6. Symmetries in medium-light nuclei: at and beyond the *N*=*Z* line*

6.1. Introduction

Symmetry is normally associated to the concept of beauty. In physics, symmetries help to better understand the world around us and, in nuclear physics, they play a key role in the understanding of the behaviour of matter. Isospin symmetry is a consequence of the (approximate) charge invariance of nucleon-nucleon forces. Although the symmetry is already broken, to some extent, at the level of strong interaction and - to a much larger extent - by electromagnetic forces, the isospin formalism remains a very powerful tool to relate the properties of corresponding levels in different nuclei, from which complementary information can be derived on the structure of the nuclear wave function. The most important component of the symmetry breaking interaction, i.e., the Coulomb force between protons, is certainly the best known part of the Hamiltonian, and its effects can be calculated as a perturbation series if the structure of unperturbed charge-symmetric states is assumed to be known.

Due to the Coulomb forces (and other non charge-invariant effects) the isospin is not - strictly speaking - a good quantum number. Every nuclear state is expected to contain, in addition to the main component of isospin T, minor components of different isospin. Although this is not the only effect of symmetry breaking forces (and perhaps not even the most important one) the square of the isospin mixing amplitude can be taken as an indicator of the size of the symmetry violation. The amount of isospin mixing in the ground state of even-even nuclei has been calculated by Colò and collaborators [146] by assuming a dominant role of the Giant Monopole Resonance. For *N*=*Z* nuclei, similar results have been obtained by Dobaczewski and Hamamoto with a self-consistent Hartree-Fock calculation (not restricted to a spherical shape) [147]. The mixing is found to increase rapidly with *A* and, for a given *A*, is maximum for *N*=*Z*.

Isospin mixing is by no means the only effect of symmetry breaking forces. At the lowest order of perturbation, the degeneracy in energy of the different members of a multiplet is broken, and, also in the absence of isospin mixing,

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Coulomb energy terms are different for nuclei of a given isospin multiplet. The resulting failure of isospin symmetry is relevant for transitions leading, within a multiplet, from one nucleus to another, as in the case of beta decay. This fact has a large potential interest for the evaluation of the Fermi coupling constant and, therefore, for the apparent lack of unitarity of the Cabibbo-Kobayashi-Maskawa quark mixing matrix [148]. It is therefore important to develop appropriate models to evaluate the necessary corrections for the nuclear matrix element of the Fermi transitions. The reliability of the models can be tested with other experimental observables related to the symmetry breaking, preferably in several nuclei and in the region where the effects are larger, i.e., on the heavier available nuclei with almost equal values of N and Z.

A large amount of theoretical and experimental work has been devoted to the investigation of isospin symmetry and symmetry breaking effects [149] in two different regions of the chart of nuclides: in the region of light nuclei with N close to Z, where members of low lying isospin multiplets are observed as bound states or very narrow resonances, and in heavier nuclei with fairly large neutron excess, where the isobaric analog states are observed as resonances in proton scattering and (p,n) reactions.

The present contribution will discuss the region of heavier nuclei with approximately equal proton and neutron number, from the $f_{7/2}$ shell up to the limit of the proton drip line. The experimental work in this area is just at the beginning, and will profit from the intense radioactive ion beams provided by future facilities. The available results are, however, sufficient to take a glance over this varied landscape, where, in comparison to lighter symmetric nuclei, one should meet larger Coulomb effects and also qualitatively new aspects, as those related to the onset of nuclear deformation.

In Section 6.2 we discuss the experimental signatures of isospin symmetry breaking (ISB). The experimental results obtained with EUROBALL are presented in Section 6.3. Finally, conclusions and perspectives are given in Section 6.4.

6.2. Isospin symmetry breaking

Coulomb energy differences and isospin mixing

If the Coulomb interaction (and other symmetry breaking forces) is assumed to take place between pairs of nucleons (excluding three-body and n-body forces), its expansion in irreducible tensors with respect to rotations in isospin space contains only three terms, with isoscalar, isovector and isotensor (of rank 2) character, respectively. The isoscalar term has the same effect on every member of a given multiplet, and can be included in the isospin conserving part of the Hamiltonian. The other two terms are responsible for the symmetry breaking. In the first order, the total energy of the different levels of a multiplet - or their excitation energy over the ground state - are related by the equation $E(i,T_z) = a_i + b_i T_z + c_i T_z^2$ where a_i, b_i and c_i are constant for a given multiplet i. This relation can be experimentally verified if at least four levels of a multiplet (with T greater or equal to 3/2) are known.

Moreover, it can be shown [150] that a large part of the isovector term is proportional to the third component of the isospin, and is therefore diagonal in the isospin representation, its only effect being a constant contribution to the Coulomb energy of every nuclide. The residual non-diagonal part of the isovector term is entirely responsible for the mixing between $T = 0$ and $T = 1$ states in self-conjugate nuclei, as well as for the (symmetry-breaking) mixing between $T = 1/2$ states in nuclei with $N = Z \pm 1$. In all other cases, both the isovector and isotensor terms contribute; their corresponding matrix element have equal magnitude in mirror nuclei, while the relative sign of the isovector and isotensor terms is opposite.

Experimental signatures of the symmetry breaking.

Every single-nucleon operator (as, e.g., those responsible for γ or β transitions) contains, at most, an isoscalar and an isovector part. Some of them are purely isovector: The *E*1 transition operator (whose isoscalar part would only involve the center-of-mass coordinates, and would only be relevant for the Thomson scattering of photons on the nucleus) and the nuclear part of the beta transition operators.

