

## Hindered Gamow-Teller Decay to the Odd-Odd $N = Z$ $^{62}\text{Ga}$ : Absence of Proton-Neutron $T = 0$ Condensate in $A = 62$

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(Received 20 November 2013; published 28 August 2014)

Search for a new kind of superfluidity built on collective proton-neutron pairs with aligned spin is performed studying the Gamow-Teller decay of the  $T = 1, J^\pi = 0^+$  ground state of  $^{62}\text{Ge}$  into excited states of the odd-odd  $N = Z$  nucleus  $^{62}\text{Ga}$ . The experiment is performed at GSI Helmholtzzentrum für Shwerionenforschung with the  $^{62}\text{Ge}$  ions selected by the fragment separator and implanted in a stack of Si-strip detectors, surrounded by the RISING Ge array. A half-life of  $T_{1/2} = 82.9(14)$  ms is measured for the  $^{62}\text{Ge}$  ground state. Six excited states of  $^{62}\text{Ga}$ , populated below 2.5 MeV through Gamow-Teller transitions, are identified. Individual Gamow-Teller transition strengths agree well with theoretical predictions of the interacting shell model and the quasiparticle random phase approximation. The absence of any sizable low-lying Gamow-Teller strength in the reported beta-decay experiment supports the hypothesis of a negligible role of coherent  $T = 0$  proton-neutron correlations in  $^{62}\text{Ga}$ .

DOI: 10.1103/PhysRevLett.113.092501

PACS numbers: 21.60.Cs, 23.20.Lv, 23.40.—s

The study of short range interactions between fermions is a subject of research in several fields of physics science. The pairing effects of two fermions arising from these interactions have been well known for decades in the field of solid-state physics where two electrons with opposite spin projections build a Cooper pair. Similar pairing of alike fermions in time-reversed orbits gives rise to nuclear superfluidity, which is a well known phenomenon having a significant impact on the microscopic structure as well as on the collective properties of the nucleus. Moreover, the

atomic nucleus consists of a combination of two fermionic fluids, those composed of neutrons and protons, leading to an additional quantum degree of freedom—the isospin  $T$ —and to the occurrence of the SU(4) symmetry. As a consequence four combinations of nucleon pairs can be formed: the isovector triplet with  $T = 1$  (three types of pairs built of fermions with opposite spin projections) and the isoscalar singlet with  $T = 0$  (a pair of different fermions with aligned spin). Isoscalar  $T = 0$  correlations can give rise to a new kind of superfluidity, i.e., the proton-neutron

pairing condensate, which cannot be observed in the field of condensed matter physics, since the isospin quantum number is not applicable. The quest for these new types of superfluidity in many-body nuclear systems is based, however, on collective proton-neutron effects that may lead to approximate SU(4) symmetry. Manifestation of these proton-neutron Cooper pairs of aligned, nonzero total angular momentum is considered most favorable in the vicinity of self-conjugate  $N = Z$  nuclei (see, e.g., Refs. [1,2] and references therein).

In medium mass  $N = Z$  nuclei, the existence of  $T = 0$  pairing has been searched for by studying the absence of Coriolis antipairing effects at high angular momentum in rotational bands [1–3]. The structure of heavier  $N = Z$  nuclei such as  $^{92}\text{Pd}$  may also be affected by proton-neutron isoscalar pairing correlations [4,5]. Nevertheless, no clear-cut signature of this pairing mode has been identified to date.

