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Spectroscopic studies with the PRISMA-CLARA set-up

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Abstract. The large solid angle magnetic spectrometer for heavy ions PRISMA, installed at Laboratori Nazionali di Legnaro (LNL), was operated up to the end of March 2008 in conjunction with the highly efficient CLARA set-up. It allowed to carry out nuclear structure and reaction mechanism studies in several mass regions of the nuclide chart. Results obtained in the vicinity of the island of inversion and for the heavy iron and chromium isotopes are presented in this contribution. The status of the new focal plane detectors specifically designed for light ions and slow moving heavy ions is also reported.

1. Introduction

Multinucleon transfer between heavy ions is a suitable mechanism to populate moderately neutron-rich nuclei making feasible the in-beam γ-spectroscopy of these nuclei. This process ranges from the quasi-elastic (i.e. few nucleon transfer and low total kinetic energy loss (TKEL)) to the deep- inelastic (i.e. many nucleon transfer and large TKEL) regime. In thick targets experiments, where one integrates the transfer flux over a broad range of angles and TKEL, γ-γ coincidences are routinely used to build the decay scheme of neutron-rich nuclei, as shown for instance in [1] and in subsequent experiments.

With the PRISMA-CLARA set-up one mainly exploits a regime closer to quasi-elastic processes [2], where a more selective identification of excited states can be obtained via γ-particle coincidences. By properly combining γ-γ coincidences in thick target experiments and γ-particle coincidence measurements performed with magnetic spectrometers (thin target experiments), weak γ transitions belonging to weakly populated transfer channels can be studied [3].

2. The PRISMA-CLARA set-up

PRISMA [4, 5, 6] is a large acceptance magnetic spectrometer designed to be used with heavy-ion beams accelerated at energies up to $E = 10A$ MeV by means of the Tandem/PIAVE-ALPI accelerator complex of LNL. Its optical design consists of a magnetic quadrupole followed by a 60° bending angle magnetic dipole (120 cm curvature radius). The spectrometer is equipped with position-sensitive entrance and focal plane detectors that allow the complete identification and trajectory reconstruction of the reaction products by using the Time of Flight (TOF) and ΔE-E techniques and the position information at the entrance and the focal plane, respectively. The relevant features of the spectrometer are a large solid angle (≈ 80 msr) and momentum acceptance ($\Delta p/p = \pm 10\%$), and a mass resolution up to $\Delta A/A \approx 1/200$. The entrance detector is based on large-area Micro-Channel Plates (MCP), mounted in a Chevron configuration [7], providing time and position signals. The Focal Plane Detector (FPD) is composed of a large area Multi-Wire Parallel Plate Avalanche Counter (MWPPAC) followed by a transverse field multi-anode Ionization Chamber (IC) at about 50 cm downstream [8]. The MWPPAC provides timing signals for both TOF measurements and Data Acquisition trigger, and position information. The IC has an active depth of about 120 cm and provides the energy (E) and the energy loss (ΔE) signals for the identification of the atomic number of the fragments with a Z resolving power $\Delta Z/Z \approx 1/60$ and an overall energy resolution $\Delta E/E \approx 1.5\%$.

CLARA [9] is an array of 25 Compton-suppressed Clover detectors. The Clovers are placed 29.5 cm from the target covering the azimuthal angles from 98° to 180°. The performance of CLARA for $E_\gamma = 1.3$ MeV are the following: photopeak efficiency ≈ 3%, peak/total ratio ≈ 45% and energy resolution ≈ 0.6% for $v/c = 10\%$. The latter value is obtained, despite the broad range of product velocities in typical multinucleon transfer reaction, thanks to the excellent event-by-event definition of the recoil velocity provided by PRISMA.

The operation of the large acceptance magnetic spectrometer PRISMA in conjunction with large γ arrays (such as CLARA or the AGATA Demonstrator) is the result of joint efforts between INFN groups involved in γ-spectroscopy and reaction mechanisms studies in collaboration with several European institutions. The experimental campaign of the PRISMA-CLARA set-up started in 2004 and has been completed at the end of March 2008 making use of about 50% of the total beam-time available at the Tandem/PIAVE-ALPI accelerator complex of LNL. Experiments were mainly addressed to obtain information on the shell evolution and the onset of new regions of deformation (collectivity, critical point symmetries) in medium-mass moderately neutron-rich nuclei.

3. Spectroscopic studies of neutron-rich nuclei

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. Changes in the density and the size of nuclei are expected for increasing N/Z ratios with the consequent modification of the average field experienced by a single nucleon. The orbital rearrangement in neutron-rich nuclei causes the breaking of shell gaps and the appearance of new magic numbers.

