Structure of neutron-rich nuclei near N=40

Silvia M Lenzi
Dipartimento di Fisica dell’Università and INFN, Sezione di Padova, Padova, Italy
Email: lenzi@pd.infn.it

Abstract. Recent experimental results obtained for neutron-rich nuclei of mass A~60-70 at LNL are presented together with the shell model interpretation. The development of a new region of deformation approaching the neutron number N = 40 in Cr, Fe and Co isotopes is discussed. A new effective interaction (LNPS) that considers the full fp shell model space for protons and the $p_{3/2}$, $p_{1/2}$, $f_{5/2}$, $g_{9/2}$, $d_{5/2}$ orbitals for the neutrons allows to reproduce, for the first time, the different structure properties of these nuclei. The configurations of the calculated states suggest the development of a new island of inversion at N ~ 40.

1. Introduction
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 indications that the traditional magic numbers of the shell structure near stability are not always preserved in this region of the table of isotopes, 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 gives the main contribution to the shell evolution [2].

Among other interesting phenomena recently observed far from stability, the development of deformation in neutron-rich nuclei at N=20 has been observed. This mass region, is known as the Island of Inversion because the ground-state wave functions are dominated by intruder configurations, while “natural” states (0$\hbar\omega$ excitations) lie higher in energy (Fig. 1 in ref. [5]). Recent experimental and theoretical studies have suggested that neutron-rich Chromium and Iron isotopes around N=40 would lie in a new Island of Inversion. In this case, the deformation is produced by the erosion of the harmonic oscillator gap at N=40 and the quadrupole correlations induced by the excitation of neutrons from the pf shell to both the $g_{9/2}$ and $d_{5/2}$ orbitals of the upper main shell [3]. These latter two orbitals form a quasi-SU3 space able to generate quadrupole collectivity, as discussed in Ref. [6].

In this work we present recent data on neutron-rich even-even Cr and Fe isotopes and odd-mass Co isotopes, obtained in the Legnaro National Laboratories using the CLARA-PRISMA detector complex. Data are compared to recent shell model calculations obtained by diagonalizing the new effective interaction LNPS [7]. The adopted shell model space is the pf shell for protons and the $f_{5/2}$ $p_{3/2}$ $p_{1/2}$ $g_{9/2}$ $d_{5/2}$ for neutrons. This interaction is able to describe both collective and single-particle behavior near N=40 and to follow the rapid evolution of the nuclear structure along the isotopic and isotonic chains.
In Sect. 2 we present the experimental method and the data. Sect. 3 is devoted to the discussion of the results. Conclusions are given in Sect. 4.

2. Experimental method and results

The knowledge of excited states in neutron-rich isotopes is rather limited due to the difficulties in the production and identification of isotopes by conventional means. In recent years, 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, has increased substantially the amount of information on the structure of previously inaccessible nuclei far from stability.

To identify online a gamma-ray emitter produced through direct or deep-inelastic reactions, it is necessary to use sophisticated instruments, especially if dealing with reaction channels that have relatively low cross section and a broad velocity distribution. In the last years different high-efficiency gamma-ray detector systems have been used in combination with ancillary detectors of increasing complexity. A research program on nuclear structure of slightly neutron-rich nuclei has been carried out at LNL with the gamma-ray array CLARA [8], coupled to the magnetic spectrometer PRISMA [9] to study the gamma decay of excited nuclei populated by multi-nucleon transfer and deep-inelastic collisions [10-13].

![Figure 1](image_url)

**Figure 1.** Mass spectrum for Fe and Co isotopes obtained with the reaction $^{70}\text{Zn}^+{^{238}}\text{U}$ (upper panels) and $^{64}\text{Ni}^+{^{238}}\text{U}$ (lower panels).

