Journal of Physics: Conference Series **445** (2013) 012026 doi:10.1088/1742-6596/445/1/012026

Deformation and shape coexistence in neutron-rich nuclei at N~40

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Abstract. The A ~ 60-70 mass region of neutron-rich nuclei with Z ≤ 28 presents several interesting properties when approaching N=40. At this subshell closure a new region of deformation develops. From the experimental side, these nuclei can be populated at relatively high spin by means of multi-nucleon and deep-inelastic collisions. Selected results on the gamma-ray spectroscopy of the neutron-rich nuclei in this mass region are discussed. In particular, the shape coexistence in ^{67}Co at low excitation energy, populated by bombarding a ^{238}U target with a 460 MeV ^{70}Zn beam at the Legnaro National Laboratory is interpreted by means of shell model calculations in a large valence space. These calculations are extended to the description of excited states in Zn isotopes.

1. Introduction

Far from the valley of beta stability, the nuclear shell structure undergoes important and substantial modifications. For many decades, theoretical models in nuclear structure were constructed relying on the experimental information obtained for nuclear systems near the stability line. The continuous experimental developments allow nowadays the study of exotic nuclei far from stability. In particular, neutron-rich nuclei are of current interest because of clear experimental indications that the extrapolation of the traditional shell model to this region of the isotope table is not straightforward. Unexpected modifications to the shell structure have been already encountered and there is evidence that some magic numbers change when increasing the neutron number, in particular in light and medium-light nuclei [1-4]. The observed changes help to shed light on specific terms of the effective nucleon-nucleon interaction and to improve our knowledge of the nuclear structure evolution towards the drip lines. In particular, it has been shown that the monopole part of the tensor force of the proton-neutron interaction is the main responsible of the shell evolution [2].

In the last few years, detailed nuclear structure information has become available both with stable and radioactive beams in Cr, Mn, Fe and Co isotopes in the mass region around N=40, where rapid changes of the nuclear shape occur along isotopic and isotonic chains. The knowledge of excited states in these neutron-rich nuclei is rather limited due to the difficulties in the production and identification of isotopes by conventional means. The first results have been obtained using beta-decay reactions. These investigations are, however, limited to a small range of spins and excitation energy. Other methods with radioactive beams consist on the use of knockout reactions and (p,p') inelastic scattering that allow to populate low-lying states in nuclei far from stability. On the other hand, a very successful method to populate relatively high-spin states in moderately neutron-rich nuclei consists on the use of binary reactions between stable neutron-rich nuclei, such as multi-nucleon transfer and deep-inelastic collisions, combined with modern gamma-ray arrays and magnetic spectrometers.

In this contribution, some recent experimental findings in this mass region are discussed in terms of the interacting shell model in a wide valence space.

2. Experimental details

A research program on nuclear structure of neutron-rich nuclei far from stability has been carried out at LNL, in Italy, with the gamma-ray array CLARA [5] and the tracking array AGATA [6], coupled to the magnetic spectrometer PRISMA [7] to study the gamma decay of excited nuclei populated by multi-nucleon transfer and deep-inelastic collisions. With these setups both gamma-ray spectroscopy and lifetime measurements have been carried out in several mass regions of the table of nuclides.
In particular, the mass region A~60-70 at N~40 has been object of several experiments. Beams of ^{64}Ni and ^{70}Zn were used to bombard targets of ^{238}U and for the first time, excited states could be identified in several neutron-rich nuclei of mass A~60 south of the "doubly magic" ^{68}Ni. Very rapid changes in shape and in collectivity have been observed in V, Ti, Cr, Mn, Fe and Co isotopes.

These experimental setups allow to measure the mass A and atomic number Z of the recoiling projectile-like nuclei. With the use of a thin U target short-living states can be observed. However, the limited solid angle of the magnetic spectrometer allows to collect only a small fraction of the cross section and therefore the statistics of gamma rays results insufficient to perform coincidence analysis. With the aim of measuring γ-γ coincidences we have performed an experiment with the GASP gamma-array [8] alone, using a thick U target. Such type of experiment produces a wide range of target-like and projectile-like fragments that are stopped at the target and cannot be identified. The resulting gamma ray spectra are therefore very complex. By using triple gamma coincidence data, useful information can be obtained for the strongest channels when at least one gamma transition is known.

