SPECTROSCOPY OF HEAVY $N = Z$ NUCLEI WITH GASP AND EUROBALL*

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The coupling of big Ge-arrays like EUROBALL or GASP with ancillary detectors for the study of the structure properties of very exotic nuclei, far from the stability valley, has given outstanding results in the last years. A large fraction of the experiments performed with both arrays has been devoted to study both proton-rich and neutron-rich nuclei populated using stable beams provided by the LNL Legnaro and IReS Strasbourg accelerators. Nuclei lying close to the $N = Z$ line are of particular interest being a laboratory where collective excitations as well as fundamental properties of the nuclear force can be tested, like isospin symmetry and isospin breaking terms, proton neutron pairing, dripline effects and coherent neutron and proton contributions to the nuclear excitations. Some of this properties are more evident (degree of isospin mixing) or can be only observed (collective effects) in heavy $N = Z$ nuclei. In this contribution we present the experimental results obtained by our collaboration along and in the vicinity of $N = Z$ line.

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1. Introduction

The interest of nuclei with $N \approx Z$ comes from the occupation symmetry between protons and neutrons orbitals. Among the topics that can be studied in these nuclei is particularly attractive the study of the possible breakdown of isospin symmetry. This is an example of the impact of nuclear physics calculations on the predictions of the standard model of the electro-weak interaction, which requires unitarity for the Cabibbo–Kobayashi–Maskawa (CKM) matrix. Available data suggest that the CKM matrix fails the unitarity test [1], pointing to physics beyond the standard model. Since such result depends on corrections for nuclear isospin mixing, which is larger for heavy $N = Z$ nuclei, the experimental results in these nuclei are vital to test the model predictions. Spectroscopic studies of $N = Z$ nuclei are relevant in this topic since the isospin mixing probability can be determined using isospin forbidden γ-transitions. If the charge symmetry of the nuclear force is exact, in the limit of long wavelengths, the E1 transition operator is purely isovector and therefore E1 transitions are forbidden in $N = Z$ nuclei between states of equal isospin and have equal strength in mirror nuclei. Failure of this symmetry rule due to the isospin non conserving Coulomb interaction can be experimentally observed as an apparent "induced isoscalar term" through the presence of forbidden E1 transitions. Alternatively is possible to evaluate the isospin non-conserving terms of the interaction with the investigation of the electromagnetic decay properties in mirror pairs. In this case the determination of the isovector and isoscalar components of E1 transitions allow higher sensitivity, compared to the determination of the transition probability of forbidden transitions in $N = Z$ nuclei, as a consequence of the interference between forbidden and allowed strengths.

In heavy $N = Z$ nuclei due to the fact that protons and neutrons occupy the same orbitals one may also expect strong neutron–proton pairing correlations, which can not be observed in stable nuclei where valence protons and neutrons occupy different shells. In particular the effects connected with the rotation of the nuclear superfluid and the competition between $T = 0$ and $T = 1$ pairing are expected to appear in such nuclei [2].

A consequence of occupation symmetry, in medium mass and heavy nuclei, is that protons and neutrons can act in phase giving rise to phenomena of coherent contributions of both kind of particles to collective excitations. As an example two of the largest measured octupole transition matrix elements have been deduced from experimental lifetimes in the ^{114}Xe nucleus. Such strong B(E3) matrix elements cannot be explained within the standard mean field approach and can be related to a coherent enhancement of the collectivity possibly due to the dynamical coupling of the proton-neutron interaction among orbitals differing of three units of angular momenta.

2. Measurements

In this contribution we are presenting results from experiments performed at the GASP and EUROBALL multidetector arrays. The measurements included γ-coincidences, linear polarization and lifetime analysis. High-spin states in the $N \approx Z$ nuclei were populated using compound nuclear reactions with the beams delivered by the TANDEM XTU of the Laboratori Nazionali di Legnaro (Italy) and the VIVITRON at IReS, Strasbourg (France). γ–γ coincidences were acquired with the gamma spectrometers GASP and EUROBALL. In some of the experiments ancillary devices were used to improve the selectivity for reaction channels involving the evaporation of charged particles and neutrons; GASP was coupled with the ISIS silicon ball [3] and a ring of six liquid scintillator neutron detectors replacing six BGO elements of the multiplicity filter, and EUROBALL with the Si-ball EUCLIDES [4] and the Neutron-wall [5] replacing the phase I detectors. For the lifetime measurements we used the Cologne plunger device [6] with a special set-up of the Si-ball EUCLIDES, using only the two forward rings of Si telescopes. More details on the different setups can be found in the references given in the following sections. In the off-line analysis the different channels were partially selected by requiring that only the events corresponding to the detection of proper number of protons, neutrons and alpha particles, in the Si telescopes and neutron detectors, were incremented into symmetrized E_γ–E_γ matrices. Moreover, when necessary, we made use of triples data by constructing E_γ–E_γ matrices in coincidence with known γ-ray transitions. The spins and parities of the levels were deduced from the analysis of the directional correlation ratios from oriented states (DCO) and from linear polarization results.