3.1. Around the island of inversion

In order to investigate the evolution of the $N = 20$ shell gap, neutron-rich nuclei in the region of the "island of inversion" were populated in deep-inelastic processes produced by bombarding a 300 μg/cm^2 ^{208}Pb target with a ^{36}S beam at $E_{\mathrm{lab}} = 215$ MeV. Projectile-like reaction products were identified by means of the PRISMA spectrometer, placed around the grazing angle corresponding to $\theta_g = 56°$, in coincidence with the de-excitation γ-rays detected in CLARA. A wide range of fragments, from Na ($Z = 11$) to Mn ($Z = 25$), were populated in this experiment. The γ-ray spectrum in coincidence with ^{36}Si is shown in figure 1. Three γ rays with energies of 1408, 1442 and 842 keV have been clearly observed. However, γ-γ coincidences were not possible because of the low statistics in such a weak channel. Consequently, the level scheme has been built revisiting data from a previous thick target deep-inelastic experiment which used the same projectile. By double gating on transitions that are observed for the first time in this experiment (1442 and 842 keV), the yrast sequence in ^{36}Si has been reconstructed for the first time up to the 6^+ state [10]. Useful information on the evolution of the shape (collectivity) has been extracted from the ratio *R*4/2 between the excitation energies of the 4^+ and 2^+ yrast states, shown in Fig. 2 for even-*A* Mg and Si isotopes with neutron numbers from 12 to 22. In particular, one can see that at $N = 22$, ^{34}Mg lies close to the rotational limit while ^{36}Si (having only two more protons) shows a nearly spherical shape behavior (vibrational limit), as confirmed by the *B*(E2) values predicted by shell model calculations.

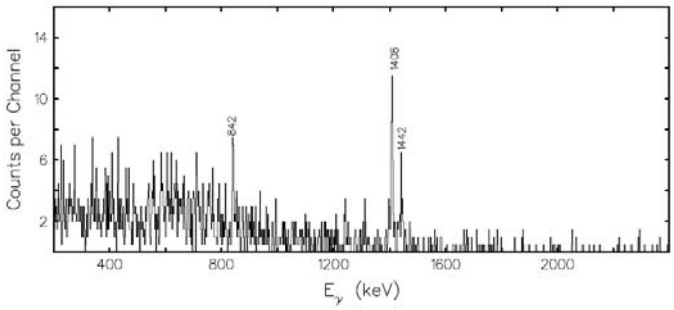

Figure 1. γ-ray spectrum measured with CLARA for ^{36}Si.

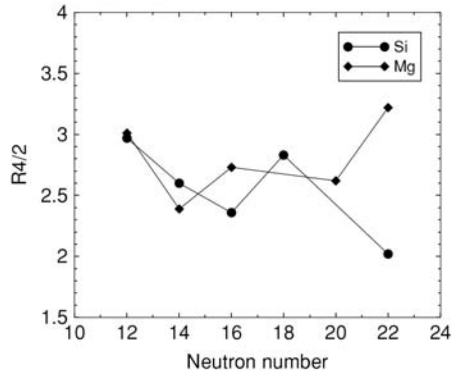

Figure 2. Systematics of the $E(4^+)$ to $E(2^+)$ ratio, *R*4/2, for Mg and Si isotopes from $N = 12$ to $N = 22$.

3.2. The onset of deformation in $A \sim 60$ neutron-rich nuclei

Besides inducing new shell and sub-shell closures, the neutron excess in nuclei can lead to the appearance of new regions of deformation through a spherical-to-deformed transition which has been interpreted as a shape phase transition. In this path, critical points (such as the *E*(5) and *X*(5) dynamical symmetries [11]), where nuclei have well-defined properties, could be encountered. Neutron-rich nuclei in the region of heavy Cr and Fe isotopes ($A \sim 60$) constitute an ideal ground for this kind of studies since their structure can be described by large-scale shell model calculations and they become deformed going towards $N = 40$. The experimental information on these nuclei, populated with the ^{64}Ni+^{238}U reaction at E_{lab} = 400 MeV, was significantly extended with the PRISMA/CLARA set-up. In particular, yrast states up to $I^\pi = 8^+$ have been observed for the first time in the neutron-rich nucleus ^{58}Cr. Based on γ-γ coincidences and considering that for all known even–even nuclei we observed mainly yrast transitions, we proposed for ^{58}Cr the level scheme shown in figure 3. The experimental values of the ratio *R*(4/2) between the excitation energies of the 4^+ and 2^+ yrast states for even-*A* chromium and iron isotopes are shown in figure 4. This ratio for the heavy Fe isotopes is very close to the 2.50 value characteristic of γ-soft rotors (*O*(6)). The ratios between the experimental energies of ^{58}Cr yrast states [12, 13] follow the expectations of the dynamical symmetry *E*(5) for a nucleus at the critical point of the shape phase transition from a spherical vibrator (*U*(5)) to a γ-soft rotor (*O*(6)). This dynamical symmetry predicts, in a parameter-free analytical way, the following energy ratios for a nucleus at the critical point: $E(4^+)/E(2^+) = 2.20$, $E(6^+)/E(2^+) = 3.59$, $E(8^+)/E(2^+) = 5.17$. The experimental values in ^{58}Cr are 2.20 (figure 4), 3.66 and 5.22, respectively.

