ELSEVIER
SCIENCE DIRECT
PHYSICS LETTERS B
Physics Letters B 551 (2003) 56–62
www.elsevier.com/locate/npe

Isospin mixing in the $N = Z$ nucleus ^{64}Ge

E. Farnea[a,b,*,1], G. de Angelis[a], A. Gadea[a,b], P.G. Bizzeti[c], A. Dewald[d], J. Eberth[d], A. Algora[b,2], M. Axiotis[a], D. Bazzacco[e], A.M. Bizzeti-Sona[c], F. Brandolini[e], G. Colò[f], W. Gelletly[g], M.A. Kaci[b], N. Kintz[h], T. Klug[d], Th. Kröll[a], S.M. Lenzi[e], S. Lunardi[e], N. Mărginean[a], T. Martínez[a], R. Menegazzo[e], D.R. Napoli[a], J. Nyberg[i], P. Pavan[e], Zs. Podolyák[g], C.M. Petrache[j], B. Quintana[e], B. Rubio[b], P. Spolaore[a], Th. Steinhardt[d], J.L. Taín[b], O. Thelen[d], C.A. Ur[e], R. Venturelli[e], M. Weiszflog[i]

[a] *Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, Legnaro, Italy*
[b] *Instituto de Física Corpuscular, Valencia, Spain*
[c] *Dipartimento di Fisica dell'Università and Istituto Nazionale di Fisica Nucleare, Sezione di Firenze, Firenze, Italy*
[d] *Institut für Kernphysik, Universität zu Köln, Köln, Germany*
[e] *Dipartimento di Fisica dell'Università and Istituto Nazionale di Fisica Nucleare, Sezione di Padova, Padova, Italy*
[f] *Dipartimento di Fisica dell'Università and Istituto Nazionale di Fisica Nucleare, Sezione di Milano, Milano, Italy*
[g] *Department of Physics, University of Surrey, Guildford, Surrey, United Kingdom*
[h] *Institut de Recherches Subatomiques, Strasbourg, France*
[i] *Department of Neutron Research, Uppsala University, Uppsala, Sweden*
[j] *Dipartimento di Fisica dell'Università di Camerino and INFN, Sezione di Perugia, Italy*

Received 24 April 2002; accepted 4 July 2002

Editor: V. Metag

Abstract

The $N = Z$ nucleus ^{64}Ge has been investigated in two experiments using the EUROBALL III and EUROBALL IV spectrometers coupled to ancillary devices. Multipole mixing ratios, linear polarization and picosecond lifetimes for various transitions have been measured. The linear polarization results determine unambiguously the multipole character of the $5^- \rightarrow 4^+$ 1665 keV transition, allowing to extract the electric dipole strength and to investigate for the first time the amount of isospin mixing implied by the presence of a forbidden E1 transition.

PACS: 23.20.En; 21.10.Hw

Keywords: Angular distribution; Linear polarization; Lifetimes; Isospin impurity

* Corresponding author
E-mail address: enrico.farnea@pd.infn.it (E. Farnea).
1 Present address: Istituto Nazionale di Fisica Nucleare, Sezione di Padova, Padova, Italy.
2 On leave from Institute of Nuclear Research, Debrecen, Hungary.

0370-2693/02
PII: S0370-2693(02)03022-8

One of the challenges of modern nuclear physics is the exploration of the limits of validity of the isospin symmetry for increasing values of Z and A. Theoretical estimates, limited to the ground state of even–even nuclei [1,2], show that the amount of isospin mixing increases with the nuclear mass A and, for a given A, is maximum for $N = Z$. A good understanding of the mechanism of isospin mixing in nuclei close to the $N = Z$ line is necessary in order to perform reliable corrections in deriving the Fermi constant G_V from the Log ft-values of superallowed Fermi β decays, which needs further experimental and theoretical investigations [3,4]. In particular, it is not clear whether and how these correction terms should vary with increasing A [5–7], and it is, therefore, important to extend the study of isospin violating processes to the heaviest nuclei available, up to the limit of the proton drip line.

