RECENT RESULTS ON NEUTRON-RICH NUCLEI SPECTROSCOPY WITH THE CLARA–PRISMA SETUP*

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(Received January 29, 2007)

The CLARA–PRISMA setup consisting of the array of Euroball Clover detectors CLARA, coupled to the LNL large acceptance magnetic spectrometer PRISMA, has been successfully working since spring 2004. Recently, new developments such as the ancillary device DANTE and the use of the differential plunger technique has improved the capabilities of the setup. Results of experiments studying the structure of neutron-rich nuclei together with the preliminary results on the commissioning of the ancillary detector array DANTE and of the plunger technique will be presented.

PACS numbers: 29.30.Kv, 23.20.Lv, 29.40.Wk, 29.30.–h

* Presented at the Zakopane Conference on Nuclear Physics, September 4–10, 2006, Zakopane, Poland.

1. Introduction

High-resolution spectroscopy of neutron-rich nuclear species plays a major role on the understanding of the nuclear structure at large isospin values. Among the open questions are of special interest; the evolution of the nuclear effective interactions in the monopole and multipole terms, the quenching of the known shell gaps and development of new ones, the evolutions of the nuclear collectivity, the shape phase transitions as the dynamical symmetries at the critical point and the onset of exotic shapes. These experimental open questions can be studied by exploring the nuclear spectrum up to medium-high angular momentum and by direct measurement of transition probabilities. Multinucleon-transfer reactions and deep-inelastic collisions have been successfully used in the last two decades to study the structure of nuclei far from stability in the neutron-rich side of the nuclear chart. The interest in studying phenomena only present in nuclei very far from stability, especially in neutron-rich medium mass or heavy nuclei, has led to the necessity of new techniques to assign the γ-transitions to the corresponding reaction product. In a joint effort, gamma spectroscopy and reaction mechanisms groups from INFN, in collaboration with several European institutes, have developed a new setup by coupling the array of Euroball Clover detectors CLARA [1] to the LNL large acceptance magnetic spectrometer PRISMA [2]. This setup is a step forward in the use of the multi-nucleon transfer and deep-inelastic collisions in gamma spectroscopy, and aims at measuring in-beam prompt coincidences of γ-rays detected with CLARA and the reaction product seen by PRISMA. The setup allows in most cases to assign univocally the transitions belonging to a particular nucleus by identifying the mass (A) and atomic (Z) numbers of the product detected by PRISMA. Instruments such as CLARA–PRISMA will lower the sensitivity limit in spectroscopic measurements based on grazing reactions, and allow to study excited states of nuclei away from stability produced with low cross sections. A consistent fraction of the experimental activity is connected to the study of the evolution of the magic numbers in neutron-rich nuclei, as well as to the study of non-yrast states populated in quasi-elastic reactions. In this contribution we will describe the results of the measurement performed with a multinucleon transfer reaction populating nuclei in the region with $N \approx 50$, focusing on the evolution of the nuclear structure at the $N = 50$ shell closure. The ancillary MCP detector array DANTE and the feasibility of lifetime measurement with the CLARA–PRISMA setup, by using the differential RDDS technique, will also be discussed.

2. Evolution of the shell structure in neutron-rich nuclei with CLARA–PRISMA

One of the most critical ingredients for 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 [3–6]. For large neutron excess the softening of the Woods–Saxon shape of the neutron potential is expected to cause a reduction of the spin–orbit interaction and therefore a migration of the high-l orbitals with a large impact on the shell structure of nuclei far from stability [7–9]. 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 nucleon–nucleon interaction. The tensor-force, one of the most direct manifestations 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. Very recently, such a mechanism has been extended to orbitals with non-identical orbital angular momentum [10, 11]. In this context, it is expected that orbitals with antiparallel spin configuration attract each other whereas orbitals with parallel spin configuration repel each other. In most of the cases both configurations coexist, leading to a competition between the attraction among orbitals with anti-parallel spins and repulsion between orbitals with parallel spins. Those effects become particularly visible when moving away from the valley of stability. In such cases removing nucleons from one of the spin-orbit partners significantly modifies the proton-neutron interaction, which in turn, affects the effective single-particle energies, hence the shell structure. Experimental studies in $N \approx 50$ nuclei had been carried out to investigate the possible impact of the new phenomena in the structure of the region.