3. Selected results

In multi-nucleon transfer and deep-inelastic experiments, several isotopes of an element can be produced. This allows to follow the evolution of the nuclear structure along isotopic and isotonic chains. In the mass A~60 region, neutron-rich Fe and Cr isotopes pass from spherical shapes at the new magic number N = 32 to very deformed shapes approaching N = 40 [9-11]. With two protons less than ^{68}Ni, the nucleus ^{66}Fe shows a well deformed prolate structure. This has been further confirmed by the measurement of the lifetime of the 2^+ state [12]. More recently, the energy of the 2^+ and 4^+ states have been measured in ^{64}Cr [11], the nucleus that seems to be the most deformed in the region, situated in the centre of the island of inversion at N~40.

To interpret the structure of these nuclei and its evolution, the best model to apply is the interacting shell model that allows to describe with good accuracy the spectroscopic properties. The problem here is the choice of the model space. Several studies have shown the inadequacy of the fp shell, and even the fpg model space to account for the development of collectivity in this mass region [9,10,13], In a recent publication [14] a new interaction has been developed that is able to reproduce very well the variety of shapes and collectivity in Cr, Fe and Ni isotopes around N=40. This is possible due to the large, appropriate model space chosen. In fact, as stated in ref. [15], the deformation can be accounted for by considering the pseudo-SU(3) plus quasi-SU(3) model spaces in different regions of the table of nuclides: The deformation can be generated by the interplay between the quadrupole force and the central field in the subspace consisting on the lowest $\Delta j = 2$ orbitals of a major shell. The new effective interaction, LNPS, is based on renormalized realistic interactions and monopole corrections in the model space consisting on the full pf shell for the protons and the $p_{3/2}$, $p_{1/2}$, $f_{5/2}$, $g_{9/2}$ and $d_{5/2}$ orbits for the neutrons [14]. It has been shown that only with the inclusion of both the neutron $g_{9/2}$ and $d_{5/2}$ orbits it is possible to obtain the correlations necessary for the development of the island of inversion around ^{64}Cr. In a forthcoming work, these results are compared with IBM-2 calculations and a very good agreement is found [16].

In Cr isotopes, the deformation develops already at N=38, while the Fe isotopes become well deformed at N=40. In both cases the deformation stabilizes al least up to N=42. While the excitation energy of the first 2^+ state in even-even nuclei can give a direct insight on the shape changes and the development of collectivity, this is not straightforward in odd and odd-odd mass isotopes. These constitute also a good test of the robustness of the interaction. In our experiments we have populated several Co isotopes, situated between the semi-magic Ni isotopes and the well deformed Fe nuclei. These isotopes follow a very regular behaviour at low excitation energy that can be interpreted in terms of a week coupling of the proton hole to the Ni core. Previously to the present investigation, a sudden development of deformation in ^{67}Co has been suggested in Ref. [16]. This was based on a beta-decay study where a $1/2^-$ state was observed at very low excitation energy. It was argued that such a state would be formed by exciting one proton from the $f_{7/2}$ orbital.

It is thus interesting to interpret the results in terms of the shell model. The experimental and theoretical energy levels of ^{67}Co are reported in Fig. 1. The structure based on the ground state is well described and can be interpreted in terms of the weak coupling with the states in ^{68}Ni. The excited structure on the left of the g.s. correspond to a well deformed band with an intrinsic configuration that confirms the two proton-hole character. The calculations are therefore able to describe at the same time both the spherical and well deformed configurations, a very challenging task for any theoretical model.