A possible way of studying the violation of isospin symmetry induced by the Coulomb interaction is the observation of E1 transitions in even–even $N = Z$ nuclei. In the long-wavelength limit, the matrix elements of the nuclear E1 operator vanish when both the initial and final states have equal isospin T and $T_3 = 0$ [8]. This is typically the case for the low-lying levels in even–even $N = Z$ nuclei, where electric dipole transitions should therefore be forbidden. However, the Coulomb interaction induces an admixture between these low-lying $T = 0$ states and the higher-lying $T = 1$ states of the same configuration having the same spin and parity. Electric dipole transitions are thus allowed between the $T = 0$ ($T = 1$) component of the initial state and the $T = 1$ ($T = 0$) component of the final one. The observed E1 strength is, therefore, a signature of the isospin mixing.

In the $N = Z = 32$ nucleus ^{64}Ge, an intense 1665 keV transition, deexciting the 5^- level to the 4^+ level with an assigned electric dipole character, was already observed by Ennis and co-workers [9]. This was pointed out as an evidence of Coulomb-induced isospin mixing. The same authors suggested that an experimental measurement of the electric dipole strength would be needed to extract the amount of isospin mixing. In that experiment, it was not possible to determine the multipole mixing ratio δ of the 1665 keV transition, which was assigned a stretched electric dipole character with $\delta \approx 0$ on the basis of systematics arguments. Since the measurement of this parameter is of paramount importance in order to firmly extract the electric dipole strength, we have investigated the angular distribution and the linear polarization of the 1665 keV transition deexciting the negative-parity band in ^{64}Ge.

Two experiments have been performed with the goal to study isospin mixing in ^{64}Ge. The first one was performed at the Laboratori Nazionali di Legnaro using the EUROBALL III γ-ray spectrometer coupled to the ISIS Si-ball [10] and to the neutron–wall described in [11]. The ^{64}Ge nuclei were populated via the ^{40}Ca(^{32}S, 2α)^{64}Ge reaction at 125 MeV beam energy, using a 1 mg/cm^2 thick ^{40}Ca target evaporated on a 12 mg/cm^2 thick gold backing. The electronic trigger condition was such that when five germanium signals, without Compton suppression, were in coincidence, the “event” was accepted and subsequently written on tape.

Multipolarities have been assigned to the transitions through comprehensive angular distribution and polarization correlation analyses. The spins of the levels concerned were initially determined through a directional correlation from oriented states (DCO) analysis, which, however, did not allow us to determine the multipole mixing ratio δ for the 1665 keV transition. Thus, we had to extract values for δ and σ/J from an angular distribution analysis. The data were sorted into separate matrices for each ring of detectors (or of individual parts of composite detectors), with the first axis corresponding to the given ring and the second axis corresponding to the whole EUROBALL spectrometer. Some firmly assigned transitions were used as an internal reference to extract the necessary parameters for the analysis of the angular distribution data, which were subsequently fitted simultaneously in the normalization parameter A_0, in δ and in σ/J with the code MINUIT [12]. A polarization correlation from oriented states analysis using the Clover detectors of EUROBALL as Compton polarimeters was performed, as described in [13]. For each intense transition, the asymmetry parameter A, defined as $A = (N_\perp - N_\parallel)/(N_\perp + N_\parallel)$, was determined, where $N_\perp$ and $N_\parallel$ stand for the number of coincidences between two sectors of the Clover in a direction perpendicular and parallel to the beam direction, respectively. The value of the polarimeter sensitivity Q, relating the measured asymmetry to the linear polarization P, was obtained through a Monte Carlo simulation using GEANT III subroutines modified to include the effect of the linear polarization [14,15]. The values of Q thus obtained were found to be in excellent agreement with the values deduced from our experimental data for firmly assigned transitions.

The decay scheme deduced from the EUROBALL data set is shown in Fig. 1. Our analysis confirms most of the results of Ennis and co-workers [9], with the notable exception of the 1665 keV transition. The results of the angular distribution and polarization correlation analyses, shown in Fig. 2, confirm a $5^- \to 4^+$ transition, but with a much larger multipole mixing ratio than the tentative assignment of Ref. [9]. In our analysis of the angular distribution data for the 1665 keV transition, two solutions are found by the fitting subroutines, one corresponding to a large multipole mixing ratio $\delta = -3.9^{+0.7}_{-0.4}$ and the other to a small multipole mixing ratio $\delta = -0.09(3)$. The former solution has a reduced χ^2 value $\chi^2_\nu = 0.54$ and is favoured by statistical arguments over the latter, which has $\chi^2_\nu = 0.80$. No other minima are found in the plot of χ^2 vs. δ. With such a large value of δ for the 1665 keV transition, one would tend to assume a mixed E2/M1 character, in contrast with the systematics of the light even germanium isotopes [16]. Our results from the linear polarization analysis support the systematics argument favouring a parity-changing transition, since the measured asymmetry for the 1665 keV γ-ray, $A = -0.09(5)$, turns out to be in agreement with a parity-changing transition with large negative δ (while it would imply no parity change in the case $\delta \approx 0$). Therefore, our conclusion is that the 1665 keV γ-ray has a mixed E1/M2 character with a large negative multipole mixing ratio, corresponding to a quadrupole content of about 93%.