Another expected fingerprint for isoscalar  $T = 0$  pairing should be the enhanced Gamow-Teller (GT)  $\beta$ -decay rates between the  $I^\pi = 0^+$  ground state of an even-even  $N = Z - 2$  ( $T_z = -1$ ) nucleus and the lowest  $I^\pi = 1^+$  state of its odd-odd  $N = Z$  ( $T_z = 0$ ) daughter. This could be interpreted as a trace of the generalized Wigner’s supermultiplets, that is, in the limit of an exact SU(4) symmetry, the GT strength would be concentrated in a single transition to the lowest  $T = 0$ ,  $I^\pi = 1^+$  state. While in light nuclei strong GT transitions to low-lying states result from the presence of an approximate SU(4) symmetry, this symmetry is suppressed in heavier nuclei due to strong spin-orbit splitting. The GT strength is then fragmented over many final states resulting in reduced  $B(\text{GT})$  values for the low-lying states [6–8]. However, with increasing nuclear mass, the phenomenon of proton-neutron collectivity is expected to arise. The role of proton-neutron coherent pairs (bosons) in  $\beta$  decay has been discussed by Iachello, Halse, and Barrett [9–11] in the framework of the proton-neutron interacting boson model (IBM-4). In fact, collective proton-neutron pairs represent a generalization of Wigner’s SU(4) symmetry for heavy nuclei. Thus, restoring the SU(4) symmetry one expects a large GT strength—with  $\log ft$  values less than 4 [9,11]—to the corresponding  $T = 0$ ,  $I^\pi = 1^+$  collective mode. These collective modes are expected to lie at low energy in odd-odd  $N = Z$  nuclei. Very recently the GT strength distribution in several  $f$ -shell odd-odd  $N = Z$  nuclei has been measured with high resolution ( $^3\text{He}$ ,  $t$ ) charge-exchange reactions [12]. In this reference sizable low-lying GT strength has been found in  $^{42}\text{Sc}$ , whereas in heavier nuclei with  $A = 46, 50, 54$  low-lying GT strength is still sizeable, indicating a partial persistence of the SU(4) symmetry, despite the fact that most of the GT strength in these nuclei is fragmented and lying at higher energy. Our work on the beta decay in  $A = 62$  extends this information to heavier systems where the effects of  $T = 0$  pairing are expected to increase and where the instability of the target  $^{62}\text{Zn}$  makes those charge-exchange reactions unfeasible. It is relevant to mention that Bertsch and Luo [13] have

suggested that well developed  $T = 0$  collectivity is predicted only beyond the mass region  $A = 130$ – $140$ . Nevertheless, more recent publications (see Refs. [14,15]) provide a deeper investigation of the effects of the low- $\ell$  orbitals, present in the  $pf$  shell at the Fermi energy, and the  $T = 0$  pairing strength.

In this Letter, a retarded GT strength for the  $\beta$  decay of  $^{62}\text{Ge}$  to  $^{62}\text{Ga}$  is reported. This is the heaviest odd-odd  $N = Z$  nucleus investigated via GT decays to date. The measured GT strengths indicate a negligible restoration of the SU(4) symmetry and thus a negligible role of coherent  $T = 0$  proton-neutron correlations in the description of  $N = Z$  nuclei up to mass  $A = 62$ .

The  $\beta$ -decay measurement of  $^{62}\text{Ge}$  was performed at GSI using the fragment separator (FRS) and the stopped RISING setup [16–18]. The heavy-ion synchrotron SIS provided a  $^{78}\text{Kr}$  beam with an energy of 750 A MeV and  $\sim 4 \times 10^9$  ions per spill with a repetition time of 9 s. At the entrance of the FRS, the beam impinged on a 4.0 g/cm<sup>2</sup> thick  $^9\text{Be}$  production target. The fully stripped  $^{62}\text{Ge}$  ions produced by fragmentation reactions were selected by means of the standard  $B\rho - \Delta E - B\rho$  technique [16]. The information provided by various scintillation time-of-flight and ionization detectors together with position tracking for each individual ion was used to perform  $A$  and  $Z$  identification. The RISING array, with an efficiency of about 9%, for the  $^{60}\text{Co}$  source 1.3 MeV transition, consisted of 15 cluster composite detectors [19] in the stopped beam configuration [20] coupled with the active implantation setup [21] in the center of the array. The active implantation setup [21] consisted of six 1 mm thick double-sided silicon strip detectors (DSSSDs), with an individual active area of  $50 \times 50$  mm<sup>2</sup> and 16 strips on each side. Three DSSSDs were aligned in a row along the beam direction to guarantee the implantation of the products of interest. The remaining detectors, positioned at both sides of the central row, were used to monitor the implantation position during the experiment. An energy degrader was inserted between the FRS and the active stopper to adjust the implantation depth of  $^{62}\text{Ge}$  ions into the DSSSD stack. Two triggers were required to investigate the  $\beta$  decay of  $^{62}\text{Ge}$ : (i) the “implantation trigger,” requiring a high-energy signal from the FRS detectors and a signal from the active stopper, and (ii) the “ $\beta$ -decay trigger,” requiring a low-energy signal,  $E \leq 10$  MeV, in the active stopper. For both triggers the complementary information from the RISING Ge array was recorded. All events carried the time information given by the synchronization system distributing a 10 MHz clock to all data acquisition branches.

