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Mirror energy differences as a probe into neutron skin evolution

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Abstract. Experimental information on charge nuclear radii is limited to ground or isomeric states in stable nuclei; the measurement of neutron radii is even more challenging. In this contribution we present an innovative approach which gives direct insight into the nuclear radii of excited states from the study of Mirror energy differences (MED). MED are a direct consequence of isospin symmetry breaking and their study has proved to give precious information on different nuclear structure features. We report the results of an experiment performed in GANIL to study the MED in rotational bands in mirror nuclei ^{23}Mg – ^{23}Na . State-of-the-art shell model calculations have been performed to interpret the data. This allowed to extract information on the evolution of the nuclear skin along excited states and its correlation with the difference between neutron and proton occupation numbers of the $s_{1/2}$ orbital.

1. Introduction

Experimental measurements of nuclear charge radii are usually performed with electron scattering or laser spectroscopy techniques. These are, however, limited to ground states or long-lived isomers in nuclei lying on the valley of stability. Direct information on neutron radii is more challenging to achieve and nuclear radii measurements of short-lived excited states are not feasible.

Indirect methods, which are sensitive to observable directly affected by the nuclear radius variations with increasing angular momentum, are therefore needed. This is the case of the energy differences between analogue states in mirror nuclei, i.e. the Mirror Energy Differences (MED), which are sensitive not only to the overall nuclear radius but also to the difference between the neutron and proton radii, the neutron skin, as we reported in a recent publication by our group [1].

On the other hand, it is well known that nuclear radii are driven by the nucleon occupation numbers in the different orbitals involved in the nuclear wavefunction [2]. In particular, low l orbitals within a main shell show much larger radii compared with the higher l ones. As a consequence, tracking the



evolution of valence orbitals occupation along a rotational band, it is possible to gain knowledge on the nuclear radius variation with increasing angular momentum and energy. Furthermore, we will show how this approach can be followed separately for neutrons and protons, giving therefore direct insight in the evolution of nuclear skin.

MED have been studied extensively in the $f_{7/2}$ shell, where they allowed to get insightful information on several nuclear structure features and their evolution as a function of angular momentum and excitation energy and to test the validity of the isospin symmetry of the nuclear interaction [3,4]. The success of the MED studies in this main shell has its roots in the large availability of experimental data up to high spin. The information in other regions of the nuclear charts is, on the other hand, scarce and limited to low-lying excited states. However, in the low sd shell the presence of rotational bands allows the study of MED on several excited states, giving the possibility to extend the approach successfully adopted in the $f_{7/2}$ shell to a lower mass region and to test its validity along the nuclear landscape. This is the case in mirror nuclei ^{23}Mg - ^{23}Na , which have been study via fusion-evaporation in GANIL.

2. Experimental study of mirror nuclei ^{23}Mg - ^{23}Na in GANIL

$T=1/2$ mirror nuclei of mass $A=23$, ^{23}Mg - ^{23}Na , have been studied up to high spin states at the CIME accelerator in GANIL. The excited levels of interested have been populated via the fusion-evaporation reactions $^{12}\text{C}(^{16}\text{O}, \alpha n)$ and $^{12}\text{C}(^{16}\text{O}, \alpha p)$ respectively. The ^{16}O beam energy was 60 and 70 MeV and the self-supported carbon target thickness was $500 \mu\text{g}/\text{cm}^2$. The reaction channel following the particle evaporation from the ^{28}Si compound nucleus was selected by means of γ -charged particles-neutron coincidences. The experimental setup consisted in: i) the γ -ray array EXOGAM [5], composed of 10 Compton suppressed clovers of 4 segmented HPGe detectors each, placed at 15 cm from the target to allow a good Doppler correction; 7 clovers were placed at 90° , and 3 clovers at 135° with respect to the beam direction; ii) the 4π charged-particle detector DIAMANT [6], consisting in 80 CsI(Tl) scintillators with excellent discrimination capabilities between protons and alpha particles; iii) the Neutron Wall array [7], made of 50 liquid scintillators placed downstream and covering $\sim 1\pi$ of the total solid angle. The extremely good neutron- γ discrimination is achieved thanks to a combination of time of flight and pulse shape analysis.