A careful inspection of the lineshapes of the transitions in spectra from the EUROBALL III experiment allowed us to ascertain that the lifetime of the $I^\pi = 5^-$ level was definitely outside the range of the Doppler shift attenuation method. Thus, it was decided to determine the transition probabilities with the recoil distance Doppler shift technique. A second experiment was therefore performed at the Institut de Recherches Subatomiques, Strasbourg, using the EU-

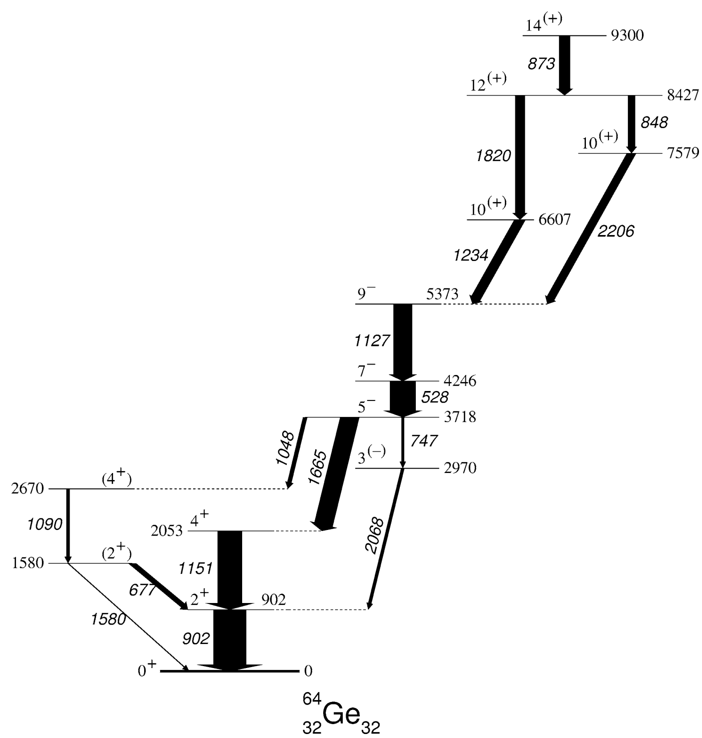

Fig. 1. Decay scheme for the ^{64}Ge nucleus, deduced from the EUROBALL III experiment. The widths of the arrows are proportional to the intensities of the transitions.

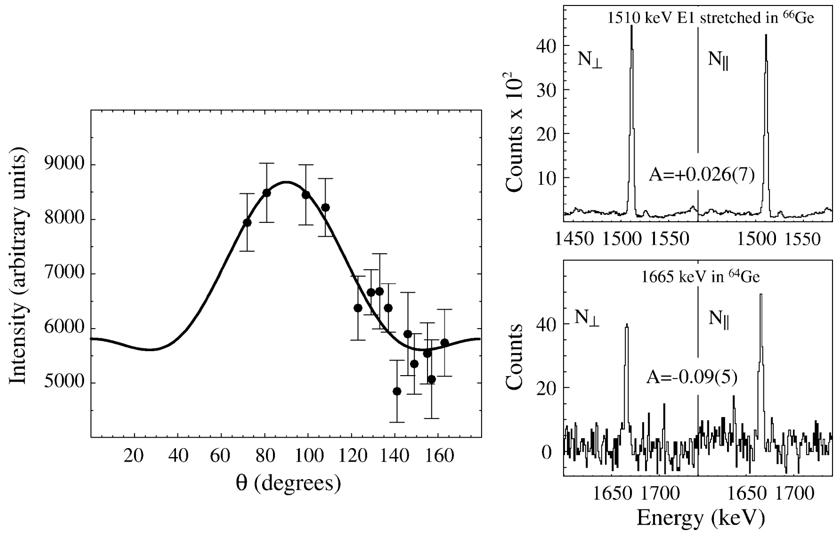

Fig. 2. Left: angular distribution data for the 1665 keV γ-ray in ^{64}Ge. The curve corresponding to the best fit values $\sigma/J = 0.38$, $\delta = -3.9$ is also sketched. Right: polarization correlation data for the 1665 keV γ-ray in ^{64}Ge ($\delta = -3.9^{+0.7}_{-0.4}$) and for the 1510 keV γ-ray in ^{66}Ge ($\delta = -0.023^{+0.005}_{-0.008}$).