A critical test to decide if a nucleus stands in the *E*(5) critical point is given by the *B*(E2) values normalized to $B(E2 : 2^+ \rightarrow 0^+)$. Although lifetimes in ^{58}Cr are not known, except the lifetime of the first 2^+ state, one can compare the *E*(5) predictions with the results of large-scale shell model calculations, which give normally a good agreement with the experiment in this region. All theoretical predictions agree quite well in the description of the transition probabilities for the yrast states giving a further hint for the realization of the *E*(5) critical point (a dynamical symmetry observed so far only in a few stable, heavier nuclei) in ^{58}Cr. Further challenging investigations devoted to the measurement of lifetimes in ^{58}Cr will provide the additional information to confirm the *E*(5) dynamical symmetry in this nucleus.

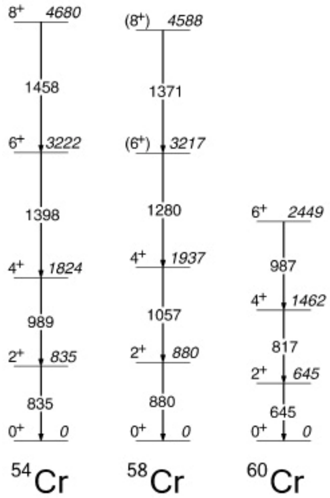

Figure 3. Level schemes of even-*A* heavy chromium isotopes.

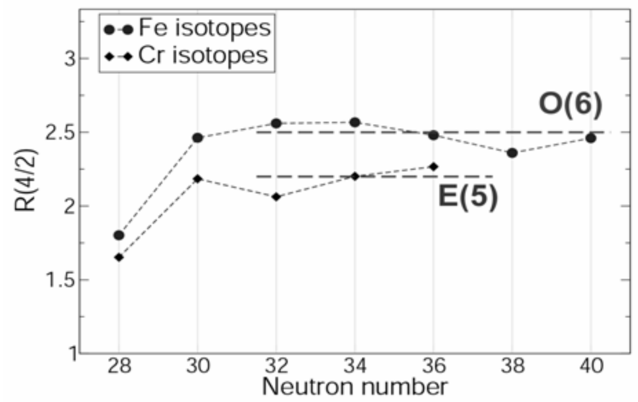

Figure 4. Systematics of $R(4/2)$ ratio in even-*A* Fe and Cr isotopes from $N = 28$ to $N = 40$.

3.3. The neutron-rich iron isotopes

In the ^{64}Ni(400 MeV)+^{238}U reaction it was possible to collect valuable information on the even-*A* neutron-rich iron isotopes up to ^{66}Fe. A second experiment was performed in order to enhance the population of heavy iron isotopes, using the ^{70}Zn(460 MeV)+^{238}U reaction [14]. The comparison of the γ-ray spectra for ^{66}Fe obtained in the two experiments, shown in figure 5, clearly proves that in the second measurement the production cross section for heavy iron isotopes was greatly enhanced.

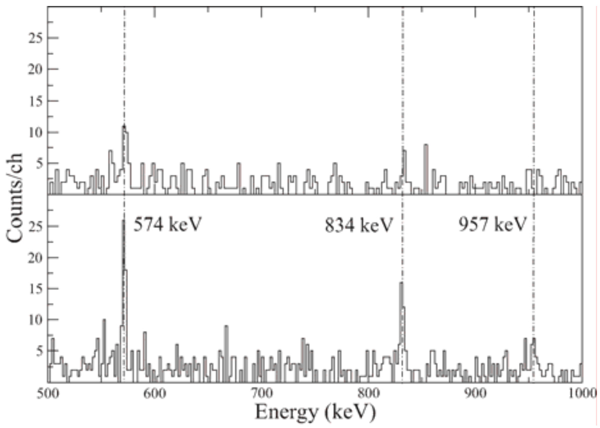

Figure 5. Spectra in coincidence with ^{66}Fe isotopes identified in PRISMA, respectively for the ^{64}Ni(400MeV)+^{238}U (top) and the ^{70}Zn(460MeV)+^{238}U reaction (bottom). In the former case, only the $2^+ \to 0^+$ ground-state transition (574 keV) was firmly assigned, while in the latter case also the $6^+ \to 4^+$ (957 keV) and the $4^+ \to 2^+$ (834 keV) transitions were identified, proving that the population of ^{66}Fe is enhanced.