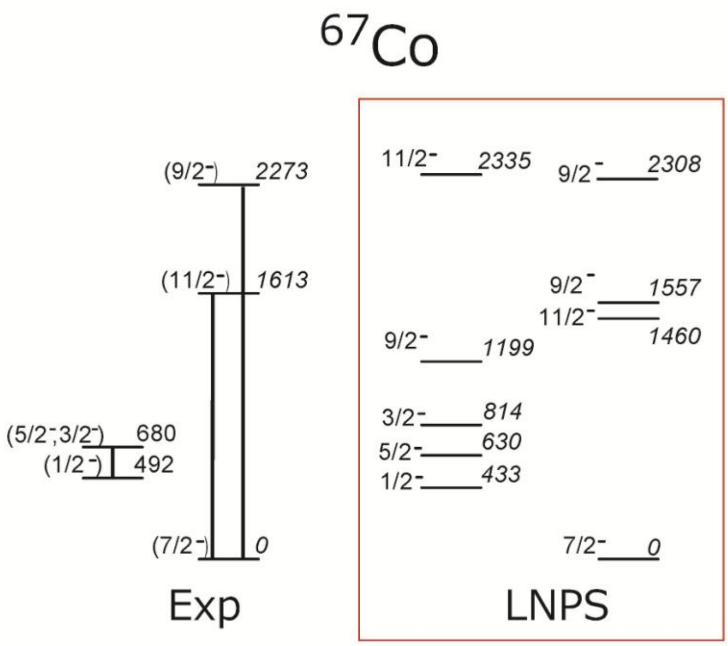

Figure 1. Experimental and theoretical levels in ^{67}Co from ref. [18].

More recently, several experiments with the tracking array AGATA have been performed at LNL. Many interesting results were obtained, in particular with lifetime measurements using the differential plunger method. Although these results are not yet published, it can be anticipated that shell model calculations using the LNPS interaction reproduce with good accuracy the transition probabilities in neutron-rich Co isotopes [19].

Another interesting region studied with AGATA is that of the neutron-rich Zn isotopes [20]. Here the protons occupy the $p_{3/2}$ shell while neutrons are filling the $g_{9/2}$ orbital. Also in this case the LNPS interaction can give a good description of the spectroscopy. In Fig. 2, the calculated excitation energy of the first 2^+ and 4^+ states are reported in comparison with the experimental data taken from the literature. The agreement is very good all along the isotopic chain.

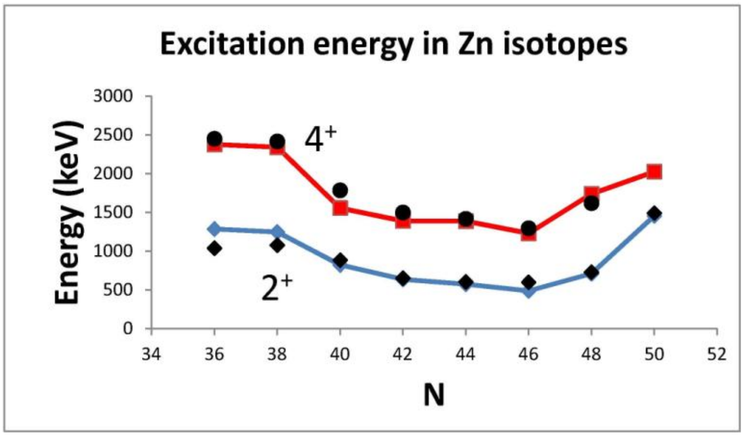

Figure 2. Excited states in Zn isotopes. Experimental values are shown with full circles and diamonds. Theoretical results are connected by coloured lines.

4. Conclusions

The development of deformation in the neutron-rich nuclei around N=40, Z<28, is a subject of current interest from both the experimental and the theoretical points of view. Data are being obtained by means of different experimental techniques. In this contribution some results recently obtained with the CLARA and AGATA gamma arrays coupled to the PRISMA magnetic spectrometer at LNL have been briefly discussed. In particular, it has been shown that ^{67}Co presents shape coexistence phenomena near the ground state. These different structures are very well reproduced by recent shell model calculations using the effective interaction LNPS [14]. A good description is also given for heavier nuclei such as the neutron-rich Zn isotopes.

Of course there are several experimental groups investigating this mass region, in particular in USA and in Japan, where the radioactive beams allow to explore regions farther than the valley of stability. This opens very exciting perspectives to our knowledge of the nuclear interaction.

Acknowledgments

I want to thank prof. T. Otsuka for the fruitful and friendly collaboration we have since many years and for the fundamental contributions he has given and continues giving to the field of nuclear structure research.

This contribution reports experimental results obtained in LNL and theoretical calculations done in collaboration with several colleagues. In particular I want to thank for the experimental part F. Recchia, S. Lunardi, V. Modamio and J.J. Valiente-Dobón. For the shell model developments I am very grateful to F. Nowacki, A. Poves and K. Sieja.

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