ROBALL IV array coupled to the Köln plunger device [17], which is especially designed for coincidence measurements. The plunger was equipped with an automatic feedback system to preserve a constant target to stopper distance, compensating the temperature dependent effects. The same reaction ^{32}S on ^{40}Ca was employed as in the Legnaro experiment, but in this case the beam energy was increased to $E = 137$ MeV, in the attempt to increase the production cross section for ^{64}Ge. The electronic trigger condition required coincidence of four unsuppressed germanium detectors. Data were collected for 8 different target-to-stopper distances, ranging between 2 and 5000 µm.

In this second experiment, we could observe levels up to the $I^{\pi} = 9^-$ at 5373 keV excitation energy. The decay of the 9^- level was found to be quite fast, since its deexciting 1127 keV γ-ray showed no stopped component already at the second smallest target-stopper distance. From our data, one can only deduce an upper limit $\tau_{9^-} \leqslant 4$ ps. In the remaining part of the analysis, we assumed $\tau_{9^-} = 0$. The decay data for the 528 keV transition deexciting the 7^- level and for the 1665 keV transition deexciting the 5^- level are shown in Fig. 3 together with the curves corresponding to the best fit values for the lifetimes of the levels. In the case of the 7^- level, the decay data for the 528 keV transition were fitted with a simple exponential curve. The errors were evaluated with the method outlined in Ref. [18], assuming a 68% confidence level. A possible side feeding with effective lifetime τ_{SF} was considered, which turned out to be negligible ($\tau_{SF} = 0$). The result was $\lambda_{7^-} = 0.0232^{+0.0016}_{-0.0013}$ ps^{-1}, implying $\tau_{7^-} = 43.1^{+2.9}_{-2.5}$ ps. In the case of the 5^- level, the non-zero lifetime of the 7^- level was taken into consideration by fitting simultaneously the decay data for the 528 keV feeding transition and the 1665 keV deexciting γ-ray. The results obtained by leaving τ_{7^-} as a free parameter or fixing it to the value obtained previously were found to be in mutual agreement. Also in this case, the effects of the sidefeeding were found to be negligible. The result was $\lambda_{5^-} = 0.041^{+0.006}_{-0.005}$ ps^{-1}, that is $\tau_{5^-} = 24.2^{+3.5}_{-2.9}$ ps.

Having at disposal the multipole mixing ratio for the 1665 keV γ-ray, the intensities of the transitions deexciting the 5^- level relative to the $2^+ \to 0^+$ transition (for which $I_0 = 1000$ is assumed), namely, $I_{1665} = 567(18)$, $I_{1048} = 130(9)$ and $I_{747} = 89(6)$ and the lifetime of the 5^- level, the transition strengths can be determined. The results for the 1665 keV transition are $B(\mathrm{E1}) = 2.47^{+0.91}_{-0.57} \times 10^{-7}$ W.u., $B(\mathrm{M2}) = 6.06^{+1.59}_{-1.13}$ W.u., where errors have been combined quadratically in the usual way. For comparison, in