A number of selection or symmetry rules can be derived as a consequence of the tensor character of the operator in the isospin space:

1) *E*1 transitions between states of equal isospin are strictly forbidden in *N*=*Z* nuclei.
2a) Beta transitions between two $I^{\pi}=0^{+}$ states (pure Fermi transitions) are only allowed between states belonging to the same isobaric multiplet,
2b) and, in particular, are strictly forbidden between states having different isospin *T*.
3) *E*1 transitions between corresponding states of mirror nuclei should have equal reduced strength.
4) Mirror β decays (e.g. transitions between two corresponding $T = 1$ states of mirror nuclei and a common state of the *N*=*Z* isobar) should have equal reduced strength.
5) Mirror γ transitions of any multipolarity with $\Delta T = 1$ should have equal reduced strength.
6) The transition amplitudes of γ analog transitions of any multipolarity between corresponding states of two given isobaric multiplets should depend linearly on T_z and, therefore, on *Z*.

These rules are strictly valid only if the isospin symmetry holds. Any failure of them implies a failure of the isospin symmetry (although not necessarily an isospin mixing, that is only implied by a failure of rules 1 and 2b). In addition, some approximate selection rules hold for γ transitions of magnetic-multipole character:

7) *M1* transitions between states of equal isospin are hindered in self-conjugate nuclei.
8) On the average, magnetic multipole transitions of any order are somewhat hindered in self-conjugate nuclei.

9) *M1* transitions between corresponding states in mirror nuclei should have similar strength.
10) On the average, *ML* transitions of any *L* between corresponding states in mirror nuclei should have similar strengths.

Rules 7-10 follow from the fact that the proton and neutron contributions nearly cancel each other in the non-diagonal part of the isoscalar magnetic moment. In the case of higher magnetic multipoles they also depend on additional approximations. Their utility for the investigation of isospin symmetry is therefore limited, while the investigation of analog magnetic transitions (also in connection with the analog Gamow-Teller transitions) can be relevant for other aspects of nuclear spectroscopy. Other selection rules can be derived for the alpha decay (transitions with isospin change are forbidden) or proton decay (transitions with isospin change greater than 1/2 are forbidden); however, this subject will not be treated here.

Finally, we must notice that the failure of any one of the above-mentioned rules is not necessarily related in a simple way to the parameters describing the symmetry breaking. For example, in the case of rule 1, a non vanishing amplitude of the forbidden *E*1 transition certainly implies an isospin mixing either in the initial or in the final state (or, very probably, in both of them). However, supposing that only one of the two levels is subject to isospin mixing, the amplitude of the forbidden transition takes the form

$$< a \mid M(E1) \mid b >= \sum_i \alpha_i < a, T = 0 \mid M(E1) \mid i, T = 1 >,$$

$$\alpha_i = \frac{< i, T = 1 \mid V_C^{(1)} \mid b, T = 0 >}{E_b - E_i}, \tag{1}$$

where $V_C^{(1)}$ is the isovector part of the isospin-violating interaction and we have assumed that the level *a* has pure isospin $T = 0$, while in level *b* some mixing occurs with levels *i* having $T = 1$. If the sum is extended to more than one level, the squared amplitude of the transition is not related in a simple way to the overall isospin mixing $\alpha^2 = \Sigma\alpha_i^2$ of the level *b*: The mixing with levels i having a negligible $E1$ transition amplitude to the level a contribute to the isospin mixing but not to the transition amplitude, while if many terms α_i $<a,T=0|M(E1)|i,T=1>$ from different levels i contribute coherently to the sum, the transition amplitude might be comparatively large while the isospin mixing α^2 remains comparatively small. Therefore, we cannot expect that a single measurement (e.g. of a forbidden $E1$ strength), even if it is a carefully selected case, will be sufficient to verify the reliability of a model which can be used to calculate corrections for a different observable (e.g. Fermi matrix element). Several independent measurements, preferably on different observables, will be necessary for this purpose.

In this work we will concentrate on the isospin symmetry studies performed by means of γ-ray spectroscopy with EUROBALL. These investigations cover a wide spectrum of experiments where self-conjugate nuclei and isobaric multiplets have been populated in fusion-evaporation reactions between heavy ions.

6.3. Isospin symmetry breaking studies with EUROBALL

Observation of forbidden E1 transitions in 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 $T_z = 0$ [151]. However, the Coulomb interaction induces the admixture between these low-lying $T = 0$ states and 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. Actually, the systematics of E1 transitions observed in light nuclei shows that the strength of isospin forbidden transitions between low-lying states is

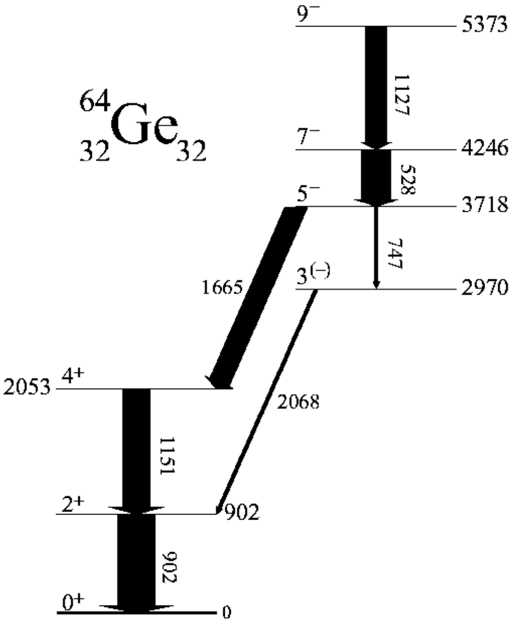

Figure 6.1: *Partial level scheme of ^{64}Ge showing the disputed $5^- \rightarrow 4^+$ transition.*

