Coherent Contributions to Isospin Mixing in the Mirror Pair ^{67}As and ^{67}Se

R. Orlandi,[1,*] G. de Angelis,[1] P. G. Bizzeti,[2] S. Lunardi,[3] A. Gadea,[1,†] A. M. Bizzeti-Sona,[2] A. Bracco,[4] F. Brandolini,[3] M. P. Carpenter,[5] C. J. Chiara,[6,∥] F. Della Vedova,[1] E. Farnea,[3] J. P. Greene,[5] S. M. Lenzi,[3] S. Leoni,[4] C. J. Lister,[5] N. Mărginean,[3,‡] D. Mengoni,[3] D. R. Napoli,[1] B. S. Nara Singh,[7] O. L. Pechenaya,[6,§] F. Recchia,[1] W. Reviol,[6] E. Sahin,[1] D. G. Sarantites,[6] D. Seweryniak,[5] D. Tonev,[8] C. A. Ur,[3] J. J. Valiente-Dobón,[1] R. Wadsworth,[7] K. T. Wiedemann,[9] and S. Zhu[5]

[1]*Laboratori Nazionali di Legnaro dell'INFN, Legnaro (Padova), I-35020, Italy*
[2]*Dipartimento di Fisica, Università di Firenze and INFN Sezione di Firenze, Sesto Fiorentino (Firenze), I-50019, Italy*
[3]*INFN Sezione di Padova and Dipartimento di Fisica, Università di Padova, Padova, I-35131, Italy*
[4]*INFN Sezione di Milano and Dipartimento di Fisica, Università di Milano, Milano, I-20133, Italy*
[5]*Physics Division, Argonne National Laboratory, Argonne, Illinois, 60439, USA*
[6]*Washington University, St. Louis, Missouri, 63130, USA*
[7]*University of York, York, YO10 5DD, United Kingdom*
[8]*Institute for Nuclear Research and Nuclear Energy, BAS, Sofia, 1784, Bulgaria*
[9]*Universidade de São Paulo, São Paulo, P.O. Box 66318, Brazil*

(Received 2 March 2009; published 28 July 2009)

Isospin symmetry breaking has been investigated in mass $A = 67$ mirror nuclei through the experimental determination of the $E1$ strengths of analog electromagnetic transitions. Lifetimes of excited states have been measured in ^{67}Se and ^{67}As with the centroid shift method. Through the comparison of the $B(E1)$ strengths of the mirror $9/2^+ \rightarrow 7/2^-$ transitions, the isovector and the isoscalar components of the electromagnetic transition amplitude were extracted. The presence of a large isoscalar component provides evidence for coherent contributions to isospin mixing, probably involving the isovector giant monopole resonance.

DOI: 10.1103/PhysRevLett.103.052501 PACS numbers: 21.10.Hw, 23.20.Js, 23.20.Lv, 27.50.+e

The choice of appropriate symmetries in the study of a physical system normally opens the gates to a more insightful understanding, and very often coincides with a considerable simplification of its mathematical description. The exchange symmetry between neutrons and protons in nuclei, expressed in the formulation of the isospin quantum number, is one such example. Isospin formalism, which describes the neutron and the proton as two states of the same particle, the nucleon, finds its place amongst the essential descriptive tools of a vast range of nuclear phenomena [1]. In this formalism, nucleons are discriminated by the projection $T_z = \pm 1/2$ of their isospin vector $\boldsymbol{T}$. Similarly, quantum-mechanical operators are conveniently recast in their isoscalar, isovector, and isotensor components. The broad success of the isospin symmetry concept belies its broken nature. Not only is the symmetry broken by the proton-neutron mass difference and the Coulomb interaction, but also in the nucleon-nucleon interaction itself at the level of $\approx 0.5\%$ [1]. This symmetry breaking, which is well known from nucleon scattering data, results ultimately from the difference between the up and down quarks [2]. The investigation of isospin-symmetry conservation and breaking effects has revealed a wealth of nuclear structure information [3].