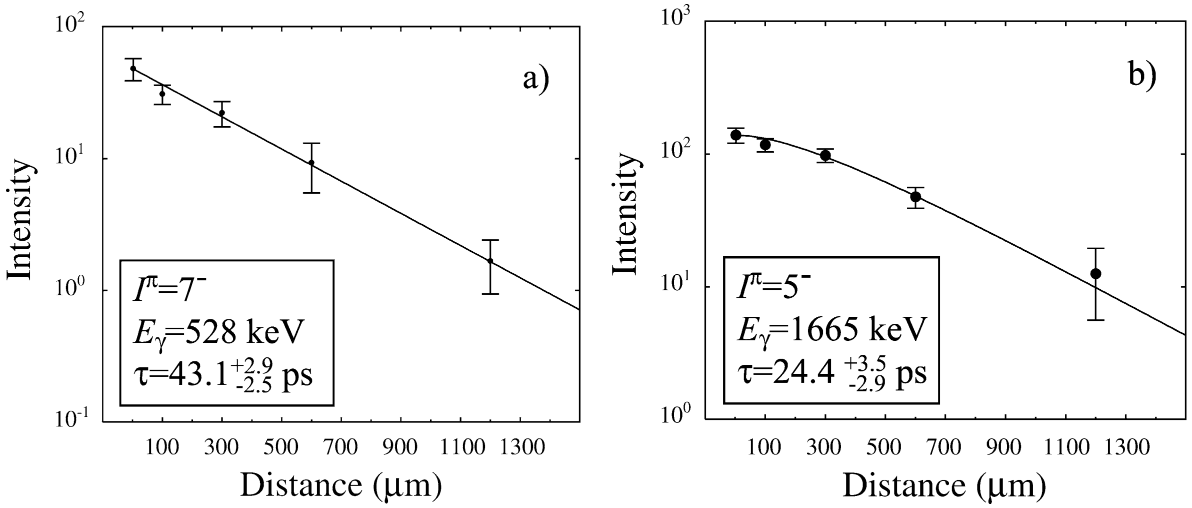

Fig. 3. (a) Decay curve for the 528 keV γ-ray deexciting the 7^- level. A simple exponential decay is assumed. (b) Decay curve for the 1665 keV transition deexciting the 5^- level. The finite lifetime of the 7^- level is considered. See text for details.

the case of ^{66}Ge the deduced strengths for the corresponding $5^- \to 4^+$ transition of 1510 keV are $B(\text{E1}) = 3.7(6) \times 10^{-6}$ W.u. and $B(\text{M2}) = 0.39(7) \times 10^{-2}$ W.u., given the lifetime of the $I^\pi = 5^-$ level $\tau = 32(3)$ ps [16]. Although the lifetimes of the $I^\pi = 5^-$ levels in ^{64}Ge and ^{66}Ge are quite similar, the B(E1) strengths differ by an order of magnitude due to the large difference in the multipole mixing ratios. The resulting B(M2) strength in ^{64}Ge is large compared to the corresponding transition in ^{66}Ge, but is not so far from that of the similar transition in ^{68}Ge, which has $B(\text{M2}) = 0.71(11)$ W.u. [16]. This suggests that in ^{66}Ge there is an accidental cancellation of the isoscalar and the isovector components of the M2 transition amplitude, which does not happen in ^{64}Ge and ^{68}Ge. Note also that other transitions with comparably large B(M2) values are reported in this mass region, as, for instance, in ^{59}Cu [19], ^{63}Cu [20], ^{65}Ga [21].

In order to estimate the amount of isospin mixing α^2 implied by the presence of a forbidden E1 transition between $T = 0$ states, a calculation has been performed with the very schematic model described below. The definition for α^2 is the following [2]:

$$\alpha^2 = \frac{1}{2}\langle N = Z|T_- T_+|N = Z\rangle. \tag{1}$$

As the level schemes in the two isotopes ^{64}Ge and ^{66}Ge [16] are almost identical in the low-energy part, we assume that the corresponding states in the two nuclei have identical wavefunctions, apart from a pair of correlated particles in ^{66}Ge (or holes in ^{64}Ge) coupled to $J = 0$, $T = 1$. Here, it is interesting to notice that the assumption made in the erratum of Ref. [9] of identical B(E2) strength for the weak E2 transitions deexciting the 5^- levels in ^{64}Ge and ^{66}Ge is well supported by our experimental results, being $B(\text{E2}, 747\ \text{keV}) = 1.0(5)$ W.u. in ^{64}Ge and $B(\text{E2}, 886\ \text{keV}) = 0.4(1)$ W.u. in ^{66}Ge [16].

In order to really behave like a "spectator", the additional pair should lie outside the region of valence (sub)shells: otherwise, the antisymmetrization of the wavefunction would imply an expansion with fractional-parentage coefficients. However, neglecting antisymmetrization could be not too bad an approximation if the wavefunctions of the parent state and of the correlated pair are superpositions of a number of different configurations.