The lifetime of  $^{62}\text{Ge}$  was determined by utilizing the spectrum of  $\beta$ -decay activity as a function of time. Disentangling the activity of  $^{62}\text{Ge}$  from the activity of the  $^{62}\text{Ga}$  daughter was achieved by constructing a correlation spectrum, where the individual  $^{62}\text{Ge}$  decays were collected on the condition that the  $\beta$  decay of the  $^{62}\text{Ga}$  daughter was detected consecutively. Figure 1 shows the exponential decay of  $^{62}\text{Ge}$ . A half-life  $T_{1/2} = 82.9(14)$  ms

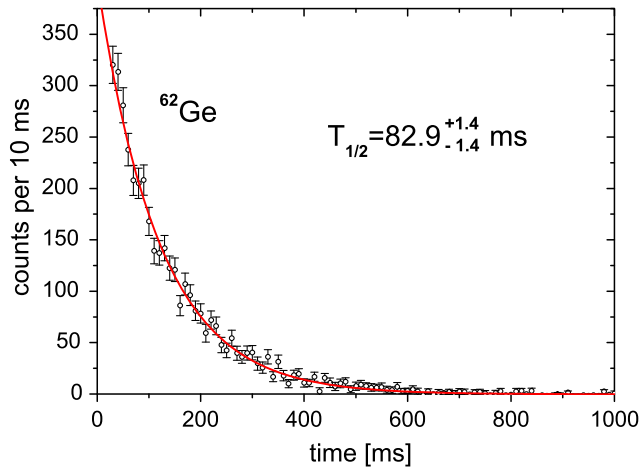


FIG. 1 (color online). Activity spectrum of  $^{62}\text{Ge}$   $\beta$  decay detected in coincidence with the  $\beta$  decay of the  $^{62}\text{Ga}$  daughter nucleus.

has been measured for the ground-state decay of  $^{62}\text{Ge}$ , in fair agreement with previous measurements [22,23].

The evaluation of  $B(\text{GT})$  strengths requires the determination of absolute efficiencies for the complete detection setup as well as the process of implantation. Thus, the active stopper efficiency for  $\beta$ -decay detection,  $\epsilon_{\text{AS}}$ , and the probability that  $^{62}\text{Ge}$  survives the implantation,  $\epsilon_{\text{IS}}$ , were determined. The values of  $\epsilon_{\text{AS}}$  and  $\epsilon_{\text{IS}}$  can be found by comparing the predicted  $\beta$ -decay rates with experimentally obtained ones. For this purpose the measurement of at least two quantities is required: (i) events with only one of the two  $\beta$  electrons registered from the  $^{62}\text{Ge} \rightarrow ^{62}\text{Ga} \rightarrow ^{62}\text{Zn}$  sequence and (ii) events where both  $\beta$  particles from the sequence were registered. Fitting the decay rates obtained experimentally to the corresponding predictions of Bateman's equations [24] leads to  $\epsilon_{\text{AS}} = 0.50^{(5)}_{(3)}$  and  $\epsilon_{\text{IS}} = 0.84^{(6)}_{(10)}$ . Furthermore, the absolute photopeak efficiency of the RISING setup has been determined for  $\gamma$ -ray energies in the range of 0.3 to 2.5 MeV with various calibration sources, placed at several positions of the implantation setup.

The Gamow-Teller decay from  $^{62}\text{Ge}$  populates  $I^\pi = 1^+$  states of  $^{62}\text{Ga}$ , which then deexcite via  $\gamma$ -ray transitions or internal conversion towards its ground state. The experimental branching ratios for GT  $\beta$  decay were determined using a  $\gamma$ -ray spectrum built under the following triple-correlation condition: implantation event,  $\beta$ -decay event in the active stopper, and  $\gamma$ -ray detection in the RISING array. The spectrum corresponding to the  $\gamma$ -ray events, histogrammed when a  $\beta$  decay was simultaneously detected by the active stopper within 600 ms after the implantation, is shown in Fig. 2. A  $\gamma$ -ray spectrum delayed with respect to  $\beta$  decay was also used to exclude random radioactive background events from the  $^{62}\text{Ga}$  spectra. A total of six  $\gamma$  transitions, listed in Table I, were identified and attributed to the deexcitation of  $1^+$  states in  $^{62}\text{Ga}$ . In previous in-beam studies, a  $1^+$  state at 571 keV was reported [25,26]. Regarding the nonyrast states in  $^{62}\text{Ga}$ , reported in Ref. [26],