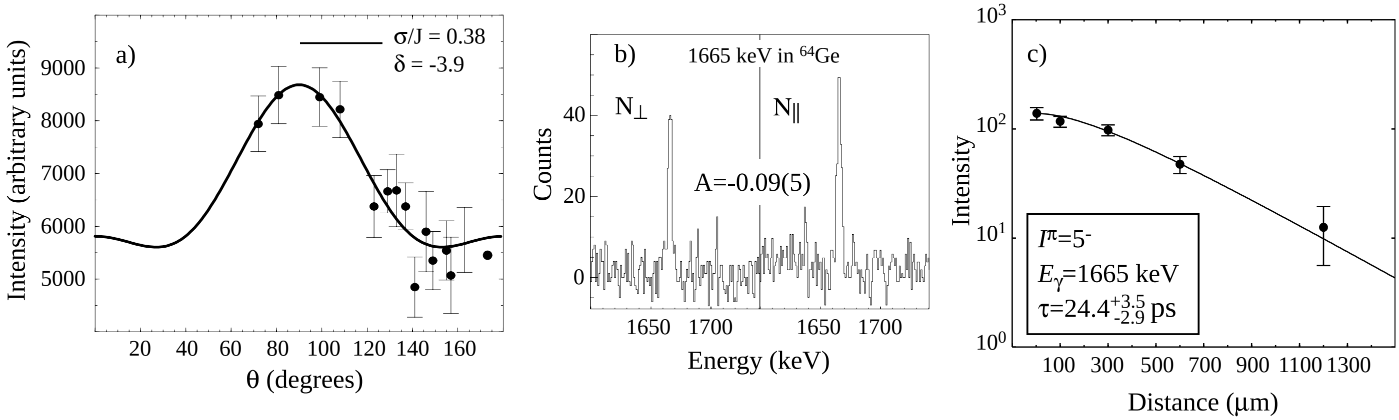

Figure 6.2: *Experimental data for the 1665 keV transition in ^{64}Ge. a) Angular distribution data, b) polarisation correlation data, and c) decay curve for the deexcitation of the 5^- level.*

significantly smaller than those in $N \neq Z$ nuclei. With increasing *Z,* the amount of isospin symmetry violation is expected to increase.

In the $N = Z = 32$ nucleus ^{64}Ge, an intense transition of 1665 keV deexciting the yrast 5^- level to the 4^+ level was already observed by P.J. Ennis and co-workers [152]. In that experiment, it was not possible to determine the multipole mixing ratio δ of the 1665 keV transition and a stretched electric dipole character was assigned on the basis of systematics arguments. In a recent investigation performed at EUROBALL, E. Farnea and collaborators [153] have measured the multipole mixing ratio δ, the linear polarisation of the 1665 keV line, and the lifetime of the 5^- level. These measurements have enabled the electric dipole strength to be extracted and hence for the first time, the amount of isospin mixing to be investigated.

In a first experiment performed at the Laboratori Nazionali di Legnaro using EUROBALL coupled to the ISIS Si-ball [4] and to the Neutron Wall [7], ^{64}Ge was 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. A partial level scheme of ^{64}Ge is shown in

Figure 6.1. The values for δ and σ/J were determined from an angular distribution analysis. A polarisation correlation from oriented states analysis was performed using the EUROBALL Clover detectors as Compton polarimeters [154]. 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 plane containing the detector and the beam direction, respectively. The value of the polarisation sensitivity Q, relating the measured asymmetry to the linear polarisation P, was obtained through a Monte Carlo simulation using GEANT III subroutines modified to include the effect of the linear polarisation [155,156].

The results of the angular distribution and polarisation correlation analyses, shown in Figure 6.2, confirm a $5^{-} \rightarrow 4^{+}$ transition, but with a much larger multipole mixing ratio than the tentative assignment of Ennis and co-workers [152]. In the analysis of the angular distribution data for the 1665 keV transition, a large multipole mixing ratio $\delta = -3.9^{+0.7}_{-0.4}$ was obtained. 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. The results from the linear polarisation 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, the conclusion is that the 1665 keV γ-ray has a mixed $M2/E1$ character with a large negative multipole mixing ratio, corresponding to a quadrupole content of about 93%.

The lifetime of the 5^{-} state was measured in a second experiment performed at the IReS Strasbourg, using the EUROBALL IV array coupled to the Köln plunger device [157], which is especially designed for coincidence measurements. The same reaction (^{32}S + ^{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 favour the production of ^{64}Ge. A lifetime of $\tau = 24.2^{+3.5}_{-2.9}$ ps was obtained and reduced transitions strengths $B(E1) = 2.47^{+0.91}_{-0.57} \cdot 10^{-7}$ W.u. and $B(M2) = 6.06^{+0.91}_{-1.13}$ W.u. were deduced. For comparison, in the case of ^{66}Ge the deduced strengths for the corresponding $5^{-} \rightarrow 4^{+}$ transition of 1510 keV are $B(E1)=3.7(6)\cdot 10^{-6}$ W.u. and

B(*M2*)=0.39(7)·10^{-2} W.u.. The resulting *B*(*M2*) strength in ^{64}Ge is large compared to the corresponding transition in ^{66}Ge, but is not far from the corresponding transition in ^{68}Ge, which has *B*(*M2*) = 0.71(11) W.u. [158]. This suggests that there is an accidental cancellation of the isoscalar and the isovector components of the *M2* transition amplitude in ^{66}Ge, which