We could assume that the levels of ^{66}Ge are obtained by coupling a pair of correlated neutrons to the $T = 0$ states of ^{64}Ge. This could be a reasonable approach, but would lead to the conclusion that the strength of the E1 transition in ^{66}Ge is the same as in ^{64}Ge, in contrast with the experimental results. Alternatively, one can assume that the relevant states of ^{64}Ge are obtained by removing a pair of neutrons (coupled to $J = 0$, $T = 1$) from the corresponding states of ^{66}Ge. However, the state thus obtained would not have good isospin. In order to project onto a pure T subspace, one must include in the wavefunction all the terms corresponding to different parent states of the isospin triplet with $A = 66$:

$$|A = 64,\ J,\ T,\ T_3 = 0\rangle = \big|\big[(A = 66, J, T = 1) \otimes \big(h^2, J = 0, T = 1\big)\big]J,\ T,\ T_3 = 0\big\rangle, \tag{2}$$

where the tensor product is performed in the isospin space, and the resulting isospin T in ^{64}Ge can be equal to 0, 1 or 2.

Now, we take into account the isospin mixing between the $T = 0$ and $T = 1$ states of equal J^π in ^{64}Ge. The wavefunctions of the initial state $|i\rangle$ and of the final state $|f\rangle$ of the E1 transition can be expressed as:

$$|i,\ J\rangle = \beta_i|J,\ T = 0\rangle + \alpha_i|J,\ T = 1\rangle, \tag{3}$$

$$|f,\ J'\rangle = \beta_f|J',\ T = 0\rangle + \alpha_f|J',\ T = 1\rangle \tag{4}$$

with $\beta_x = \sqrt{1 - \alpha_x^2} \approx 1$ if $\alpha_x \ll 1$, to obtain:

$$(i,\ J\|\mathcal{M}^{(1)}(\mathrm{E1})\|f,\ J') = \alpha_i(J,\ T = 1\|\mathcal{M}^{(1)}(\mathrm{E1})\|J',\ T = 0) + \alpha_f(J,\ T = 0\|\mathcal{M}^{(1)}(\mathrm{E1})\|J',\ T = 1). \tag{5}$$

The values of the reduced matrix elements for ^{64}Ge can be related to the corresponding one in ^{66}Ge by standard methods of tensor coupling (in the isospin space). One obtains:

$$(i, J\|\mathcal{M}^{(1)}(\mathrm{E1})\|f, J')_{(^{64}\mathrm{Ge})} = \Delta\alpha \cdot \sqrt{\frac{2}{3}}(i, J\|\mathcal{M}^{(1)}(\mathrm{E1})\|f, J')_{(^{66}\mathrm{Ge})} \tag{6}$$

with $\Delta\alpha = \alpha_i - \alpha_f$. To estimate the *minimum* isospin mixing necessary to account for the experimental results, one considers the situation giving the maximum E1 strength for a given value of $\alpha_i^2 + \alpha_f^2$. This happens for $\alpha_i = -\alpha_f \equiv \alpha$. We obtain, in this case:

$$B\big(\mathrm{E1},\ J \to J',\ ^{64}\mathrm{Ge}\big) = \frac{8}{3}\alpha^2 B\big(\mathrm{E1},\ J \to J',\ ^{66}\mathrm{Ge}\big). \tag{7}$$

However, one should remember that the mixing with other $T = 1$ states could alter the above conclusions. For instance, mixing the initial (final) state with $T = 1$ states having a negligible E1 transition amplitude to the final (initial) state, would increase the isospin impurity of the state without any consequence on the $B(\mathrm{E1})$. On the other side, if several $T = 1$ states contribute to the E1 amplitude through their mixing in the initial or final state, the resulting $B(\mathrm{E1})$ can be substantially larger than the weighted sum of individual $B(\mathrm{E1})$'s if the contributing amplitudes add coherently [22].

Substituting the experimental values into Eq. (7), one would obtain an isospin mixing $\alpha^2 = 2.50\%^{+1.0\%}_{-0.7\%}$. This value is of the same order of magnitude as predicted by various theoretical calculations of isospin mixing in the ground states of even–even nuclei, see, i.e., Colò and co-workers [1] and Dobaczewski and Hamamoto [2]. One should not forget, however, that the model discussed above considers only a two-level mixing and makes ad-hoc assumptions to relate the ^{64}Ge and ^{66}Ge wavefunctions, while the quoted theoretical calculations are based on microscopic wavefunctions and include mixing with a complete set of states.

To the knowledge of the authors, the present work is the first experimental investigation of isospin impurity in medium-mass nuclei through the observation of forbidden E1 transitions. It is interesting to observe that some recent results obtained in β-decay experiments (see, for instance, the study of ^{52}Mn by Schuurmans and co-workers [23]) only imply isospin mixing values approximately two orders of magnitude lower than the theoretical expectations. However, the Fermi transition is even more selective than the E1 γ-decay, probing just the isospin impurity related to the mixing with one particular state (the analog of the daughter state).