An example of PID spectra from DIAMANT and the Neutron Wall is reported in Fig.1

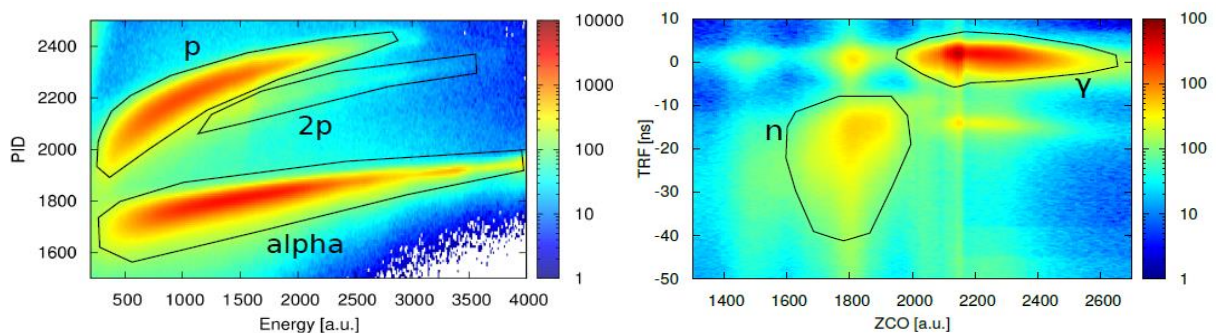


Fig.1 Particle identification plots from DIAMANT (left) and the Neutron Wall (right). The excellent discrimination capabilities between protons and alpha particles (DIAMANT) and neutrons and γ rays (Neutron Wall) allow to unambiguously identify the reaction channel.

Particle- γ and γ - γ coincidence analysis allowed to assign the observed γ rays to the corresponding reaction channels and to reconstruct therefore the level schemes of the nuclei of interest. The γ -ray spectra for ^{23}Na and ^{23}Mg are reported in Fig.2. The previously known transitions [8] have been observed and confirmed up to the highest spin values and, in addition, 4 new transitions have been identified in ^{23}Mg , extending both the *yrast* and *yrare* bands up to $J = 15/2^+$. The updated level schemes from this work are reported in Fig. 3; only the most intense transitions between positive parity states, which are of interest for the following discussion, are shown.