A sensitive test of isospin symmetry breaking is obtained by comparing $E1$ transition rates of analogue electromagnetic decays in mirror nuclei ($T_z = \pm 1/2$). In the long-wavelength limit ($kR \ll 1$) the $E1$ operator has a pure isovector character. Consequently, if isospin is conserved, corresponding $E1$ transitions in mirror nuclei should exhibit the same strength. Similarly, in $N = Z$ nuclei ($T_z = 0$) $E1$ transitions between states of equal isospin are forbidden. Investigations of the latter selection rule have been performed via studies of the isospin mixing of the excited 5^- state in the nucleus ^{64}Ge [4].

In pairs of mirror nuclei, asymmetric $E1$ transition strengths could result either from the small isoscalar components of the $E1$ operator, which only vanish in the long-wavelength limit, or from an asymmetry in the analogue nuclear states, induced by isospin-non-conserving interactions. The latter can be expressed as an "induced isoscalar $E1$ operator", acting on unperturbed isospin-symmetric states. A nonzero isoscalar term would in fact give rise to an interference pattern in the transition rates summing up either coherently or destructively with the isovector term [5]. Such a term causes the strong asymmetries in the branching ratios of mirror $E1$ transitions recently observed in the $A = 31$, 35, and $A = 51$ mirror pairs [6–8]. In this Letter we report an experimental investigation of the absolute value of the electromagnetic matrix elements of two $E1$ transitions in the isospin doublet ^{67}Se-^{67}As, currently the only such measurement for mirror nuclei with valence nucleons in the fpg shell. The two matrix elements were used to discriminate between the isoscalar and isovector components of the $E1$ mirror transitions and to examine a likely origin of this asymmetry.

The nuclei of interest were produced in the fusion-evaporation reactions ^{40}Ca(^{32}S, αp)^{67}As and ^{40}Ca(^{32}S, αn)^{67}Se. The 90-MeV ^{32}S beam, pulsed with a period of 82.5 ns, was provided by the ATLAS accelerator at Argonne National Laboratory. The target was made of 550 μg cm^{-2} of ^{40}Ca evaporated onto a Au backing of 10 mg cm^{-2}, and covered by a 30 μg cm^{-2} Au front layer to prevent it from oxidizing. The emitted γ rays were detected by the Gammasphere array [9], which at the time of the experiment consisted of 77 HPGe detectors. The high selectivity required for the identification of the different reaction channels was obtained with the employment of the 95-element 4π CsI(Tl) Microball [10] and the 30-element liquid-scintillator neutron shell [11] for detection of evaporated charged particles (particularly protons and α particles) and neutrons, respectively. The neutron shell occupied the five forward rings of Gammasphere. A mixed trigger was applied: either a minimum of 3 coincident γ rays or a liquid-scintillator event plus 2 coincident γ rays. Data were sorted into two- and three-dimensional matrices under the conditions of detecting either 1 α particle and 1 proton (^{67}As), or 1 α particle and 1 neutron (^{67}Se). Without the five forward Gammasphere rings, the measured intensity of a given γ-ray line is affected by the γ-ray angular distribution. To correct for this bias, the different ring contributions were combined with different weights, chosen to cancel the effect of the angular-distribution terms of rank 2 and 4. An additional requirement of minimizing the statistical error was imposed to determine the ensemble of weights.

The partial level schemes of ^{67}As and ^{67}Se, determined in this work, are presented in Fig. 1. These findings overall confirm the level scheme of ^{67}As published by Jenkins *et al.* [12], but the previously reported 1602-keV line was not observed; a 1518-keV line connecting the $15/2^+$ and $13/2^+$ states was seen instead. Eight new γ-ray transitions have been added to the previously known level scheme of ^{67}Se [13]. The measured branching ratios of the 717-, 303-, and 1364-keV γ-ray lines, which deexcite the $9/2^+$ state are shown in the third column of Table I.