3. Iospin mixing on the ^{64}Ge nucleus

In the case of $T_z = 0$ ($N = Z$) nuclei one can investigate experimentally the amount of isospin impurity in the low-lying states through E1 lifetime measurements. In fact the electric dipole transitions in $N = Z$ nuclei between states of equal isospin are forbidden by isospin conservation. Therefore, E1 transitions between low-lying states of even-even $N = Z$ nuclei can only proceed through the mixing of $T = 0$ and $T = 1$ states induced by the Coulomb interaction. An example is offered by the ^{64}Ge nucleus, where an intense 1665 keV transition, previously assigned as a pure E1 from systematic [7], was observed to connect the low-lying 5^- and 4^+ states. In Fig. 1 a partial level scheme of the $N = Z$ nucleus ^{64}Ge, obtained from previous works [7] and recent experiments performed at EUROBALL with the reaction ^{32}S (125 MeV)+ ^{40}Ca [8], is compared with that of the isotope ^{66}Ge [9]. The presence in both nuclei of the strong $5^- \to 4^+$ transition is rather surprising because in the self-conjugate ^{64}Ge nucleus the E1 transition between $T = 0$ states should be forbidden by the isospin selection rule. Under the assumption that the $5^- \to 4^+$ has a E1 character, such transition in ^{64}Ge is only possible through isospin mixing with $T = 1$ states of equal spin and parity which lie ≈3 MeV higher in excitation energy.

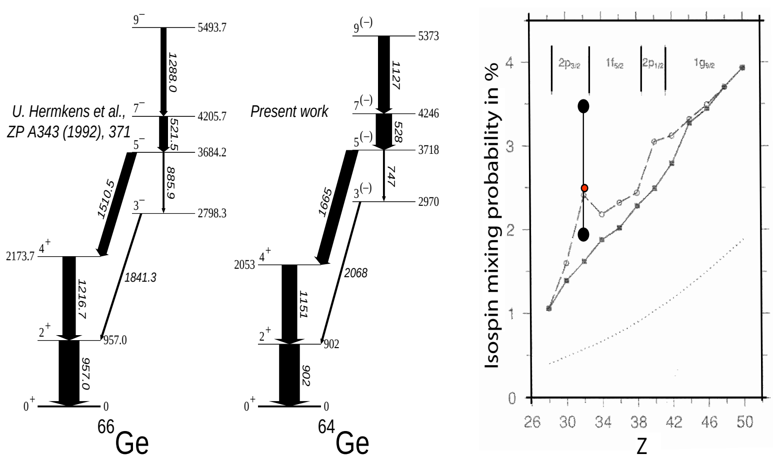

Fig. 1. Partial level scheme of ^{66}Ge and ^{64}Ge with the width of the arrows proportional to the transition intensity. Experimental isospin mixing probability α^2 compared with the theoretical predictions from Ref. [10].

For a quantitative determination of the isospin mixing probability both the multipole character and the partial lifetime of the $5^- \to 4^+$ transition in ^{64}Ge have been measured. The production in the same reaction of the $N = Z+2$ ^{66}Ge nucleus has allowed a direct comparison between the angular distribution and polarization data also for the $5^- \rightarrow 4^+$ 1510 keV transition in ^{66}Ge and the same quantities for the corresponding 1665 keV transition in ^{64}Ge. The multipolarity for both the 1665 and 1510 keV transitions were inferred through angular distribution and DCO analysis; the mixing ratio δ and the alignment parameter σ/J were deduced simultaneously from a fit of the angular distribution data. In the case of the 1665 keV transition, the best fit gives $\delta = -3.93 - 0.41 + 0.75$, with a reduced χ^2=0.80, whereas it gives $\delta \approx 0$ for the 1510 keV transition in ^{66}Ge.