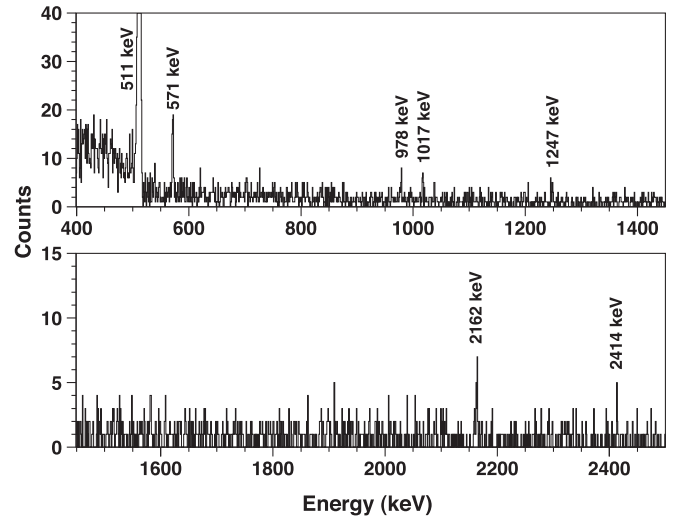


FIG. 2.  $^{62}\text{Ga}$   $\gamma$ -ray spectrum observed in the  $\beta$  decay of  $^{62}\text{Ge}$ . Vertical labels mark the energies of peaks assigned to decays of  $1^+$  states of  $^{62}\text{Ga}$  populated by GT transitions.

a state lying at 1016.7 keV excitation energy was identified and assigned to be  $I = 2$ . This state is found to deexcite to the first  $I^\pi = 1^+$  state via a  $\gamma$  ray of 445.5 keV, in contrast to the 1017.1 keV level identified in the present work, which feeds the ground state. A 978 keV state has also been recently observed in a knockout reaction at relativistic energies [27]. The experimental  $B(\text{GT})$  strengths are listed in Table I with uncertainties calculated by means of the Monte Carlo technique (see Ref. [28]) where propagation and possible correlations of the uncertainties have been taken into account. These experimental  $B(\text{GT})$  values represent an upper limit for the  $B(\text{GT})$  transition probability, due to a possible population of states at high excitation energy deexciting to the measured ones, with transition intensities below the experimental sensitivity. Figure 3 shows the level scheme for  $^{62}\text{Ga}$  following the  $\beta$  decay of  $^{62}\text{Ge}$  built under the assumption that all transitions deexcite to the ground state. Correlation spectra used in the above analysis were constructed with the help of the data analysis code CRACOW [29], where additional procedures were introduced to handle sequential beta decay events.

The measured GT strength distribution has been interpreted in terms of two different theoretical approaches, the interacting shell model (ISM) and the quasiparticle random phase approximation (QRPA). The shell-model calculations have been performed using the code ANTOINE [30] in the  $pf$  valence space, allowing up to five nucleons to be excited from the  $f_{7/2}$  shell to the rest of the  $pf$  orbitals. Up to 180 Lanczos iterations have been computed to achieve the convergence of excited states in the region of interest. The three most reliable effective interactions in this mass region have been considered: KB3G [31], GXPF1A [32], and UPF [33]. A quenching factor  $(g_A/g_V)_{\text{eff}} = 0.74(g_A/g_V)_{\text{free}}$  has been applied to the calculation of the theoretical GT strength following the prescription of Ref. [34]. The strength distributions

TABLE I. Experimental results for the  $\gamma$ -ray transitions observed in the  $^{62}\text{Ge} \rightarrow ^{62}\text{Ga}$  Gamow-Teller decays. The energy of the  $\gamma$ -ray transitions corresponds to the energy of the levels in  $^{62}\text{Ga}$ . The  $B(\text{GT})$  values correspond to upper limits (see text for details).

$E_\gamma$ (keV)	$I^\pi$	Intensity (%)	Log $ft$	$B(\text{GT})$
571.3(2)	$1^+$	$3.9^{+0.8}_{-0.6}$	$4.75 \pm 0.15$	$0.070^{+0.017}_{-0.017}$
978.0(4)	$(1^+)$	$2.1^{+0.7}_{-0.6}$	$4.91 \pm 0.15$	$0.050^{+0.015}_{-0.017}$
1017.1(4)	$(1^+)$	$2.2^{+0.8}_{-0.6}$	$4.88 \pm 0.15$	$0.054^{+0.013}_{-0.019}$
1247.2(5)	$(1^+)$	$2.1^{+0.9}_{-0.7}$	$4.84 \pm 0.13$	$0.059^{+0.016}_{-0.022}$
2162.4(6)	$(1^+)$	$3.5^{+0.9}_{-1.0}$	$4.36 \pm 0.17$	$0.17^{+0.05}_{-0.05}$
2413.9(6)	$(1^+)$	$1.8^{+0.8}_{-0.7}$	$4.54 \pm 0.17$	$0.12^{+0.03}_{-0.05}$