The lifetimes of the $9/2^+$ states were determined by measuring the centroid shifts of the relative-time spectra for coincident Ge detectors [14]. Time spectra were obtained by setting energy gates on the first two axes of a $E(\gamma_1)E(\gamma_2)\Delta T$ cube, where $\Delta T = T(\gamma_2) - T(\gamma_1)$. By gating on transitions above and below the $9/2^+$ isomeric state, the centroid of the time distribution undergoes a shift with respect to the prompt position, equivalent to the lifetime of the state; by reversing the ordering of the γ-ray gates, the time distribution shifts by the same amount in the opposite direction. In the absence of other effects, the difference between these centroid positions, properly calibrated, corresponds to twice the lifetime of the isomeric state [15]. The dependence of the centroid shift on the signal amplitude, which becomes important at lower energies, was determined from the study of prompt γ-ray transitions, and taken into account in the analysis. The applicability

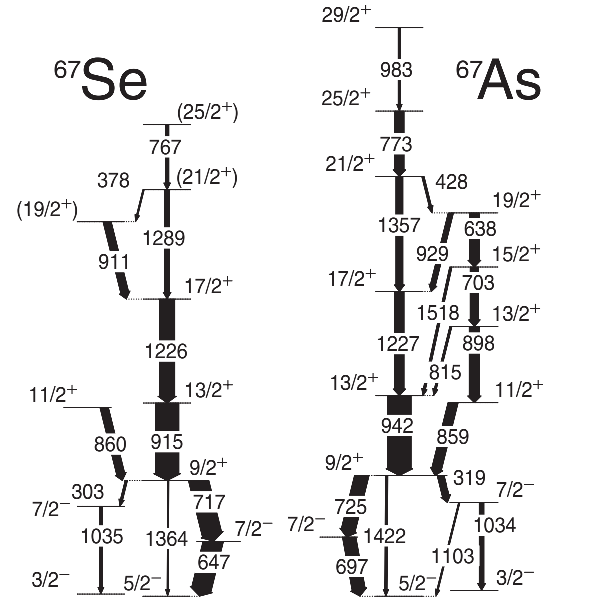

FIG. 1. Proposed partial level schemes for (left) ^{67}Se [16] and (right) ^{67}As determined from the present data. The energy labels are given in keV and the widths of the arrows are proportional to the relative intensities of the γ rays. Spin and parity assignments in ^{67}Se are based on symmetry considerations and on the measured ADO ratios (see text).

of this technique to the present case was tested against the known lifetime of the $9/2^+$ state in ^{69}As, which in this work was measured to be 2.1(2) ns, in excellent agreement with the published value of 1.94(5) ns [17]. This result supports the validity of the method in the time range of interest.

The time spectra obtained using gates both above and below the $9/2^+$ states in ^{67}As and ^{67}Se, and with the same gates but in reversed order, were compared with those of prompt pairs, chosen to be either both above or below the state of interest. A representative set of measured centroid shifts is reported in Fig. 2. Combining the results, the determined $9/2^+$-state lifetimes in ^{67}As and ^{67}Se are, respectively, $\tau = 0.7(2)$ ns and $\tau = 1.5(6)$ ns. No trace was found of the reported 12(2)-ns isomer in ^{67}As [12], nor of a similarly long-lived isomer in ^{67}Se.

To extract the $B(E1)$ strengths, the multipole character of the transitions had to be determined. The mixing ratio of the lines of interest was determined from the ratios of angular distributions from oriented states, also known as ADO ratios. The ADO ratio for the transition γ_1 in coincidence with a feeding transition γ_2 is defined as

$$R_{\mathrm{ADO}} = \frac{I_{\gamma_1}(\text{at } \theta_1 \text{ weighted coinc. with } \gamma_2)}{I_{\gamma_1}(\text{at } \theta_2 \text{ weighted coinc. with } \gamma_2)}.$$

Ratios were normalized to those corresponding to pure quadrupole transitions. The aforesaid weights were used to cancel the effects induced by the anisotropy of Gammasphere. The available data enabled the measurement of ADO ratios in different pairs of rings, 90° vs 162.7°,

TABLE I. Measured ADO ratios, branching ratios, mixing ratios, $E1$ and $M2$ strengths for transitions deexciting the $9/2^+$ states in ^{67}As and ^{67}Se.