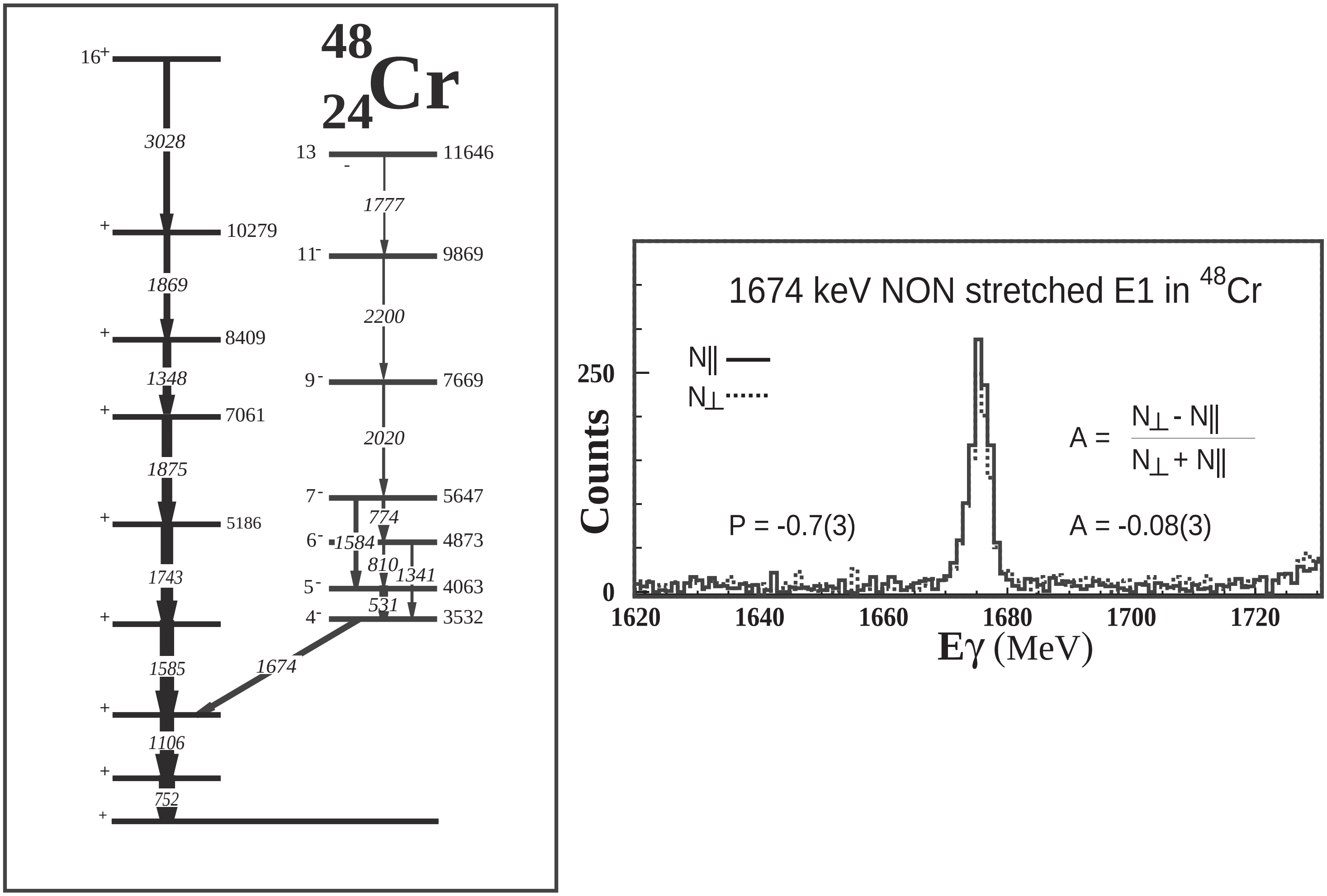

Figure 6.3: *Level scheme and polarisation data for* ^{48}*Cr.*

Analog *E*2 transitions in mirror nuclei

Nuclei in the middle of the $f_{7/2}$-shell are well known to be deformed and to display rotational bands. Here the number of active nucleons and the number of orbitals in the model space is large enough to make coherent phenomena important, and collective excitations having a simple geometrical meaning naturally emerge from the large scale shell model description. The success of large scale shell model calculations in describing rotational motion in this mass region is already well established [162,163]. Calculated energy levels and reduced transition probabilities are in very good agreement with the experimental findings.

The Coulomb energy differences (CED) along rotational bands in mirror nuclei have been investigated in the last few years in the $f_{7/2}$ shell. The first experiments on CED in this mass region were performed at Daresbury by J. Cameron and collaborators [164]. In later experimental studies by M.A. Bentley, C.D. O'Leary and co-workers the CED have been extended up to the band termination states and interpreted as evidence of nucleon alignment and shape changes [165,166]. In spite of the fact that coincidence with neutrons and/or charged-particles has been required to enhance the relative yield of neutron deficient channels, the statistics obtained was not sufficient to allow the measurement of lifetimes to better establish the changes in structure as a function of spin.

It is with the advent of EUROBALL that these measurements have become feasible. In an experiment done at LNL using EUROBALL combined with ISIS and the Neutron Wall the lifetimes in the *E*2 cascades of the mirror nuclei 47Cr-47V were measure by D. Tonev and collaborators [167]. This is the first determination of lifetimes of high-spin states in mirror nuclei of the 1*f*7/2 shell. The reaction was the same as that described above for 48Cr. The 47Cr nucleus was populated after the evaporation of two alpha particles plus one neutron, with a relative yield of 0.5%, while for the exit channel 47V+2αp a yield of 8% was obtained. Lifetimes were determined using the Doppler Shift Attenuation Method (DSAM). In Figure 6.4 the level schemes and measured lifetimes are reported. The lifetime values in ^{47}V are in agreement with data from earlier measurements. In ^{47}Cr the lifetimes are determined for the first time. It should be noted that the derivation of lifetimes in ^{47}Cr and ^{47}V in the same experiment makes the determination of the ratios of the corresponding transition strengths very precise since uncertainties related to the stopping powers nearly cancel.

