Exploring the changing of shell structure of nuclei at N=50

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One of the most critical ingredient in determining the properties of a nucleus from a given effective interaction, is the overall number of nucleons and the ratio N/Z of neutrons to protons. One aspect which is presently strongly discussed concerns the modification of the average field experienced by a single nucleon due to the changes in size and diffusivity for nuclei with strong neutron excess [1]. For large neutron excess the softening of the Woods-Saxon shape of the neutron potential is expected to cause a reduction of the spinorbit interaction and therefore a migration of the high-l orbitals with a large impact on the shell structure of nuclei far from stability [2]. A different scenario has been recently suggested where the evolution of the shell structure in going from stable to exotic nuclei can be related to the effect of the tensor part of the nucleonnucleon interaction [3]. The tensor-force, one of the most direct manifestation of the meson exchange origin of the nucleon-nucleon interaction, is responsible of the strong attraction between a proton and a neutron in the spin-flip partner orbits. A recent generalization of such mechanism foresees a similar behavior also for orbitals with non identical orbital angular momenta. It is expected an attraction for orbitals with antiparallel spin configuration and a repulsion for orbitals with parallel spin configuration [4]. In most of the cases one is dealing with a combined effect of the attraction among orbitals with antiparallel spins and repulsion between orbitals with parallel spins. The change of the shell structure based on such mechanism has been recently discussed in different mass regions [4,5] of the nuclear chart. In such contest neutron-rich nuclei close to shell gaps are particularly interesting since, when compared with the shell-model prediction, they allow to search for anomalies into the shell structure [5]. It is predicted, for example, that the Z=28 gap for protons in the pf-shell becomes smaller moving from 68Ni to 78Ni as consequence of the attraction between the proton $f_{5/2}$ and

neutron $g_{9/2}$ orbits and the repulsion between the proton $f_{7/2}$ and the neutron $g_{9/2}$ configurations.



Fig. 1. Mass spectra from the PRISMA spectrometer obtained for the different elements produced in the 82 Se + 238 U reaction.

The same argument also predicts a weakening of the N=50 shell gap when approaching the 78 Ni nucleus due to the attraction between the neutron $g_{9/2}$ and $d_{5/2}$ configurations with the proton $f_{5/2}$ state and the repulsion between the neutron $g_{7/2}$ with the proton $f_{5/2}$ state. Properties inconsistent with shell closure have been found in several neutron-rich systems around shellmodel magic numbers-(see reference [6] and references therein).

Here we report on an experimental study of the excited structures of the neutron-rich N=50 and 51 isotones. New experimental information has been obtained on a wide range of nuclei close to the N=50 shell closure by means of multi-nucleon transfer and deep-inelastic collisions. The reaction mechanism allows the population of medium and high-spin yrast states. The systematic of the N = 51 single-neutron states, extended down to Z=34, can be used to test the predictions of the shell evolution based on the effects of the tensor interaction as well as of the different effective interactions.

Excited states of previously unknown isotopes have been identified using the CLARA γ -detector array [7] in coincidence with the PRISMA spectrometer [8]. The N \approx 50 nuclei have been populated using the reaction ⁸²Se + ²³⁸U. The combination of the Tandem-XTU and the superconductive LINAC ALPI accelerators at the Laboratori Nazionali di Legnaro, Italy, was used to accelerate a beam of ⁸²Se ions at an energy of 505 MeV. The target, isotopically enriched, was of a thickness of 400 µg/cm2. Projectile-like nuclei, produced following multinucleon transfer, were detected by the PRISMA spectrometer [8,9,10], placed at an angle of 64° , covering an angular region around the grazing angle of the reaction. PRISMA is a magnetic spectrometer of large acceptance (\approx 80 msr) with an energy acceptance of $\pm 20\%$, consisting of a quadrupole singlet followed by a dipole magnet. The position of the incoming ions entering the spectrometer were measured using a position sensitive MCP detector placed at 25 cm from the target. After the magnetic elements, the position of the ions were determined again at the focal plane of the spectrometer using a 10 elements, 100 cm long, multiwire PPAC detector. Finally the ions were stopped in a 10×4 elements ionization chamber measuring the time of flight (TOF). Such information allows а reconstruction of the trajectories, the identification of the atomic number Z, of the mass A and of the absolute value of the velocity. The mass resolution obtained in the present experiment, shown in fig.1, is of about 1/180, allowing a good identification of all isotopes.

Gamma rays following the de-excitation of the reaction products were detected by the CLARA array [7] consisting of 25 clovers detectors, placed in the hemisphere opposite to the entrance of the spectrometer, 29.5 cm far from the target position, covering the azimuthal angles from 98° to 180° . The Doppler correction for γ -rays detected in coincidence with the projectile-like ions was performed on an event-by-event basis, using the information of the recoil-velocity vector determined by the reconstruction of the ion trajectories. The energy resolution obtained for the γ -rays was of 0.8% FWHM over the whole range of velocities, ranging from 4.5% to 10% of the velocity of the light. The γ -ray spectra observed after selection on mass and charge for the N=50 ⁸¹Ga, ⁸²Ge and ⁸³As isotones are shown in fig.2. Similar spectra have been obtained for the N=51 ⁸⁵Se and ⁸⁷Kr nuclei.

Within the shell-model, the description of the nuclear mean field is conventionally obtained by considering the so-called monopole Hamiltonian constructed from the centroids of the two-body interaction. The eigenvalues of this Hamiltonian, usually referred as effective single particle energies, provide the average energies of the specific spherical configurations. They should reproduce the energies of single-proton or single-neutron states in odd-A nuclei with Z or N equal to a magic number plus or minus one proton or one neutron.



Fig.2: Gamma-ray spectra of the $N=50^{-81}Ga$, ^{82}Ge and ^{83}As nuclei after mass and charge identification through the PRISMA spectrometer. The γ -rays assigned to the selected N=50 isotones are indicated in the spectra.

The nucleon-nucleon residual interaction, and in particular the tensor force part, changes the spherical single-particle energies through the nuclear chart. As reported in Ref. [4,5] the monopole effect of the tensor force shifts systematically the single-particle levels as protons and neutrons fill certain orbits, the protonneutron part being the dominant. It is interesting to mention here the good agreement obtained between the energy of the newly identified excited states of the N=50 isotones ⁸¹Ga and ⁸²Ge and the predicted values of the shell-model calculation using a recently developed new effective interaction [11] which implicitly takes into account the core-polarization contributions of the ⁷⁸Ni core. As an example, using such interaction the excitation energy of the 9/2⁻ level of the ⁸¹Ga nucleus is calculated to be 1374 keV above the 5/2 g.s., in very good agreement with the measured value of 1236 keV.

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