Nucleus	E_γ (keV)	Branching ratio	R_{ADO} 162.7°:90°	δ	$B(E1)$ (e^2 fm^2)	$B(M2)$ μ_N^2 fm^2
^{67}As	725	0.59(2)	0.28(4)	$-0.16^{+0.08}_{-0.13}$	$1.4^{+0.4}_{-0.4} \times 10^{-6}$	8^{+16}_{-6}
^{67}Se	717	0.77(16)	1.7(6)	$0.47 < \delta < 3.49$	$0.4^{+0.4}_{-0.4} \times 10^{-6}$	120^{+90}_{-100}
^{67}As	319	0.30(1)	0.50(11)	$0.05^{+0.10}_{-0.14}$	$8.3^{+2.4}_{-2.5} \times 10^{-6}$	30^{+210}_{-30}
^{67}Se	303	0.09(5)	not available	not available	$<1.4(9) \times 10^{-6}$	$<1.7(12) \times 10^3$
^{67}As	1422	0.12(2)	1.14(58)	$\cdots$	$\cdots$	2.2(7)
^{67}Se	1364	0.14(8)	not available	$\cdots$	$\cdots$	1.5(10)

145.5° (obtained by adding detectors at 142.6° and 148.3°), and 129.9°. After normalization, pure quadrupole transitions should yield a ratio of 1 in all rings, while for a pure dipole transition, ratios of 0.43, 0.5, and 0.64 should be obtained at 162.7°, 145.5°, and 129.9°, respectively. The mixing ratios δ were determined from the intersection of the theoretical $E1 + M2$ normalized ADO ratios, plotted vs arctan(δ), with the experimental results. The method is illustrated in Fig. 3(a) for the 725- and 717-keV transitions, where the experimental result and their uncertainties correspond to the regions confined by the horizontal lines. In ^{67}As, the 725- and 319-keV transitions give double-valued solutions in each ring. However, comparing different rings, only the solutions corresponding to small and negative arctan(δ) were found to be consistent (stable solutions), and chosen. The R_{ADO} measured for the transitions in ^{67}Se suffer from larger uncertainties because of the lower yield, as revealed by the spectra of Fig. 3(b). The R_{ADO} for the 717-keV transition implies a large positive δ. For 303-keV line the ratio is consistent with the entire negative range of arctan(δ) or arctan(δ) small and positive. Hence for this transition the reduced strengths can only be assigned an upper limit. $B(\sigma\lambda)$ transition strengths were determined for all the transitions deexciting the isomeric $9/2^+$ state, i.e., the 725-, 319- and 1422-keV lines in ^{67}As and the 717-, 303- and 1364-keV lines in ^{67}Se. Table I shows the measured branching ratios, ADO ratios, mixing ratios δ, and the corresponding $B(E1)$ and/or $B(M2)$ values determined in this work.

For both pairs of $E1$ transitions (725/717 and 319/303 keV), the $B(E1)$ strengths consistently differ in the two mirror nuclei. Since the transition matrix element can be expressed as the sum of an isovector and an (induced) isoscalar term, $B(E1) = \langle J_i; T_i T_3 || \mathcal{M}_{\mathrm{IV}} + \mathcal{M}_{\mathrm{IS}} || J_f; T_f T_3 \rangle^2/(2J_i + 1)$, from the experimental $B(E1)$ values one can deduce, for the 725/717 mirror transitions, $|\langle J_i || \mathcal{M}_{IV} || J_f \rangle| = 2.9(6) \times 10^{-3} e$ fm and