obtained with the different effective interactions are in good relative agreement. However, the KB3G interaction is the one that reproduces the experimental data best. The left panels of Fig. 4 show the experimental and calculated—with the KB3G interaction—single level  $B(\text{GT})$  and accumulated  $B(\text{GT})$  values. In this calculation a moderate strength is obtained below 1.5 MeV excitation energy, which compares well with the experimental findings. Between 1.5 and 2.5 MeV excitation energy, two states concentrate most of the strength, in good agreement with the data. However, the calculated excitation energies are about 0.5 MeV lower than the experimental ones. These calculations have already been presented in Ref. [8]. The total  $B(\text{GT})$  below 2.5 MeV reproduces well the data as well as the results from the accumulated  $B(\text{GT})$ .

Beyond mean field calculations have been performed in the framework of the deformed QRPA approach. In these calculations the quasiparticle basis is obtained self-consistently from an axially deformed Hartree-Fock mean field generated by a density-dependent Skyrme force with pairing correlations between like nucleons in the BCS

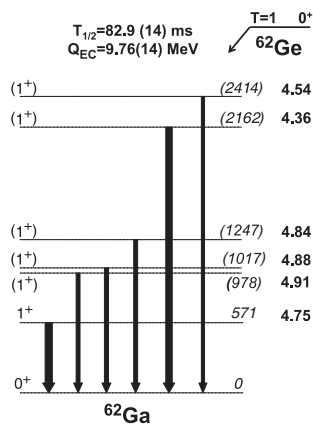


FIG. 3.  $^{62}\text{Ga}$  level scheme observed in the  $^{62}\text{Ge}$   $\beta$  decay built under the assumption that the populated  $(1^+)$  states will deexcite preferentially to the ground state. The excitation energies of the levels are in keV. The log  $ft$  values are indicated in the right side of the levels in bold characters.

framework. It is worth noticing that no explicit proton-neutron pairing is included in this formalism. In this scheme the equilibrium deformation of the ground state is obtained self-consistently as the nuclear shape that minimizes the energy. Calculations of the GT strength distributions are performed afterwards for this deformed shape. The SLy4 force has been chosen as a representative of modern Skyrme parametrizations [35], but results obtained with other Skyrme forces are very similar. To describe the GT transitions, a residual spin-isospin force is introduced consistently with the Skyrme force. Details of the formalism can be found in Refs. [36,37]. The theoretical results shown in the right panels of Fig. 4 have been scaled by the same standard quenching factor mentioned before. Also in this case the calculation agrees well with experiment. The strength is mainly concentrated in three energy regions located at excitation energies of the daughter nucleus around 0.7, 1.2, and 2.4 MeV. The total strength found in the measured energy range is well reproduced by the calculation. It should also be mentioned that the results obtained for the oblate solution are not in agreement with the data, since in that case the GT strength is concentrated at an excitation energy around 1.2 MeV. In contrast to the QRPA approach the shell-model calculations include all correlations (within the truncated approximation) and in particular the proton-neutron pairing ones; however, these correlations do not imply any proton-neutron pairing condensate.

Juillet and collaborators [38] have calculated the energy spectrum of  $^{62}\text{Ga}$  in the framework of the IBM-4. The calculation foresees the two  $I^\pi = 1^+$  states, belonging to the same SU(4) supermultiplet, within 1 MeV excitation energy. In pure SU(4) symmetry only one state will be populated in the GT decay and in the case of a partial conservation of the SU(4) symmetry [pseudo-SU(4)], the