2.1. Investigation of the stability of the $N = 50$ shell gap

Neutron-rich $N = 50$ nuclei have been produced using a multi-nucleon transfer reaction with a ^{82}Se beam at an energy of 505 MeV, delivered by Tandem-ALPI accelerator complex of the Laboratori Nazionali di Legnaro (LNL). A neutron-rich heavy reaction partner is necessary to reach nuclei far from stability, in this case it has been used a $^{238}UO_2$ 400 μg/cm^2 target.

Projectile-like nuclei, produced following the multi-nucleon transfer reaction, were detected by the PRISMA spectrometer placed at an angle of 64°, covering an angular region of ±6° around the grazing angle of the reaction. The reconstruction of the trajectories of the ions has allowed the identification of the atomic number Z, the mass A and the absolute value of the velocity. The mass resolution obtained in the present experiment was $\approx 1/190$, well above the resolution necessary to obtained a good identification of all beam-like products. Almost every ^{238}U-like product, from transfer processes, was undergoing fission. In such a reaction more than 100 nuclei have been observed with PRISMA in coincidence with γ-rays detected in CLARA. 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 from the reconstruction of the ion trajectories. The range of velocities (v/c) of the projectile-like ions was ranging from 4.5% to 10%. The energy resolution obtained for the γ-rays, detected with CLARA, was of the order of 0.8% FWHM.

For the construction of the level schemes as well as for the spin and parity assignment we have assumed that the population is mainly yrast and used, where possible, γ-coincidence data obtained in this experiment and in a second one performed at the GASP detector array [12]. Level schemes, for some even and odd $N = 50$ isotones, are shown in Fig. 1.

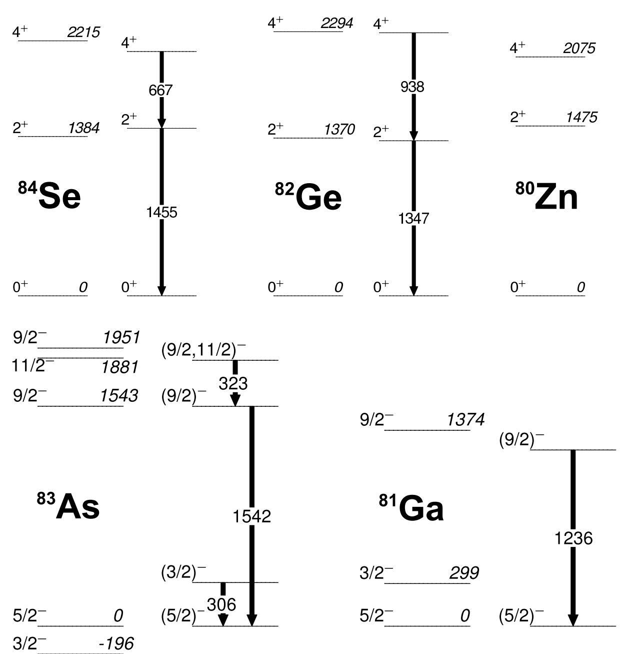

Fig. 1. Experimental level schemes and shell-model calculations, performed with the OXBASH shell-model code [13] and the interaction described in Ref. [14], for the even mass (upper panel) and odd mass (lower panel) $N = 50$ isotones. For the unobserved ^{80}Zn nucleus only shell-model calculation are shown.

Shell model calculations, performed with OXBASH [13] and a new version of the effective interaction reported in Ref. [14], is also shown for each one of the experimental level schemes as well as for the unobserved two-proton valence nucleus ^{80}Zn. It is interesting to notice the good agreement obtained between the newly identified excited states of the $N = 50$ isotones, and the shell-model calculation. Regarding the most exotic nuclei populated in this reaction, using aforementioned interaction, the excitation energy of the $9/2^-$ level of the ^{81}Ga nucleus is calculated to be at 1374 keV above the $5/2^-$g.s., close to the measured value of 1236 keV. The interaction used for the shell-model calculations consider the contribution of the core polarization in the vicinity of ^{78}Ni, taken into account in the evolution of the monopole component of the interaction. The overall good agreement found between the shell-model calculations and the experiment indicates that for $N = 50$ isotones, at least down-to ^{81}Ga, there is no evidence of a substantial reduction of the $N = 50$ shell gap.