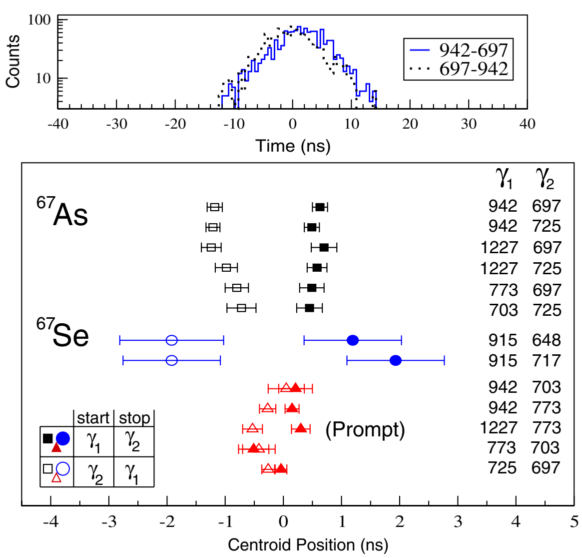

FIG. 2 (color online). Top: relative-time distributions for the 942- and 697 keV γ-ray pair. Bottom: Centroids of the relative-time distributions for different pairs of γ transitions (shown on the right), in direct or reverse order. Delayed coincidences, across the $9/2^+$ isomeric states, are shown in the upper part of the figure, prompt coincidences in the lower part. The systematic effect related to the transition energy (apparent in the 1227–773 keV pair) has been accounted for in the analysis.

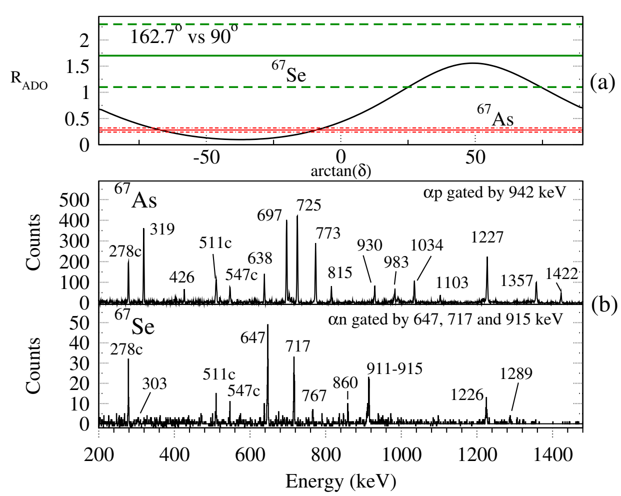

FIG. 3 (color online). (a) Calculated ADO ratios as a function of mixing ratio (solid black line) for $E1(+M2)9/2^+ \rightarrow 7/2^-$ transitions. The horizontal solid lines represent the experimental results for the 725-keV transition in ^{67}As (lower) and for the 717-keV transition in ^{67}Se (upper) with their uncertainty limits (dashed lines). See text for further details. (b) Gated γ-ray spectra for the αp and αn channels. Contaminant peaks, either from Coulomb excitation of the Au backing or β decay, are labeled by a "c".

$|\langle J_i||\mathcal{M}_{\rm IS}||J_f\rangle| = 0.9(6)\times 10^{-3}e$ fm (where the isoscalar term was assumed to be the smaller). For the 319/303 mirror transitions, the values are confined by the following limits: $4.5(7)\times 10^{-3}e\ \text{fm} < |\langle J_i||\mathcal{M}_{\rm IV}||J_f\rangle| < 6.4(9)\times 10^{-3}e$ fm and $2.7(9)\times 10^{-3}e\ \text{fm} < |\langle J_i||\mathcal{M}_{\rm IS}||J_f\rangle| < 4.5(7)\times 10^{-3}e$ fm. These two results, compatible with each other in the relative sizes of the isovector and isoscalar parts, indicate a large isoscalar contribution, with a $|\langle J_i||\mathcal{M}_{\rm IS}||J_f\rangle|/|\langle J_i||\mathcal{M}_{\rm IV}||J_f\rangle|$ ratio of 0.30–0.40. It is also important to note that in both cases the $B(E1)$ strength is larger in ^{67}As than in ^{67}Se.