In the rotational model [18], the $B(E2)$ values can be related to the transition quadrupole moments:

$$B(E2, I \to I-2) = \frac{5}{16\pi} < IK20 \mid I-2\ K >^2 \ (Q_t)^2 \qquad (2)$$

In the case of the ground state bands in the mirror nuclei A = 47, the Qt values obtained in this way correspond to the intrinsic quadrupole moment $Q0$ of the rotational model for a band with K = 3/2. This can also be related to the deformation parameter β:

$$Q_0 = \frac{3}{\sqrt{5\pi}} ZeR_0^2 \beta(1 + \tfrac{1}{8}\sqrt{\tfrac{5}{\pi}}\beta) \qquad (3)$$

The Q_t values for the mirror nuclei ^{47}Cr and ^{47}V are shown in Figure 6.5 together with the deduced deformation parameter β as a function of spin. The experimental data are compared with the results of a full *pf* shell model (SM) calculation performed with the code ANTOINE using the KB3 interaction [168]. The Q_t's show a systematic decrease with increasing spin in good agreement with SM calculations. At $I^\pi = 19/2^-$ the change of the experimental Q_t's is smoother than that of the theoretical values. The insert to Figure 6.5 at the left bottom side shows the CED's between the levels of the g.s. bands in ^{47}Cr and ^{47}V. The abrupt decrease of the CED at $I^\pi = 19/2^-$ has been interpreted by Bentley *et al.* [165] as evidence for particle alignment in both nuclei. Due to the blocking effect of the unpaired nucleon, a pair of protons aligns first in ^{47}V and a pair of neutrons aligns at the same spin in ^{47}Cr; when a pair of protons aligns the Coulomb repulsion decreases which gives rise to an additional compression of the levels in ^{47}V. The reduction of the Q_t values starting at the $19/2^-$ state confirms a change of regime in both mirror nuclei which reduces the deformation with increasing spin. The alignment of nucleons becomes energetically favored with respect to the collective rotation at high angular momentum in these rather light nuclei. The bands terminate when the angular momentum reaches the maximum value ($I^\pi = 31/2^-$) that can be obtained in the $(f_{7/2})^7$ configuration.

It is important to note that the ratios of the mirror *E*2 strengths are close to those of the square of the total charges, as one would expect for two geometrically identical and uniformly charged rotors.

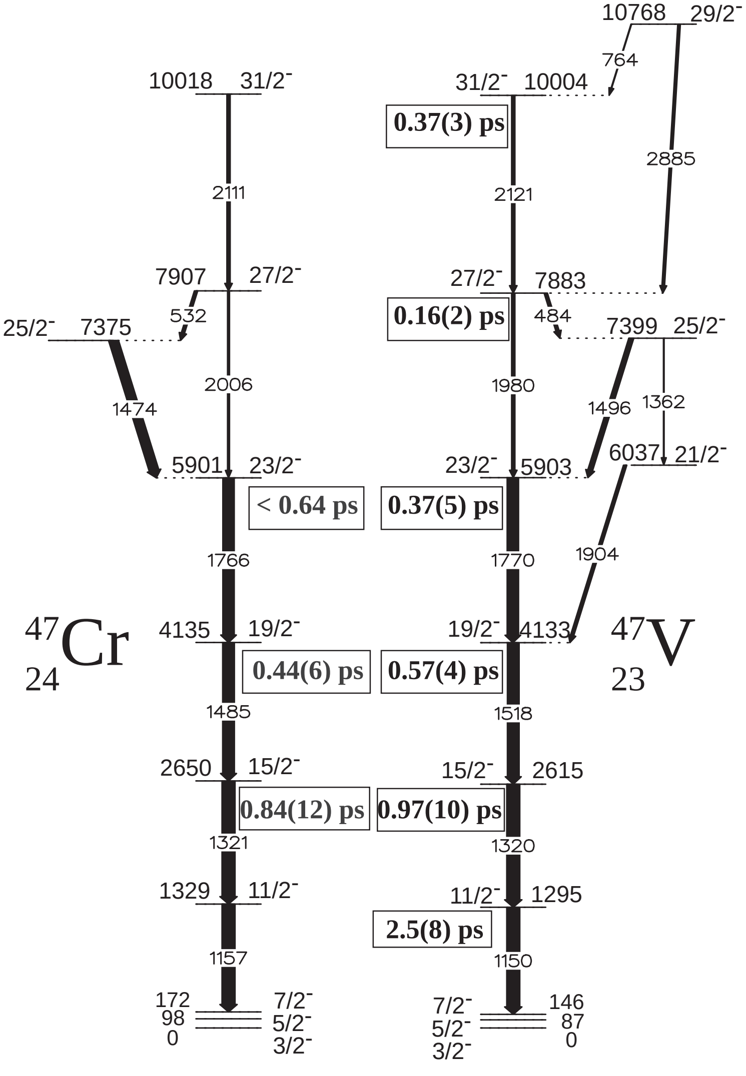

Figure 6.4: *Level schemes of the T=1/2, A= 47 mirror nuclei.*

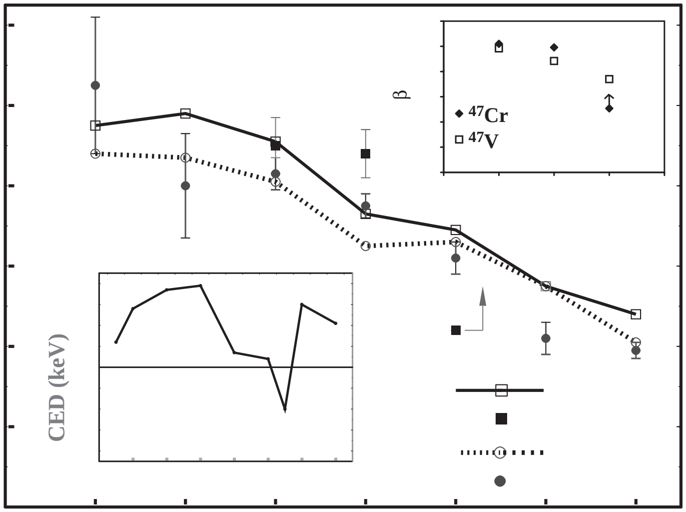

Figure 6.5*: Experimental and theoretical* Q$_t$ *values for the yrast* E*2 cascades in the mirror nuclei* ^{47}*Cr and* ^{47}*V.*

Coulomb energy differences

Isospin symmetry is revealed experimentally as nearly identical spectra in pairs of mirror nuclei. The Coulomb contribution to the bulk energy in a nucleus, which is proportional to Z^2, can be of the order of hundreds of MeV. The displacement energies (CDE) between analog ground states, which vary as Z, can be as large as tens of MeV. When we come to Coulomb energy differences between *excited* analog states in mirror nuclei, the effects become so small (10-100 keV) that they can be treated in first order perturbation theory, i.e., by taking the expectation value of the Coulomb potential between nuclear wave functions of good isospin. Given that large effects have been eliminated in the CED, and that the wave functions remain essentially unperturbed, the Coulomb field becomes a delicate probe of *nuclear* structure.