Neutron-rich nuclei in the mass region A~60-70 were produced in two experiments at the Tandem-ALPI accelerator complex of LNL. In the first experiment the beam was $^{64}\text{Ni}$ at 400 MeV bombarding energy and in the second one a $^{70}\text{Zn}$ beam was used. In both cases the target was a self supporting Uranium target, 400 $\mu$g/cm$^2$ thick. For each projectile-like ion detected in PRISMA, we determined the atomic number $Z$, the mass $A$, the initial direction of the ion flying away from the target and the absolute value of its velocity. The $\gamma$-rays following the de-excitation of the reaction products were detected with the CLARA array, placed in the hemisphere opposite to the PRISMA spectrometer, 29.5 cm from the target, uniformly covering the azimuthally angles from 98° to 180°. The Doppler correction for the photons in coincidence with the ions detected in PRISMA was performed on an event-by-event basis, using the recoil velocity vector obtained after trajectory reconstruction in the
spectrometer. The \(\gamma\)-ray energy resolution obtained was 0.8% FWHM over the whole broad velocity distribution of the projectile-like products, ranging from 4.5% to 10% of the speed of light. In several cases it was possible to observe gamma lines in nuclei where no excited states were known. In the most exotic nuclei produced, the statistics was not enough to allow a \(\gamma\)-\(\gamma\) coincidence analysis. In this type of reactions, the population of yrast states is favored. Based on this assumption, the level schemes of the neutron-rich isotopes were proposed taking into account the relative yields and the systematic of neighboring nuclei. A complementary method that produces higher statistics is to use the same type of reaction but with a much thicker target (~50mg/cm\(^2\)) and a very high efficiency \(\gamma\) array. The knowledge of some \(\gamma\) lines in a nucleus allows \(\gamma\)-\(\gamma\)-\(\gamma\) coincidence analysis and therefore the construction of the level scheme on a more solid basis [14].

In the first experiment reported in this paper, neutron-rich isotopes of V [13], Cr [10], Mn [12] and Fe [11] were produced with good statistics, allowing to follow the evolution of the nuclear structure along the isotopic chains. The second experiment was due to the study of the heavier Fe, Co and Ni isotopes [15]. The relative yields observed in both cases for Fe and Co isotopes can be seen in figure 1.

A rapid change of structure is observed in Cr and Fe isotopes. The nucleus \(^{56}\)Cr behaves as a semimagic nucleus with the new shell closure at \(N=32\). \(^{58}\)Cr shows the characteristic excitation-energy sequence of a critical point of the E(5) shape-phase transition from spherical to \(\gamma\)-unstable, while \(^{60}\)Cr [10,14] shows a level scheme consistent with a deformed nucleus. A rapid shape evolution is also observed in Fe isotopes, as reported in Ref. [11]. For the case of \(^{60}\)Fe, only one excited level was observed in the first experiment, but in the second one three \(\gamma\) lines were observed, which were interpreted as the cascade from the \(6^+\) to the ground state. In addition the transition from the first \(2^+\) state in \(^{68}\)Fe (\(N=42\)) was observed. Both spectra are reported in figure 2.

![Figure 2](image_url) - Spectra of \(^{66,68}\)Fe isotopes obtained with the multinucleon transfer reaction \(^{70}\)Zn+\(^{238}\)U at 460 MeV bombarding energy with the CLARA + PRISMA experimental setup at LNL.

Cobalt isotopes were also populated in the reaction. Yrast transitions were observed for the first time in the \(N=40\) \(^{65}\)Co. Spectra corresponding to the decay of \(^{65,67}\)Co are reported in figure 3. The transition of 2273 keV in \(^{67}\)Co is interpreted as the decay to the ground state from the second excited state. Such a high energy transition is only observed in this isotope. This state is interpreted as resulting from the coupling of the proton hole to the \(2^+\) state in \(^{68}\)Ni [16]. A \(\gamma\) line of 190 keV, feeding an intruder \(J^p=1/2^-\) state at 491 keV was also observed. This state is very interesting as it corresponds to the excitation of a proton across the \(Z=28\) gap.
3. Shell model description and discussion

The variety of the structure and its rapid evolution along the isotopic and isotonic chains when approaching $N=40$ is a challenge for any nuclear model, and in particular for the shell model. In fact, such a description implies to consider a wide shell model space and the development of an effective interaction that involves more than one main shell. While Cr isotopes up to $N=34$ can be very well described within the fp shell, neutron-rich Fe isotopes up to $N=36$ need the inclusion of the $g_{9/2}$ neutron orbital in the model space ($^{48}$Ca core) \[12\]. This latter model space is also good enough to account for the spectroscopy of moderately neutron-rich Co and Mn \[14\] isotopes. However, when approaching $N=40$ these fp calculations fail to describe the structure of neutron-rich nuclei, in particular, $^{60-64}$Cr \[10\] and $^{66-68}$Fe \[11,19\].