A polarization correlation analysis was performed using the Clover detectors of EUROBALL. The asymmetry $A = \left(N^+ - N^{||}\right) / \left(N^+ + N^{||}\right)$ for the 1510 keV transition in ^{66}Ge was found to be positive which, combined with the angular distribution results, confirms its stretched E1 character. A similar analysis for the 1665 keV line in ^{64}Ge gives a negative asymmetry, which is compatible with the large δ value resulting from the angular distribution fit with a predominant M2 character of the transition (93%) and a very small E1 component. Despite the fact that ^{64,66}Ge nuclei have almost equal level schemes, reflecting the same intrinsic structure for the excited states, their different isospin is reflected in the strong hindrance of the E1 transition in the $N = Z$ nucleus. Lifetimes ^{64}Ge has been measured in a dedicated plunger experiment using the RDDS method. In this experiment the EUROBALL IV Ge array was coupled to the Cologne plunger as previously described. In the experiment we could follow the decay of ^{64}Ge up to the 9^- level at 5373 keV. The 1127 keV transition de-exciting this level appears completely shifted at a target-stopper distance of 100 μm, suggesting a quite short lifetime of the level. The decay curve of the 528 keV γ-ray de-exciting the 7^- level at 4246 keV corresponds to a meanlife of τ = 43±8 ps. For the decay curve of the 1665 keV γ-ray de-exciting the 5^- level at 3718 keV a two level fit including the lifetime of the 7^- levels gives τ= 26 ± 13 ps. Considering the multipole mixing ratio, the experimental strengths are $B(\mathrm{E1}, 1665\,\mathrm{keV}) = 2.3 \pm 1.3 10^{-7}$ W.u. and $B(\mathrm{E2}, 747\,\mathrm{keV}) = 1.0 \pm 0.5$ W.u. The latter value is in good agreement with the systematics of the even Ge isotopes. In order to estimate the amount of isospin mixing 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. As the level schemes in the two isotopes ^{64}Ge and ^{66}Ge 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 $J = 0$, $T = 1$. 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. With this assumptions and at the limit of small isospin mixing we obtain:

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

with $\Delta\alpha = \alpha_i - \alpha_f$ the difference between the isospin mixing amplitude for the initial and final states. 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 $\alpha_i = -\alpha_f = \alpha$. We obtain, in this case:

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

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(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(E1) can be substantially larger than the weighted sum of individual B(E1)'s if the contributing amplitudes add coherently. Substituting the experimental values one obtains 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 (Dobaczewski and Hamamoto [10] see Fig. 1 and Coló *et al.* [11]).

4. High spin evidences for p–n pairing

The existence of a p–n pair condensate induced by the strong correlations in $N \approx Z$ nuclei is still an open question. In $N = Z$ nuclei the wave functions of protons and neutrons are essentially identical in addition to the standard $T = 1$ pairing (isovector) it is possible the $T = 0$ pairing (isoscalar). It has been pointed out that the phenomena connected with the $T = 0$ pairing mode will only exist in nuclei with $N \approx Z$ [2].

It is well known that the aligning frequency of particles in a rotating nucleus is determined by the competition between pairing and the Coriolis force and therefore the band crossing frequency is an indicator of the correlation strength. In an early experiment on ^{72}Kr [12] it was shown a delay in the crossing frequency between the g.s. and S-band, latter corroborated in GAMMASPHERE experiments [13, 14], and it was suggested that this phenomena can be an evidence for n–p pairing correlations even if other possible mechanisms could not be excluded. A systematic observation of delay band crossing in $N = Z$ nuclei compared with neighbouring isotones and isotopes is necessary to elucidate the mechanism participating and to evaluate the contribution of the pairing correlations.

Recent GAMMASPHERE experiments on the nuclei ^{76}Sr and ^{80}Zr also suggested the delay alignment frequency for both cases [13].