In particular, as stated in the previous section, the alignment of pairs of nucleons in the backbending region can be inferred from CED's between mirror nuclei. These studies were so far limited to odd-mass (T = 1/2) nuclei and their extension to even-mass nuclei (T = 1) became feasible only with EUROBALL.

One of the best rotors in the $f_{7/2}$ shell is the nucleus ^{50}Cr [163] (β = 0.25) which presents a backbending at $I^{\pi}=10^{+}$. No γ rays were known in its mirror (N = Z - 2, T_Z = -1) nucleus ^{50}Fe. An experiment was done in LNL using EUROBALL to investigate the high spin structure in ^{50}Fe. Together with ^{50}Cr it constitutes the heaviest T = 1 mirror pair studied using γ-ray spectroscopy techniques and it is the first case in which T = 1 rotational bands can be investigated at the backbending region. The nucleus ^{50}Fe was produced in the reaction ^{28}Si+ ^{28}Si at 110 MeV bombarding energy, after the evaporation of one α-particle and two neutrons [169]. The target consisted of 0.85 mg/cm^2 of ^{28}Si (enriched to 99.9%) with a 15 mg/cm^2 gold backing. Gamma rays were detected with the EUROBALL array where the forward 1π solid angle was covered by the Neutron Wall. Charged particles were detected with the ISIS array.

In Figure 6.6(a) a spectrum corresponding to a sum of gates on the lowest three transitions assigned to ^{50}Fe is shown. It was obtained from a matrix constructed by adding a γ-γ matrix in coincidence with neutrons and one α-particle plus another matrix coincident only with neutrons (with a veto for any charged particle). The latter matrix takes into account those α-particles not detected due to the low efficiency detection. For comparison, the spectrum for ^{50}Cr (α2p reaction channel) is shown in Figure 6.6(b). It was obtained as a sum of spectra gated on the first three analog transitions in ^{50}Cr in a γ-γ matrix in coincidence with one proton. Due to the different trigger conditions in the two cases, it is difficult to give a precise relative cross section. An estimated ratio of the cross sections is $\sigma(^{50}\mathrm{Cr})/\sigma(^{50}\mathrm{Fe}) \approx 10^4$.

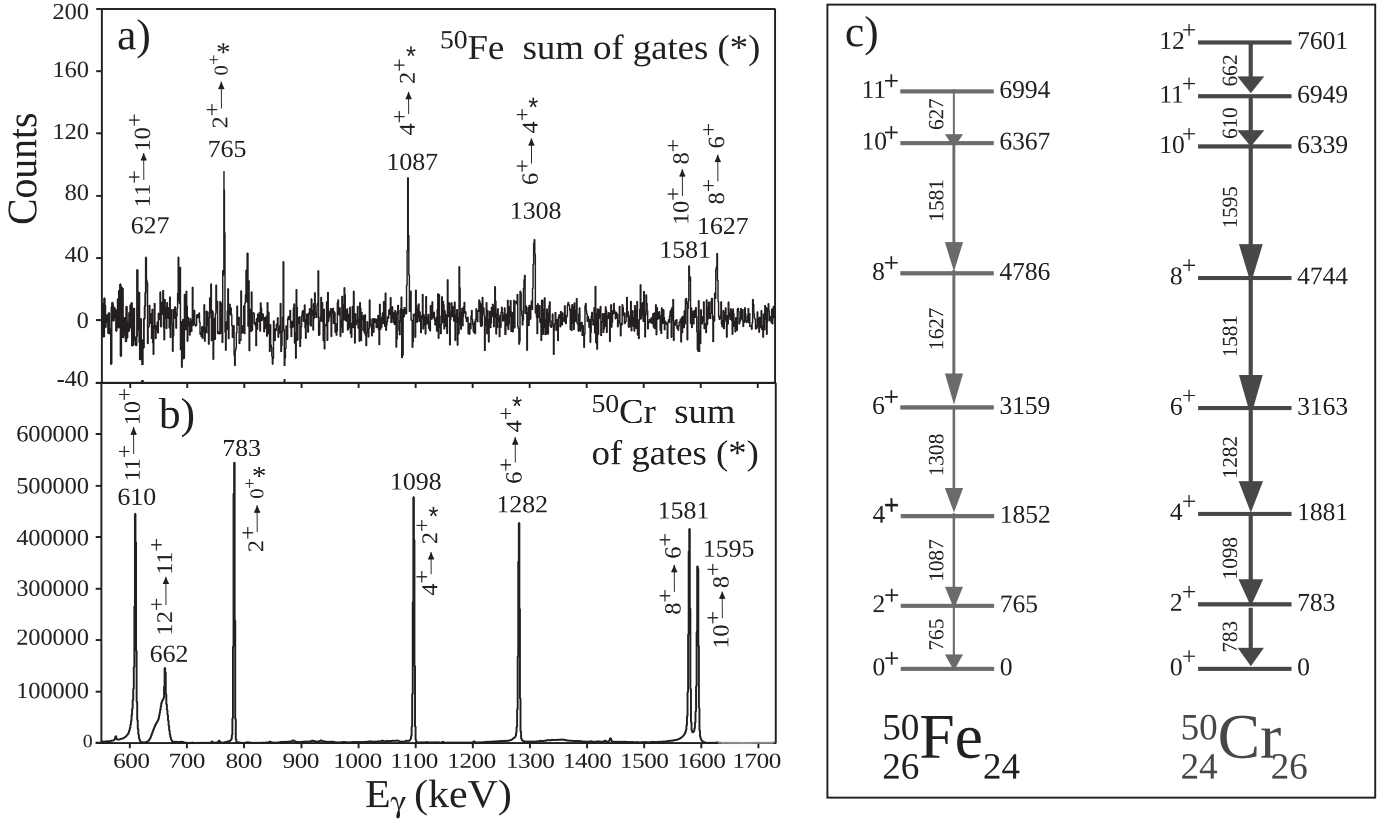

Figure 6.6: *Gamma-ray spectra and partial level schemes for the T = 1 mirror nuclei ^{50}Fe and ^{50}Cr.*