3. Commissioning of the ancillary detector array DANTE

DANTE is a heavy-ion position-sensitive ancillary array, based on Micro-Channel Plates detectors of the CORSET [15] type, suited to be installed in the reaction chamber of the CLARA-PRISMA setup. The main characteristics are its position resolution of 1 mm while the time resolution is measured to be ≈ 130 ps. A more complete description of the detector and its performance can be found in Ref. [16]. DANTE allows to measure γ-γ coincidences, for the events outside the acceptance of PRISMA, with a Doppler correction done using the position given by the detectors of DANTE and a velocity estimated by using the binary kinematics of the reaction leading to the product of interest. The in-beam performance has been assessed in commissioning and test experiments. It has been observed that the energy resolution after Doppler correction, where the velocities have been calculated taking into account the kinematics of the reaction is of the order of 1.3%. Fig. 2. shows the schematic and reconstructed image of DANTE, and a gated spectra of the inelastic reaction channel. The reaction used was ^{64}Ni beam at 400 MeV energy impinging on a ^{238}U target.

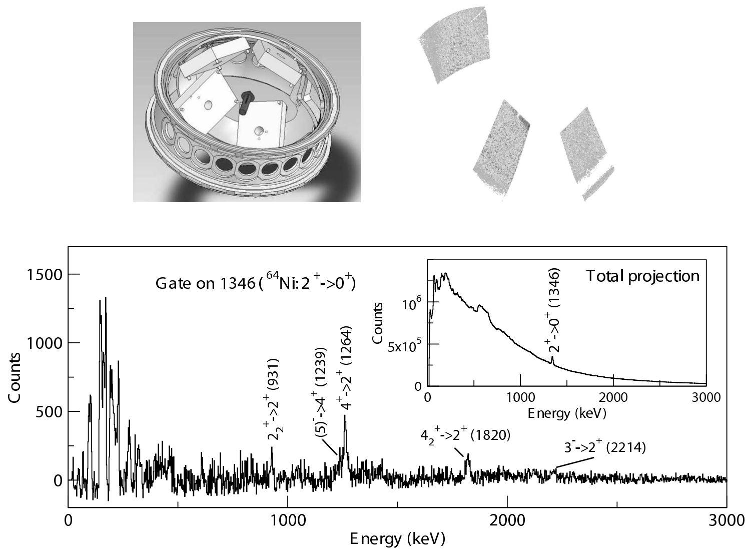

Fig. 2. The upper panel shows the scheme of DANTE in the 58° configuration and the reconstruction of three detectors from this configuration build by identifying the position where the heavy ions impinged into the detector. The lower panel shows the γ-γ gated spectrum from the inelastic channel. The insert shows the total projection, where it can be noticed the large background coming from the fission of the target-like products. The reaction used was ^{64}Ni at 400 MeV energy on a ^{238}U target.

4. New development of the lifetime measurements with the RDDS technique at the CLARA–PRISMA setup

The direct measurement of transition lifetimes, in neutron-rich nuclei, following a multinucleon transfer or deep-inelastic collision, can provide spectroscopic information at the moment only reachable in radioactive beam facilities with Coulomb excitation experiments at low and relativistic energies. During the first quarter of 2006 the prototypes of a plunger-target device (see Fig. 3) were developed at the IKP Cologne, and before summer 2006 a commissioning experiment, to check the technique, was performed at the CLARA–PRISMA setup, using the reaction ^{64}Ni (400 MeV) + ^{208}Pb. The target was 1 mg/cm^2 of ^{208}Pb on a 1 mg/cm^2 ^{93}Nb backing. The backing was fundamental to allow stretching the target foil. The degrader of the differential plunger was made of a ^{24}Mg foil with a thickness of 2 mg/cm^2. In order to cover from 1–10 ps lifetime range, various fixed distances, ranging from 30 μm to 300 μm were required. The commissioning was finally done with a limited beam intensity and about 1 day of beam-time and therefore, it was only possible to measure at one distance, 150 μm between target and degrader. Since the CLARA detectors positioned close to 90° can not be used with the RDDS technique, the efficiency of the CLARA, excluding such detectors, amounts to about 1%. One of the main goals of the commissioning was to determine the capability to identify the masses in PRISMA after the energy losses and straggling of the products in the target and degrader. The mass resolution measured with PRISMA was $\approx 1/130$, more than enough to identify all reaction products. In Fig. 3 the RDDS γ-ray spectra obtained after gating at different velocity ranges is shown.