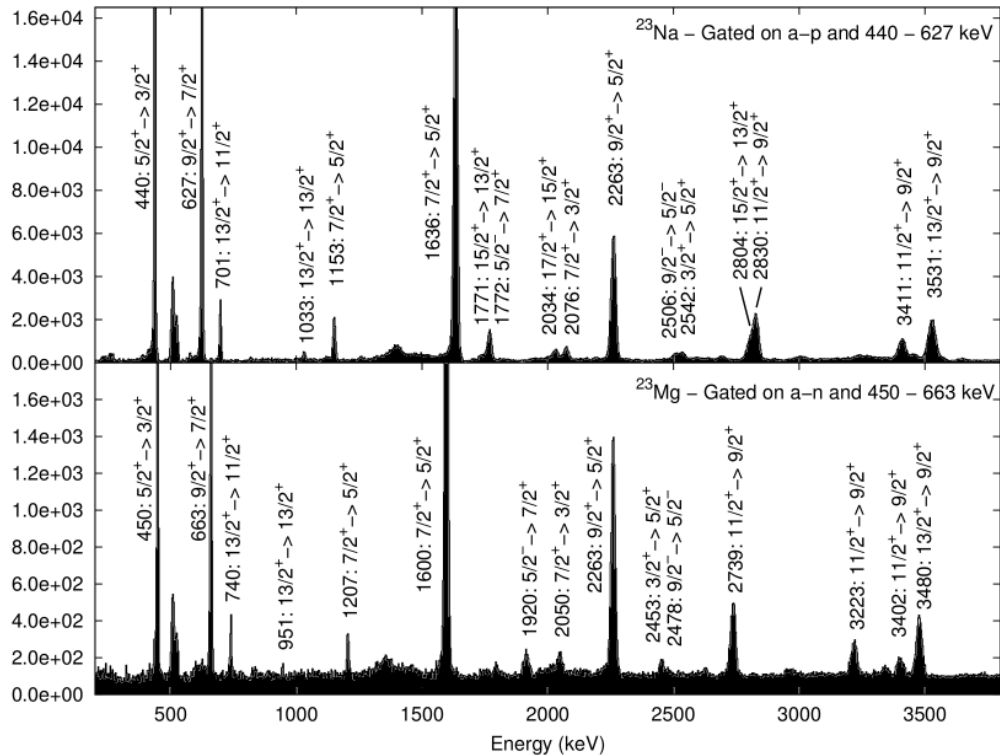


Fig.2 γ -ray spectra derived from particles- γ analysis for ^{23}Na (top) and ^{23}Mg (bottom).