In summary, for the first time the strength of the forbidden E1 $5^- \to 4^+$ transition has been determined unambiguously in the $N = Z$ nucleus ^{64}Ge by measuring the multipole mixing ratio and the linear polarization of the transition and the lifetime of the 5^- state. In order to relate the observed E1 strength with the amount of isospin mixing, we have developed a very schematic model, where each one of the relevant states of ^{64}Ge results from the coupling of a $J = 0$ neutron–hole pair to the corresponding state of ^{66}Ge. The result is consistent with mean-field theoretical predictions of isospin mixing for the ground state.

Acknowledgements

This work has been partially supported by the European Union under TMR contracts Nos. ERBFMGECT-980110 and HPRI-CT-1999-00078. Two of us (E.F. and A.G.) acknowledge support from the EU under contracts ERBFMBICT983126 and ERBFMBICT-983127. We are grateful to the staff of the Tandem XTU and of the Vivitron accelerators for the smooth operation of the machines during the experiments. Many thanks are due to R. Isocrate, D. Rosso, I. Kojuharov and A. Buscemi for their skillful help in the preparation of the experiments. Fruitful discussions with P.H. Regan, I. Hamamoto, J. Dobaczewski and A. Vitturi are kindly acknowledged.

References

[1] G. Colò, M.A. Nagarajan, P. Van Isacker, A. Vitturi, Phys. Rev. C 52 (1995) R1175.
[2] J. Dobaczewski, I. Hamamoto, Phys. Lett. B 345 (1995) 181.
[3] W.E. Ormand, B.A. Brown, Phys. Rev. C 52 (1995) 2455.
[4] H. Sagawa, N. Van Giai, T. Suzuki, Phys. Rev. C 53 (1996) 2163.
[5] D.H. Wilkinson, Nucl. Instrum. Methods Phys. Res. A 335 (1993) 201.
[6] G. Savart, et al., Phys. Rev. Lett. 74 (1995) 1521.
[7] I.S. Towner, J.C. Hardy, nucl-th/9809087.
[8] L. Radicati, Phys. Rev. 87 (1952) 521.
[9] P.J. Ennis, et al., Nucl. Phys. A 535 (1991) 392;
P.J. Ennis, et al., Nucl. Phys. A 560 (1993) 1079, Erratum.
[10] E. Farnea, et al., Nucl. Instrum. Methods Phys. Res. A 400 (1997) 87.
[11] Ö. Skeppstedt, et al., Nucl. Instrum. Methods Phys. Res. A 421 (1999) 531.
[12] F. James, M. Roos, Comput. Phys. Commun. 10 (1975) 343.
[13] A. Gadea, et al., in: B. Rubio, M. Lozano, W. Gelletly (Eds.), Proc. Conf. on Experimental Nuclear Physics in Europe, Sevilla, Spain, June 1999, in: AIP Conf. Proc., Vol. 495, Am. Inst. Physics, New York, 1999, p. 195.
[14] P.G. Bizzeti, A.M. Bizzeti-Sona, T. Fazzini, N. Taccetti, F. Velatini, LNL–INFN (Rep) 047/91 (1991) 152.
[15] L.M. García-Raffi, et al., Nucl. Instrum. Methods Phys. Res. A 391 (1997) 461.
[16] U. Hermkens, et al., Z. Phys. A 343 (1992) 371.
[17] A. Dewald, et al., in: J. Styczen, Z. Stachura (Eds.), Selected Topics in Nuclear Structure, in: Proceedings of the XXV Zakopane School on Physics, Vol. 2, World Scientific, Singapore, 1990, p. 152.
[18] D. Cline, P.M.S. Lesser, Nucl. Instrum. Methods Phys. Res. 82 (1970) 291.
[19] C.M. Baglin, Nucl. Data Sheets 69 (1993) 733.
[20] M.M. King, Nucl. Data Sheets 64 (1991) 815.
[21] M.R. Bhat, Nucl. Data Sheets 69 (1993) 209.
[22] M. Bini, P.G. Bizzeti, P. Sona, Lett. Nuovo Cimento 41 (1984) 191.
[23] P. Schuurmans, et al., Nucl. Phys. A 672 (2000) 89.