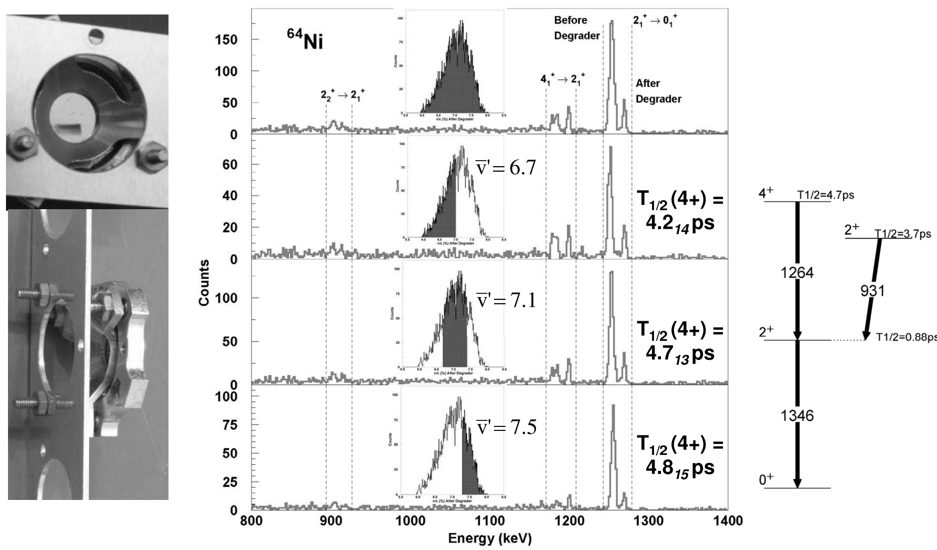

Fig. 3. The left panel shows a picture of the target-plunger device developed at IKP-Universität zu Köln. The right panel shows the RDDS spectra for 150 μm for the inelastic channel of ^{64}Ni with different conditions on the velocity (and therefore energy) of the recoil.

One of the limitations of the RDDS method is the determination of the side feeding of an excited level after the reaction. If the parameters describing the feeding are not well determined, one can get unrealistic lifetimes. The RDDS method coupled to a magnetic spectrometer might solve this problem since it is possible to gate at different recoil energies and look at the different feeding intensities of the excited states. As can be seen in Fig. 3, the relative intensities of the gamma rays coming from the de-excitation of the states in ^{64}Ni depends on the velocity range (Q-value) selected from the recoils. In Fig. 4 it is shown the in beam spectrum measured for ^{60}Fe produced in the two-proton pickup two-neutron-stripping channel, with the 150 μm target degrader distance. Despite the limited number of counts, it was possible to determine an effective lifetime of 8.2(15) ps for the 824 keV ($2^+ \longrightarrow 0^+$) transition, in complete agreement with the previous measurement of 8.0(15) ps with the DSA technique [17].

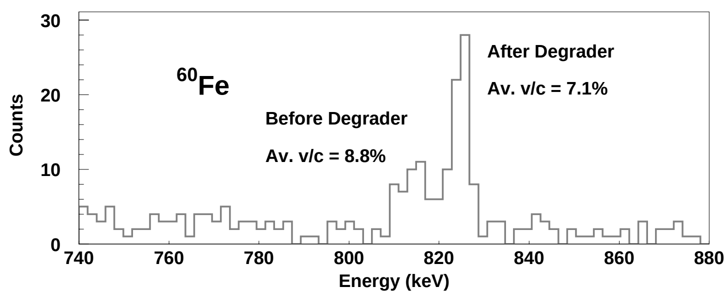

Fig. 4. Excerpt of spectrum corresponding to the 824 keV ($2^+ \longrightarrow 0^+$) transition in ^{60}Fe, measured at the CLARA–PRISMA RDDS setup with the ^{64}Ni (400 MeV) + ^{208}Pb reaction. The two components with different average velocities are indicated.

In conclusion, the CLARA–PRISMa setup, with the beams delivered by the Tandem-ALPI complex of the LNL, has been successfully used to study the nuclear structure in several neutron-rich regions of the nuclides chart. During 2006 the setup has been improved withn the ancillary detector DANTE. The RDDS technique performed with a differential plunger target, developed in collaboration with the IKP-Universität zu Köln group, has been also commissioned in this period.

This work has been partially supported by the European Commission within the Sixth Framework Program through I3-EURONS (contract no. RII3-CT-2004-506065).

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