The contribution of the GASP collaboration to this subject is coming form the investigation of the two heaviest $N = Z$ nuclei were it has been possible to do γ-spectroscopy studies, *i.e.* the ^{84}Mo and ^{88}Ru [15,16]. These nuclei have been studied with the GASP array coupled with the ancillary detectors described in the measurements section. Both nuclei have been populated in the 2n channels in the reactions ^{28}Si + ^{58}Ni at 90 MeV and ^{32}S + ^{58}Ni at 105 MeV. The spectra of both nuclei suggest delay alignment frequency compared with neighbour nuclei (see Fig. 2), even if the investigation higher angular momentum states is necessary to further clear up of the problem. In addition it is necessary the comparison with self-consistent microscopic calculations not yet available.

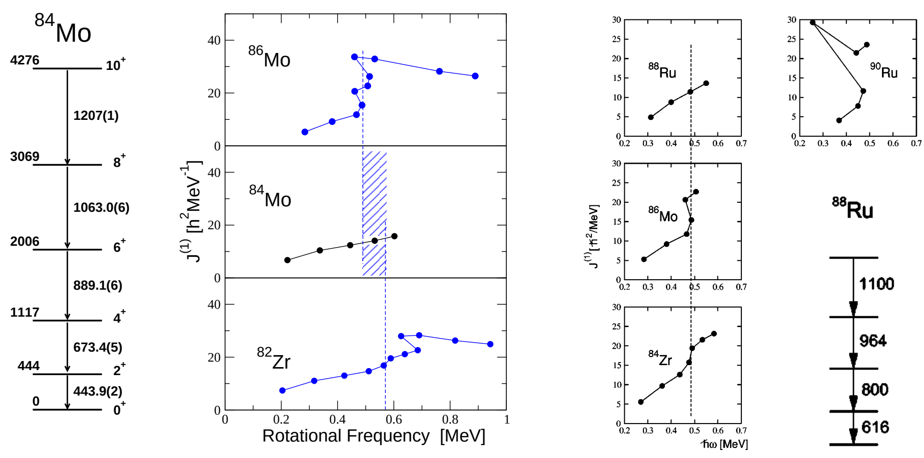

Fig. 2. The ^{84}Mo and ^{88}Ru level schemes together with the kinematic moments of inertia as a function of rotational frequency for them and neighboring isotopes and isotones.

5. Enhancement of the octupole collectivity in ^{114}Xe

Octupole correlations in nuclei are generated by the interaction between orbitals of opposite parity near the Fermi surface which differ by three units of angular momentum. In particular, it has been suggested that octupole correlations should appear at low and medium spins in the light Te, I and Xe nuclei [17]. The strongest octupole collectivity has been predicted for the very light Xe and Ba isotopes with $N \approx Z \approx 56$ when the Fermi surface for both protons and neutrons lies between the $d_{5/2}$ and the $h_{11/2}$ orbitals [17, 18]. In the vicinity of the $N = Z$ line enhanced polarization can be expected, due to the presence of an isoscalar proton and neutron $(\pi(\nu)d_{5/2}\ \nu(\pi)h_{11/2})_{3^-}$ term. Experimentally, excited rotational bands have been found and interpreted as built on the octupole excitation first in ^{114,116}Xe [19, 20] and then more recently in ^{108,109,110}Te [21–23]. The main argument to assign a negative parity to these bands in the case of even-even nuclei or positive parity for odd nuclei, which is crucial for the octupole scenario, is the E1 character of the transitions linking the excited bands to the yrast bands. Such E1 assignments have been normally based only on measurements of branching ratios and angular correlations. Since confirmation of the electric character of these dipole transitions is of paramount importance to establish firmly the octupole nature of the observed bands. Therefore the linear polarization of the gamma rays in ^{114}Xe nucleus have been measured in an EUROBALL experiment with the ^{58}Ni(210 MeV)+^{58}Ni reaction. In addition, using the plunger method (see measurements section), we have measured the lifetimes of the two lowest levels of the octupole band (5^- and 3^- at 2000 and 1623 keV excitation energy, respectively) which allow the determination of the strength of the transitions linking the proposed octupole band to the g.s. band [24]. The results firmly establish the octupole character of the excited band built on the state at 1623 keV. Furthermore, two new E3 transitions deexciting the states of the octupole sequence 5^- (to the 2^+) and 3^- (to the ground state) with γ-transitions of 1549.1(5) and 1623(1) keV, respectively (see Fig. 3), have been the observed.