The above defined "isoscalar" term can have different origins, either related to higher-order terms in the evaluation of the transition operator, or to the level mixing induced by the isovector part of the Coulomb interaction [5]. The nature of this term will be extensively discussed in a forthcoming paper [18]. Here we report the main results. An estimate of the higher-order terms in the transition operator shows that, in the present case, their contribution is very small (of the order of 10^{-4} in comparison to the main isovector term). One can consider therefore (to first order) the level mixing induced by the isovector part of the Coulomb interaction, which has an opposite sign in the two mirror nuclei: the mixing between the close-lying $7/2^-$ levels, fed by the two $E1$ transitions, is estimated to be too weak and would give opposite asymmetries for the two doublets, in disagreement with the experimental results. Contributions from the mixing with higher-lying levels [6] are, individually, even smaller. Their combined effect, however, can be large if each one of the mixing matrix elements is to some extent coherent in phase with the $E1$ amplitude involving the same level [19]. In the isovector Coulomb operator $\sum_i (e/2)\tau_3(i)\sum_{j\neq i}[e/(2r_{ij})]$ we can approximate the second sum with the Coulomb potential inside a uniformly charged sphere of radius R [20], to obtain $[(A-1)e^2/(4R^3)][3R^2T_3 - \sum_i r_i^2\tau_3(i)/2]$. Here, the first term is diagonal and does not contribute to the mixing, while the second is proportional to the isovector monopole operator. It can be assumed, therefore, that most of the contribution to the mixing is due to an isovector giant monopole resonance (IVGMR) built over the considered state. The IVGMR is thought to lie ≈ 20 MeV above each level. Summing together all products of the mixing coefficients with the corresponding $E1$ amplitudes, and using the closure approximation, one obtains the induced isoscalar operator

$$\mathcal{M}_{\rm IS} \approx \frac{(A-1)e^2}{4R\Delta E_0}\Bigg[\sum_i \frac{r_i^3}{R^2}\frac{e}{2}Y^{(1)}(\hat{r}_i) + \sum_i \frac{e}{2} r_i Y^{(1)}(\hat{r}_i)\tau_3(i)\sum_{j\neq i}\frac{r_j^2}{R^2}\tau_3(j)\Bigg].$$

The matrix element of the one-body term between "unperturbed" states can be easily evaluated. The two-body terms are known to contribute with the opposite sign to the one body, producing a substantial quenching in the $N = Z$ case [20]. However, in mirror doublets the quenching effect is expected to be much smaller, particularly for wave functions involving an active particle coupled to a $T = 0$ core state. The resulting induced isoscalar term can be as large as 1/4 of the isovector one, accounting for the asymmetry observed in the experiment.

In summary, the measurement of the $E1$ transition strengths in the $A = 67$ mirror nuclei ^{67}Se-^{67}As has revealed an unusually large fraction of isoscalar $E1$ component. Such a finding provides evidence for a coherent effect of the IVGMR.

This work was partly supported by the U. S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357 and Grant No. DE-FG02-88ER-40406. We thank the accelerator crew of ANL for excellent support.

*Present address: The University of the West of Scotland, Paisley, PA1 2BE, Scotland, United Kingdom. Riccardo.Orlandi@uws.ac.uk

†Present address: IFIC (CSIC), Valencia, Spain.

‡Present address: NIPNE, Bucharest, Romania.

§Present address: Department of Radiation Oncology, Washington University, St. Louis, USA.

‖Present address: Nuclear Engineering Division, Argonne National Laboratory, Argonne, IL, 60439, USA.

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