ze^2}{R_C^3}\right)\langle\vec{l}\cdot\vec{s}\rangle, \qquad (2)$$

where g_s and g_l are the gyromagnetic factors, m_N is the mass of the nucleon, and R_C is the charge radius. The sign of E_{EMSO} is opposite for neutrons and protons and for orbits with parallel or antiparallel spin-orbit coupling. For the nuclei of interest, the effect of the EMSO is to reduce the energy gap between the $f_{7/2}$ and $d_{3/2}$ orbitals for protons by ∼120 keV and to increase it for neutrons by a similar amount.

The E_{ll} term, of Coulomb origin, depends only on the orbital quantum number l and does not act on neutrons. For a proton in a main shell with principal quantum number N, above the closed shell Z_{cs} [21],

$$E_{ll} = \frac{-4.5Z_{cs}^{13/12}[2l(l+1) - N(N+3)]}{A^{1/3}\left(N+\frac{3}{2}\right)}\ \text{keV}. \qquad (3)$$

The effect of this term on the energy gap between the proton $f_{7/2}$ and $d_{3/2}$ orbitals is to further reduce it by ∼20 keV.

Because of these single-particle shifts, the energy of a state whose configuration involves the excitation of one proton from the $d_{3/2}$ to the $f_{7/2}$ will be smaller than that of the analog state in the mirror nucleus, where a neutron undergoes the excitation. This will significantly affect the MED values. In contrast, small contributions from these single-particle effects will be obtained whenever the configuration of the states involves the excitation of one proton or one neutron with similar probabilities [6], as the effects compensate each other. In addition to the single-particle effects, we have calculated the contribution of the multipole Coulomb interaction using the Coulomb matrix elements obtained in the harmonic oscillator basis.

The different contributions to the MEDs are reported in Figs. 4(b) and 4(d), for the yrast negative-parity states of $A = 35$ and $A = 39$, respectively. An interesting result of the calculations is that the multipole Coulomb term (E_{CM}) assumes large values and follows the trend of the experimental curves. This is contrary to what was expected from the systematics in the $f_{7/2}$ shell, where the calculated values do not exceed 100 keV, as discussed in Ref. [6]. The contributions arising from the single-particle terms are proportional to the difference between the orbital occupation numbers of protons and neutrons. As shown in Figs. 4(b) and 4(d), the EMSO interaction gives a contribution to the MEDs similar to that of the multipole Coulomb term. Smaller contributions are obtained for the E_{ll} term. The sum of these three components is compared to the experimental data in Figs. 4(a) and 4(c). For $A = 35$ the trend of the MEDs is well reproduced but overestimated. In particular, the sudden jump at $J^\pi = 13/2^-$ is nicely described. We note that for the nonyrast states $J^\pi = 11/2^-_2$ and $J^\pi = 15/2^-_2$ (see Fig. 3), the calculated MED values are of the same order of magnitude. In the case of $A = 39$ the calculated MEDs are in excellent agreement with the data. The only MED value not well reproduced is the one corresponding to the $J^\pi = 9/2^-$ state. A possible explanation could be that excitations from the $d_{5/2}$ shell are involved at low spin, as it is for the positive-parity states.