The extracted branching ratios for the 5^- and 3^- levels at 2000 and 1623 keV of excitation energy have been obtained from the coincidence data gating on the 558 keV (for the 5^-level) and on the 558 and 377 keV (for the 3^- level) γ-transitions, respectively (see Fig. 3). The contributions to the observed intensity ratios from the sum of coincident γ-rays has been estimated smaller than 0.5% of the reported intensities and it has been included in the evaluation of the errors. The collectivity of the 3^- state is strongly corroborated by the lifetime measurements. The deduced B(E3) transition matrix elements correspond to ≈77(27) and 68(17) W.u. for the $3^- \to 0^+$ and $5^- \to 2^+$ transitions, respectively. These are among the largest mea-

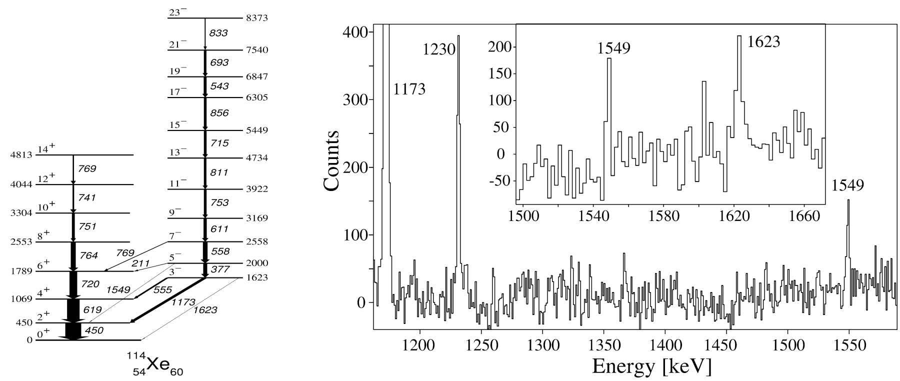

Fig. 3. Right: Partial level scheme of ^{114}Xe. Left: Coincidence gamma ray spectrum obtained gating on the 558 keV γ-line of the negative parity band. In the inset the coincidence spectrum obtained by gating on the 377 and 558 keV γ-transitions is displayed.

sured transition moments hitherto. They are twice as large as the B(E3) of the $3^- \to 0^+$ transition (37 W.u.) in ^{146}Gd. The strength is actually similar to the $12^+ \to 9^-$ transition in ^{148}Gd (78(6) W.u.) which corresponds to the two-phonon to one-phonon de-excitation. Analogous to ^{146}Gd, the octupole collectivity in the neutron deficient Ba-Xe region originates mainly from the stretched $(\mathrm{d}_{5/2}\mathrm{h}_{11/2})_{3^-}$ coupling. In order to compare the collectivity of ^{114}Xe and ^{146}Gd, we have calculated the B(E3) matrix elements by means of the Tamm–Dankoff approximation, using the experimental energy of the 3^- as an input to the calculations. The spherical calculations yield similar values of the B(E3) matrix elements for both nuclei. In addition, due to the presence of quadrupole deformation in ^{114}Xe, one would expect a reduction of the B(E3) strength with respect to ^{146}Gd. We are thus facing the fact that one is dealing with an exceptional enhancement of the octupole strength for the case of ^{114}Xe. Since the dominant component of the octupole phonon in ^{146}Gd originates from the contribution of the proton $\mathrm{d}_{5/2} - \mathrm{h}_{11/2}$ configuration, the strength of the transition in ^{114}Xe, almost twice the one of ^{146}Gd, suggests a coherent contribution of both protons and neutrons. Clearly, standard mean field calculations cannot account for the experimental findings. As discussed above, the neutron (proton) Fermi surface is just above (below) the Ω=1/2, $h_{11/2}$ orbit. However, pairing correlations smooth out the occupation probabilities implying that the quasi-particle occupation factors of protons and neutrons become similar. A possible mechanism for the observed enhancement in ^{114}Xe can be related to the vicinity to the $N = Z$ line. In $N = Z$ nuclei, one does not only encounter the standard $\pi(\nu)\left(d_{5/2}-h_{11/2}\right)$ coupling but also may recouple protons and neutrons into an isoscalar $\left(\pi(\nu)d_{5/2}-\nu(\pi)h_{11/2}\right)_{3^-}$ term.

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