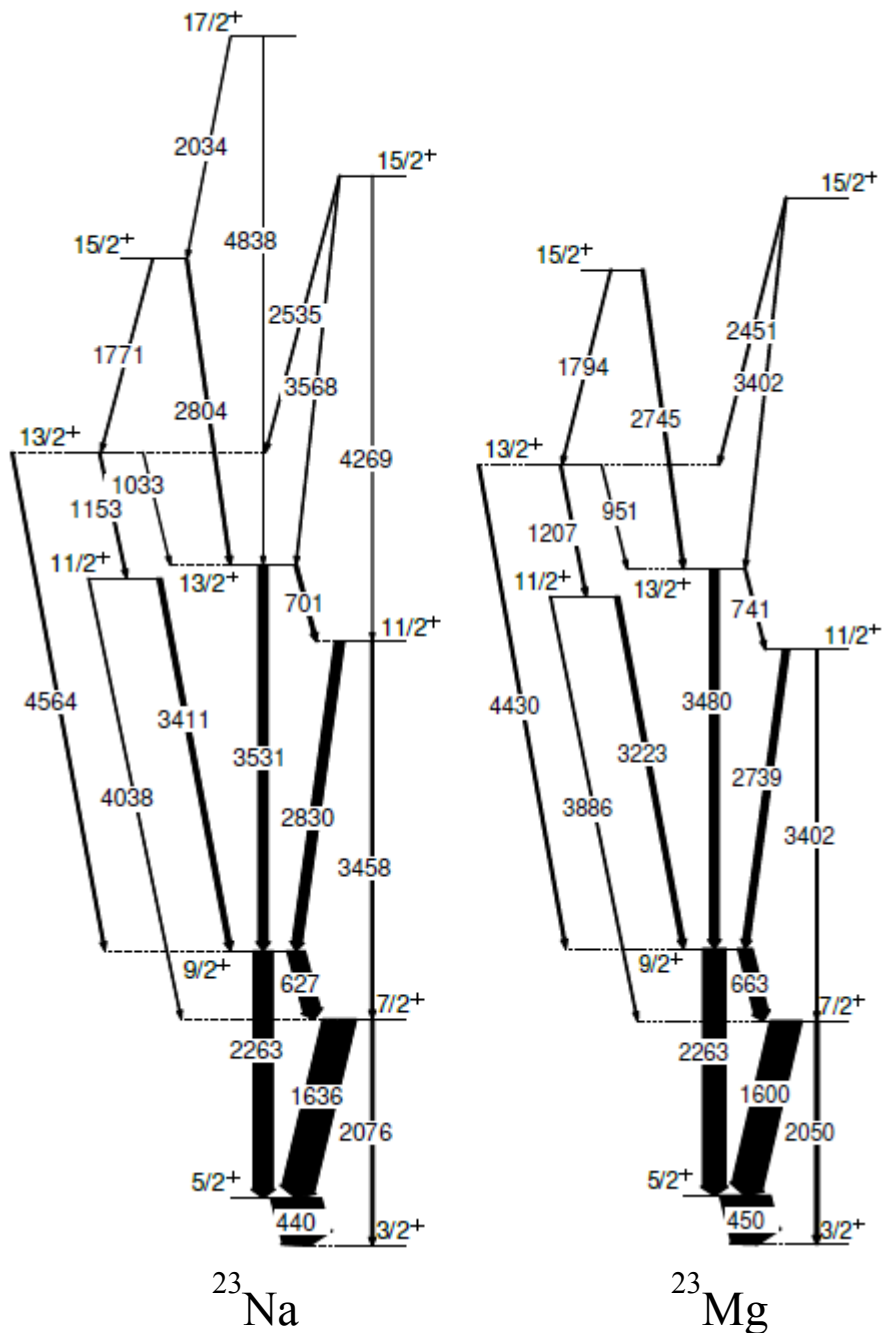


Fig.3 Level schemes for ^{23}Mg and ^{23}Na derived from this work. Only the most intense transitions between positive parity states are shown.

The experimental data have been compared with shell model calculations performed with the ANTOINE code. As a first approach the same procedure successfully adopted in the $f_{7/2}$ shell and outlined in [4] has been followed. A detailed discussion on this is reported in [1]. We focus here on an alternative approach, based on the work by Bonnard et al. [2]. The charge-dependent effective interaction MCI [9], derived from the chiral N3LO realistic potential [10] has been adopted in a no-core approach. In this way, all the isospin symmetry breaking terms, both of nuclear and electromagnetic

origin, are directly included in the analysis. The matrix elements of the MCI interaction are calculated in the harmonic oscillator basis, where a crucial ingredient is the size parameter $\hbar\omega$, which is inversely proportional to the radius ρ [2,11]. An important mechanism, referred to as Isovector Monopole Polarizability (IMP) has been highlighted in [9]: when a nucleon is added to a system it affects the radii of neutrons and protons in different directions. In our approach, it suggests the use of different size parameters for neutrons and protons. In principle, four different radii should be therefore determined: proton and neutron radius for each of the mirror nuclei. Isospin symmetry, however, implies that the proton radius of a nucleus should be equal to the neutron radius of its mirror partner, and vice versa. Moreover, the proton radius of the $T=1/2$ nucleus is known experimentally, leaving only its neutron radius to be determined. In other words, this means including the neutron skin in our treatment.

Mean square proton radii have been fitted by Duflo and Zuker with the formula [11]:

$$\rho_{\pi} = A^{1/3} \left[\rho_0 - \frac{\zeta}{2} \frac{t_z}{A^{3/4}} - \frac{v}{2} \left(\frac{t_z}{2} \right)^2 \right] e^{g/A} + \lambda \mathcal{D}_{v\pi}$$

Where $t_z = N - Z$ and the parameters ρ_0 , ζ and v are related to the scalar, vector and tensor components of the radius. The reader is referred to [11] for a detailed description. The term ζ is directly related to the neutron skin via the relation:

$$\Delta r_{v\pi} = \rho_v - \rho_{\pi} = \frac{\zeta t_z}{A} e^{g/A}$$

Once ρ_{π} is experimentally determined, ζ allows to fix the neutron radius ρ_v and, therefore, all the 4 size parameters needed to calculate the matrix elements are fixed.

The quality of the fit turns out to be independent from the value of ζ in the range 0.3-1.2 [2]. This offers a unique possibility: starting from the experimental MED, we can determine the value of ζ that allows to reproduce the measured value for each excited state. In other words, Mirror Energy Differences prove to be a sensitive probe to test the neutron skin and its evolution with increasing spin and energy. Moreover, the variation of ζ is related to shift in all the MED but does not affect the relative values: the calculated MED decrease linearly with increasing ζ .