It has been pointed out that to reproduce the quadrupole collectivity in this mass region, the inclusion of the neutron $d_{5/2}$ orbital is needed \[3\]. This can be explained in terms of the quasi-SU3 approximate symmetry: 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 \[6\]. Recently, a new interaction for this model space (LNPS) has been developed that can reproduce the different phenomena suggested by the available data in this mass region \[5\]. The LNPS interaction has been obtained by adapting a realistic CD-Bonn potential to this model space after many-body

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Figure 3. Spectra of Co isotopes: $^{63}$Co (upper panel), $^{65}$Co (central panel) and $^{67}$Co in the lower panel \[16\].
perturbation techniques [20] and monopole modifications. The quality of the results of shell model calculations with the new LNPS interaction for the neutron rich isotopes of Cr and Fe can be appreciated in figure 4. In particular, large transition probabilities are predicted for Cr and Fe isotopes, consistent with the development of a new region of deformation at N≈40. Moreover, the configuration of the wave functions of the ground states indicates the development of a new island of inversion in this mass region, similar to that observed already in Na and Mg nuclei at N=20.

The B(E2) values reported in the lower panel of figure 4, show a sudden increase in Cr isotopes at N=38 that remains almost stable up to N=42. For the case of Fe isotopes, the increase of collectivity continues increasing and reaches its maximum at N=42. For Cr isotopes, no experimental information on transition probabilities are yet available. For $^{62,64}$Fe, on the other hand, recent data has been obtained in multi-nucleon transfer reactions at GANIL [21]. At MSU, lifetimes have been measured in $^{62-66}$Fe, produced after knock-out reactions [22]. The present theoretical predictions are in good agreement with the experimental findings.

The new effective interaction can describe these collective properties as well as single-particle behavior, including shape coexistence near Z=28. This is observed for the case of Co isotopes. The yrast structure is not collective while, as stated above, for the case of $^{67}$Co, a 1/2$^-$ state, that results from the excitation of a proton from the $f_{7/2}$ to the $p_{3/2}$, comes down in energy to 491 keV [17]. This is possible due to the quadrupole correlations generated in the excitation of neutrons to the $g_{9/2}$ and $d_{5/2}$ across N=40. The shell model can reproduce this shape coexistence in $^{67}$Co [7,16].

![Figure 4](image-url)  
**Figure 4.** Excitation energy of the first 2$^+$ state (upper panel). Full lines connect the experimental values, open symbols connected with dashed lines correspond to the theoretical calculations with the LNPS effective interaction. In the lower panel, the calculated transition probabilities for the decay to the ground state are reported.

4. Conclusions

The development of deformation in the neutron-rich nuclei around N=40 for 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 particular, data on neutron-rich Fe and Co isotopes recently obtained with the CLARA-PRISMA setup at LNL have been presented and discussed here. Such a degree of collectivity is very well reproduced by recent shell model calculations in a model space that includes the pf shell for protons and the $f_{5/2}$, $p_{3/2}$, $g_{9/2}$, $d_{5/2}$ for neutrons. The new effective interaction for this space, LNPS [7], is able to reproduce the rapid changes of structure in this mass region, together with the phenomena of shape coexistence.

With the AGATA Demonstrator coupled to the PRISMA magnetic spectrometer at LNL, experiments due to measure the lifetimes in these nuclei are in progress. This will allow to have a
better understanding on the nuclear structure properties of these nuclei and will test the new effective interaction LNPS developed for this mass region.

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