Both level schemes are shown in Figure 6.6(c) where the backbending above $I^{\pi}=8^{+}$ can be seen. Different interpretations have been given to this backbending in terms of band crossing with a high *K* band or with an oblate band. Shell model calculations indicate that the rotational behaviour changes at $I^{\pi}=10^{+}$ to a weakly deformed regime. This is consistent with the sharp decrease of quadrupole collectivity observed in lifetime measurements at the 10_1^+ state [160]. Above this spin the extracted $B(E2)$ values suggest that the ground state band continues in the yrare 10_2^+ and 12_2^+ states [160,163].

By resorting to the CED, the effect of nucleon alignment can be inferred. The role of the Coulomb force is clear: Repulsion is weakest for aligned protons, because the overlap of wave functions is smallest. Hence, we expect a jump in CED at backbending, whose sign will depend on which fluid (neutrons or protons) aligns first. While in odd-mass nuclei the blocking effect in the odd fluid favours alignment in the even one [165,170], in even-even nuclei the choice is not *a priori* evident. Experimental and shell model CED's for the A = 50 mirrors are reported in Figure 6.7(a). A rapid increase is observed at I = 8 followed by a decrease at I = 10. The trend is reproduced but grossly emphasized by shell model calculations in the full *pf* shell (dashed line). The interaction is KB3 with Coulomb matrix elements in the harmonic oscillator basis, except for those involving only the $f_{7/2}$ orbits, which are extracted from the CED of the ^{42}Ti-^{42}Ca mirror nuclei. In Figure 6.7(b) we report the difference in the expectation value of the operator $A = [(a^{+}a^{+})^{J=6}\,(aa)^{J=6}\,]^{0}$ which "counts" the number of maximally aligned pairs in the $f_{7/2}$ shell [171]. In this plot, the difference is between the number of aligned protons minus the number of aligned neutrons in ^{50}Cr (the opposite happens in ^{50}Fe). The similarity of the curves in the Figures 6.7(a) and (b) suggests the connection between backbending and alignment. One can thus deduce that a pair of protons in ^{50}Cr (neutrons in ^{50}Fe) aligns first, and pairs in the other fluid later, at higher angular momentum. This agrees with the predictions done in the framework of cranked shell model calculations [172].

To have a better quantitative description of the experimental data in CED's, in Ref. [169] one has to consider the change in radii along the yrast bands. In the *pf* shell they originate in differences between the 1*f* and 2*p* orbits. The latter have a larger radial extension, which leads to the Thomas-Ehrmann shift in ^{41}Sc where the excitation energy of the $p_{3/2}$ level is 200 keV below its analog in ^{41}Ca. The deformed yrast states have large $p_{3/2}$ admixtures, and hence larger radius and smaller Coulomb energies than their aligned counterparts. Within the shell model, orbital occupancies are translated into

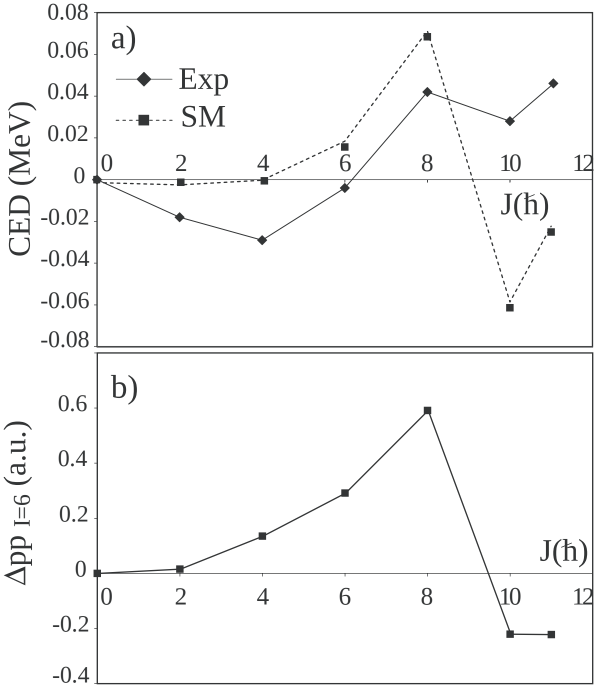

Figure 6.7: *Coulomb energy differences and alignment for the mirror pair* ^{50}*Fe and* ^{50}*Cr.*

changes in radii. This is a residue of the monopole Coulomb contribution and taking it into account the theoretical description improves.

However, this is not enough to reproduce satisfactorily the data and in Ref. [169] the need for a renormalization of the multipole component of the Coulomb contribution was suggested. This gave a good quantitative agreement for the CED's not only in the case of $A = 50$ but also for the $T = 1/2$ mirror pairs measured in the $f_{7/2}$ shell ($A = 47$, 49 and 51) [173].