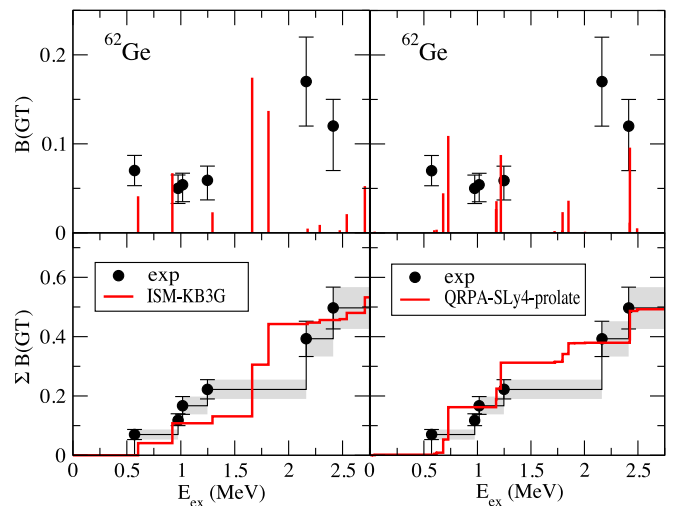


FIG. 4 (color online). Experimental (black) and calculated (red) single level  $B(\text{GT})$  and accumulated  $B(\text{GT})$  values for the  $^{62}\text{Ge}$  to  $^{62}\text{Ga}$   $\beta$  decay. Left panels use the ISM approach using the KB3G interaction and right panels use the QRPA approach using the SLy4 interaction. Experimental uncertainty corridors are indicated in gray.

orbital mixing will distribute the strength between the lowest two states [39].

In the ideal case of a pure SU(4) supermultiplet for collective bosons, the  $B(\text{GT})$  value of transitions from the even-even  $T = 1 I^\pi = 0^+$  state to the lowest odd-odd  $T = 0 I^\pi = 1^+$  state is expected to be of the order of  $3 g_A^2/4\pi$  [6,10]. The measured GT strength for the decay of the  $N = Z - 2$   $^{62}\text{Ge}$  to the lowest lying  $1^+$  state in  $^{62}\text{Ga}$ , is 0.070 (0.017)  $g_A^2/4\pi$ . This value is in good agreement with the theoretical calculations, both ISM and QRPA, but it is about 40 times smaller than the value predicted by the IBM-4 and about 8 times smaller than the  $B(\text{GT})$  to the lowest  $T = 0 I^\pi = 1^+$  state in the equivalent decay in mass  $A = 58$  [6]. This result confirms that the SU(4) symmetry is strongly broken in  $A = 62$  (even more than in  $A = 58$ ) by the spin-orbit interaction. Therefore the expected phenomenon of the  $T = 0$  proton-neutron collectivity that should lead to formation of the  $T = 0$  boson states and, hence, to the restoration of the Wigner SU(4) symmetry, is ruled out and no significant role of the isoscalar proton-neutron pairing condensate in the odd-odd  $N = Z$  nuclei for this mass region is observed.

In summary, state-of-the-art experimental techniques have allowed us to measure the low-lying GT strength for the very neutron deficient  $^{62}\text{Ge}$ . The quantitative comparison between experimental data and theoretical calculations shows a good agreement. The measured  $B(\text{GT})$  value for the first  $1^+$  state is much smaller than the one expected if the SU(4) symmetry was applicable for this mass region. Therefore, the isoscalar  $T = 0$  pairing condensate is excluded in  $A = 62$ .

This conclusion is in agreement with the findings in Ref. [40], suggesting that, on the basis of mass measurements and systematics, isoscalar ( $T = 0$ ) pairing is relevant for  $N = Z$  nuclei with  $A \gtrsim 80$ . It is also supported by calculations in the frame of the isospin generalized BCS equation and Hartree-Fock-Bogoliubov model [41]. Future radioactive ion beam facilities together with cutting-edge detection techniques will be required to investigate  $N = Z$  nuclei in heavier mass regions, using  $\beta$ -decay studies, contributing to unveil the intricate role of the isoscalar pairing condensate in nuclear structure.

The present work has been supported by the Generalitat Valenciana, Spain, under Grant No. PROMETEO/2010/101 and by MINECO, Spain, under Grants No. AIC-D-2011-0746, No. FPA2011-29854, No. FIS2011-23565, No. FPA2011-24553, and No. SEV-2012-0249. The experimental activity has been partially supported by the EU under the FP6-Integrated Infrastructure Initiative EURONS, Contract No. RII3-CT-2004-506065, FP7-Integrated Infrastructure Initiative ENSAR, Grant No. 262010, and the Science and Technology Facilities Council (UK), the Swedish Science Council, Istanbul University Scientific Research Projects, No. 21658, and OTKA Contract No. K100835. The authors are grateful to Prof. Francesco Iachello for the fruitful discussions leading to the present work.

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