From the calculations for $A = 35$ it emerges that the leading configuration of the $11/2^-_2$, $13/2^-$, and the two $15/2^-$ states involves the excitation of one proton to the $f_{7/2}$ orbit for the proton-rich ^{35}Ar ($\pi(d^1_{3/2}\ f^1_{7/2})\otimes\nu(d^1_{3/2})$) and, conversely, the excitation of one neutron in the neutron-rich ^{35}Cl ($\pi(d^1_{3/2})$ $\otimes\nu(d^1_{3/2}\ f^1_{7/2})$). Therefore, the effect of the single-particle terms is to increase the energy of these states in ^{35}Cl and to lower the energy of the analog states in ^{35}Ar, which makes the MEDs assume large negative values. For the higher spin states $19/2^-$ and $23/2^-$, three particles are promoted to the *fp* shell, two protons and one neutron for ^{35}Ar and two neutrons and one proton for the mirror ^{35}Cl. Also in this case, the overall difference between the number of nucleons excited to the $f_{7/2}$ orbit is one proton and one neutron, respectively, which allows the single-particle effects to play an important role in producing large negative MED values. However, the configuration of states that show small MED values, such as the $7/2^-$ and $11/2^-_1$, is more complex, involving the excitation to the *fp* shell of one proton or one neutron with similar probabilities that translates into small MED values for these states. The consistency between the calculated configurations and the measured MED values constitutes a stringent test for the shell-model calculations. In other words, although the absolute MED values for $A = 35$ are overestimated, the calculated configurations seem to be in agreement with the data.

As previously stated, in the case of $A = 31$ a shell-model analysis needs to enlarge the valence space including the $d_{5/2}$ orbit. This valence space has been used in Ref. [15] to study the structure of ^{31}P with the Monte Carlo shell model (MCSM) [23] and the SDPF-M interaction [24]. Mixed configurations were obtained for the $7/2^-$, $11/2^-$, and $15/2^-$ states, whereas for the $9/2^-$ and $13/2^-$ states the calculated configuration involves the pure single-particle excitation to the $f_{7/2}$ shell. This is consistent with the observed MED values for the mirror pair ^{31}S-^{31}P.

It is important to note that the terms considered so far do not exhaust the INC effects on the MEDs. As pointed out by Zuker *et al.* [4], effects resulting from changes in radii with increasing spin, which are of monopole Coulomb origin, and from the multipole *nuclear* INC interaction could contribute to the MEDs, as shown for the mirror nuclei studied in the $f_{7/2}$ shell. The radial effect, proportional to the average of proton *plus* neutron occupation numbers, needs very good wave functions. Preliminary calculations indicate, however, that this term does not give important contributions in the cases studied here. Moreover, the nuclear INC term, derived in the *fp* shell from the data of the mirror nuclei with $A = 42$, has to be obtained empirically for this mass region. These calculations will have to await better shell-model descriptions of the spectroscopy of these nuclei.

So far we have discussed the MEDs for negative-parity states. Regarding positive-parity states, the MED values for the two excited states measured in ^{35}Ar ($5/2^+$ and $7/2^+$) are quite small and the calculated values reproduce them well. While only the *sd* shell is involved for these states, at higher spins the excitation of two nucleons to the *fp* shell becomes necessary. In particular, shell-model calculations predict the excitation of one proton *and* one neutron for the yrast $13/2^+$ and $17/2^+$ states, implying that, owing to cancellations of single-particle effects, these states are expected to lie at similar excitation energies in both mirror nuclei. These shell-model predictions strengthen, therefore, our suggestion according to which the nonobservation of the $13/2^+$ and $17/2^+$ states in ^{35}Ar, in the present experiment, is most probably due to the differences in the $E1$ strength of analog transitions rather than to shifts in excitation energy of positive-parity analog states.

IV. CONCLUSIONS

The level schemes of the $A = 35$ mirror nuclei have been extended to high-spin states. Two interesting main features arise from the comparison of the two nuclei. One is related to the different decay pattern and could be associated with isospin mixing of the involved states. The other involves the observation of large energy differences between analog states with a dominant pure single-particle excitation to the $f_{7/2}$ shell. For the first time, large-scale shell-model calculations show that, in contrast to what has been observed in nuclei of the $f_{7/2}$ shell, the multipole Coulomb term gives large contributions and reproduces the trend of the experimental MED curves. Important contributions also arise from the electromagnetic spin-orbit interaction $E_{\rm EMSO}$. Although the effective interactions in this mass region are not completely reliable, and the valence space has to be truncated to cope with the present computational capabilities, the wave functions predicted by shell-model calculations are consistent with the MED data, which demonstrate their use as a powerful tool to provide direct information about the configuration of the states.

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