Only very recently, when data for $T = 1$ bands in the $N = Z$ odd-odd members of the multiplets were available, it became clear that the Coulomb effects were not the only thing responsible for the isospin symmetry breaking. The experimental triplet energy differences [174] cannot be reproduced with the renormalisation suggested in Ref. [169]. Data indicate that

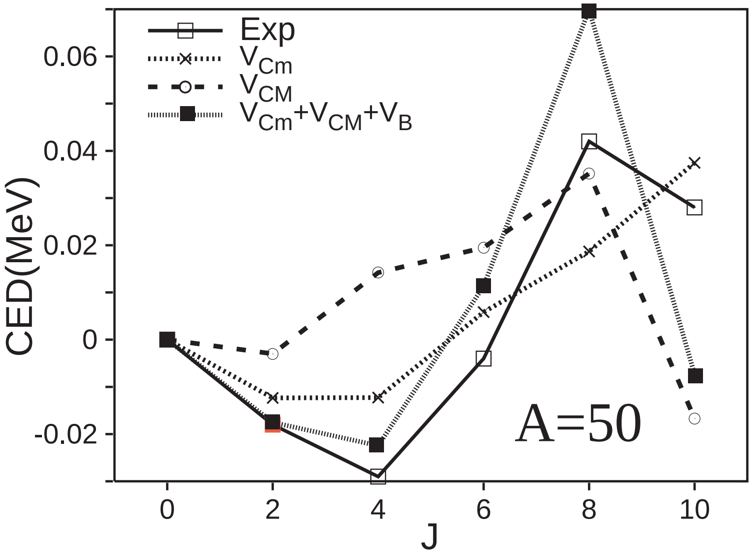

Figure 6.3: *Coulomb energy differences for the mirror nuclei A = 50.*

the role of isospin non conserving *nuclear* forces could be as important as the one of the Coulomb field in the observed CED's between mirror nuclei and among the members of the triplets [174].

Following the notation of Ref. [174], the CED's at spin *I* for a mirror pair can be obtained theoretically as:

$$CED_I = E_I^*(Z > N) - E_I^*(Z < N) = < V_{Cm} >_I + < V_{CM} >_I + < V_B >_I \qquad (4)$$

where *V*Cm is the monopole component of the Coulomb field that accounts for the changes in nuclear radii. *V*CM is the multipole Coulomb component calculated using harmonic oscillator matrix elements in the *pf* shell; and *V*B is the "nuclear" isospin non conserving term. This latter term is deduced from the A=42 data, thus allowing for a parameter free description of the CED data for the heavier mirrors in the $f_{7/2}$ shell. The calculated CED for the mirror nuclei 50Fe-50Cr is shown in Figure 6.8 (taken from Ref. [174]).

Very good fits are also obtained for the CED of the other mirror nuclei in this mass region. When the *N*=*Z* odd-odd member [175] of the T=1 A=50 triplet is taken into account in calculating the triplet energy differences, the agreement with the experimental data is excellent [174].

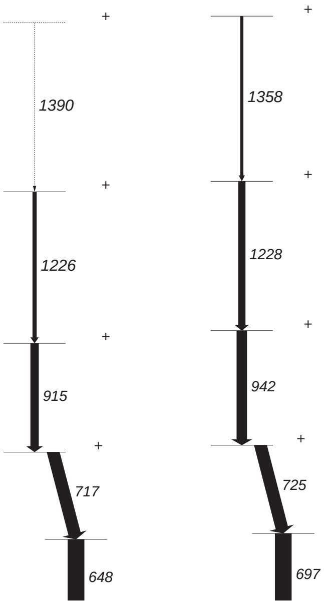

Figure 6.9: *Partial level schemes of the mirror nuclei* ^{67}*Se and* ^{67}*As.*

In an experiment performed on April 2003 with EUROBALL, EUCLIDES and the Neutron wall, the ground-state band of the extremely neutron-deficient nucleus ^{54}Ni was observed up to $I^{\pi} = 6^{+}$ by A. Gadea and collaborators. The measured CED with its mirror ^{54}Fe gives almost the same absolute values as obtained for the cross-conjugate pair in the $f_{7/2}$ shell ^{42}Ca-^{42}Ti and as expected from the particle-hole symmetry. In particular, an increase of the CED at I = 2 is observed in these two pairs, which cannot be explained by considering only the Coulomb interaction and constitutes the basic ingredient in the "nuclear" isospin non-conserving term.

The extension of these investigations to other mass regions is in progress. In particular, new data from EUROBALL has been obtained recently for the mirror nuclei *A*=67 with the reaction 32S on 40Ca at 90 MeV bombarding energy. The mirrors 67Se and 67As were studied at IReS Strasbourg with EUROBALL IV combined with the charged-particle array EUCLIDES and the Neutron Wall. The level schemes shown in Figure 6.9 are taken from Ref. [176]. In this case an unexpected behaviour is observed for the CED's which awaits for new detailed theoretical calculations.

6.4. Conclusions and perspectives

In the last few years, we have explored new aspects of the isospin symmetry in nuclei at high angular momentum with EUROBALL. These investigations have been possible thanks to the high efficiency for detecting gamma rays and to the high sensitivity achieved with ancillary detectors such as the charged-particle arrays ISIS and EUCLIDES, the Neutron Wall, and the Köln plunger.

The measurement of forbidden *E*1 transitions in *N*=*Z* nuclei has enabled an estimate of their degree of isospin mixing. A great amount of information has also been obtained from mirror nuclei. The measurement of the lifetimes in *E2* cascades (A=47) probes the nuclear structure and shape changes at the backbending region in rotational bands.

Comparisons of the excitation energies in mirror nuclei have revealed the nature and the mechanism of backbending in rotating nuclei. Moreover, they also give information on the evolution of radii along the yrast bands and provide direct evidence for charge symmetry breaking of the nuclear field.

In the future the availability of high intensity stable beams and radioactive proton rich beams will enable these studies to be extended to analog yrast or quasi-yrast bands up to the limit of nuclear stability. In particular, it will be interesting to explore isobaric multiplets with $T > 1$ and heavier mirror nuclei, where the effects of isospin symmetry breaking are expected to be stronger.

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