To study in more detail the remarkable results of this analysis, we exploited the relation between the variation of the nuclear radius and the occupation of the $s_{1/2}$ orbital, pointed out in [2]. We look therefore for possible correlations between the difference in the occupation numbers of neutrons and protons in the $s_{1/2}$ and the neutron skin. The results are reported in Fig. 4 for mirror nuclei of mass 23 (upper panel) and the other mirror nuclei with sufficient experimental data in the sd shell (lower panel).

The correlation is outstanding. The trend of the nuclear phase parameter ζ is in phase with the $s_{1/2}$ neutron and proton occupation number difference for all the reported mirror nuclei except than the $A=23$ pair. The reason behind this effect is still unclear and under investigation.

In summary, remarkable findings have risen from the shell model analysis of experimental data on mirror nuclei in the sd shell: the neutron skin has been proved to have a sizeable effect on the evolution of Mirror Energy Differences with increasing angular momentum and excitation energy. This allows to extract from experimental MED insightful information on the neutron skin of short-living excited states, which would be otherwise inaccessible. Moreover, the skin evolution along rotational bands is strikingly correlated to the difference in occupation number of neutron and protons in the $s_{1/2}$ ‘halo’ orbital, highlighting a new *isovector* term to be included in MED description.

Further work towards a quantitative description of this correlation is ongoing. This will offer the possibility to deduce the neutron skin from occupation number shell model calculations, which will be a remarkable step towards the understanding of nuclear radii evolution in excited states.

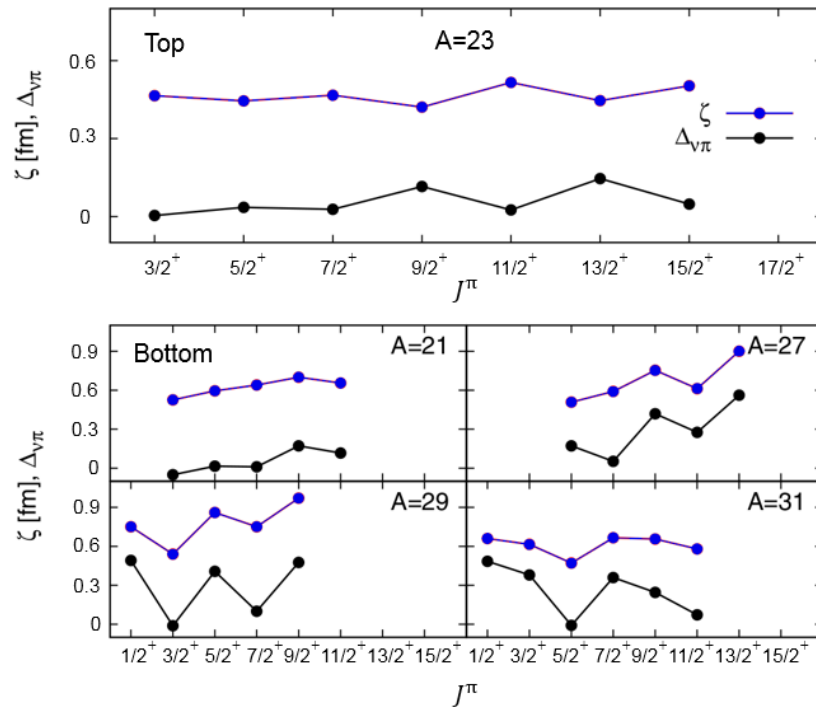


Fig.4 Comparison between the trend of the neutron skin parameter ζ and the difference in neutron and proton occupation numbers of the $s_{1/2}$ orbital: (a) for the mirror nuclei $A=23$; (b) for the other $T=1/2$ mirror nuclei in the sd shell.

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