The decay schemes for the even-*A* neutron-rich iron isotopes populated in this experiment is presented in figure 6 together with the result from large-scale shell model calculations. The effective interaction used is called *fpg* and is described in Ref. [15]. Its ingredients are an inert core of ^{48}Ca, with a valence space including the whole *fp* shell for the protons and the $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, and $g_{9/2}$ orbitals for the neutrons [16]. Suitable truncations were imposed to limit the dimensions of the matrices.

Iron isotopes evolve towards more collective structures when approaching $N = 40$. Inspection of figure 6 shows in fact that the excitation energy of the 2^+ state (usually considered a first fingerprint of nuclear collectivity) decreases with increasing neutron number in the even-*A* iron isotopes. In particular, at $N = 40$ (that for nickel isotopes acts as a sub-shell closure [17]), the drop in the 2^+ excitation energy is large, which suggests increasing collectivity. This can be understood in terms of a decrease of the energy gap between the *fp* shell and the intruder $g_{9/2}$ orbital when the $1f_{7/2}$ proton shell is not completely filled and more neutrons are occupying the upper shell [18]. The fact that the $f_{7/2}$

shell is not fully occupied weakens both the effect of the attractive monopole tensor interaction with the neutrons in the $f_{5/2}$ orbital and the repulsion with those in the neutron $g_{9/2}$ orbital.

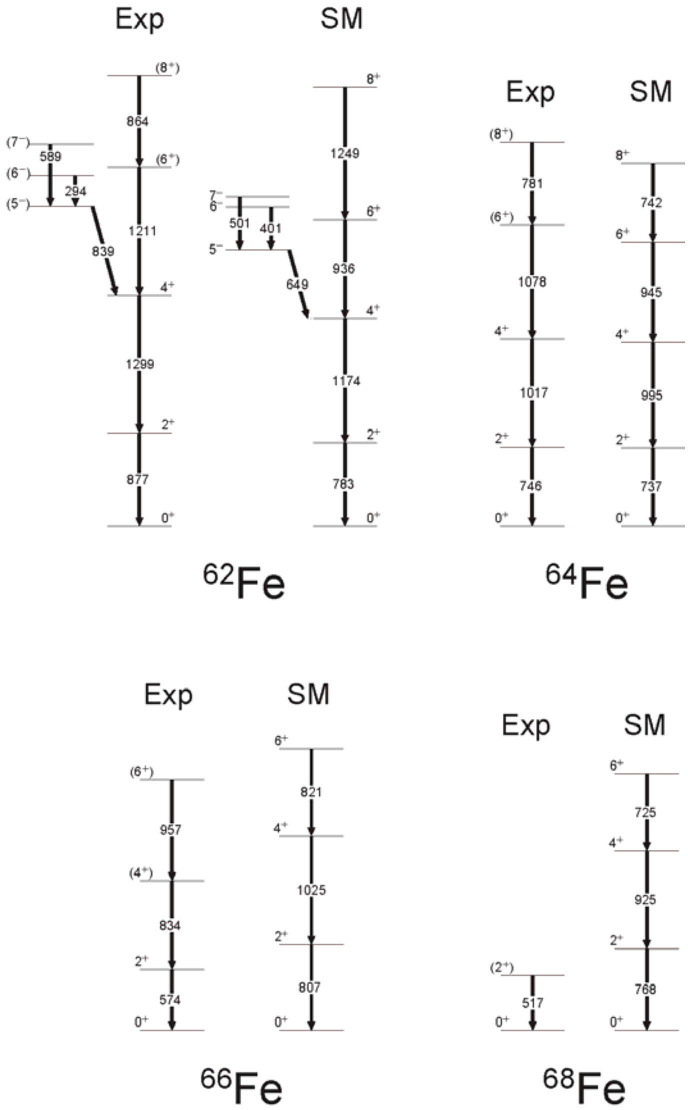

Figure 6. Decay schemes for the even-*A* iron isotopes ^{62,64,66,68}Fe obtained during the PRISMA-CLARA campaign, compared with the results from large-scale shell model calculations performed with a *fpg* interaction. See text for details.

The theoretical description of the even-*A* isotopes ^{62,64}Fe (figure 6) is quite satisfactory, although the calculated level schemes are more compressed than the experimental ones. Furthermore, in the case of ^{66}Fe, the excitation energy of the 2^+ state is predicted too high. The dramatic decrease of the energy of the 2^+ state in this nucleus suggests that the $d_{5/2}$ orbital has to be considered as well, as suggested in Ref. [16].

4. Ongoing developments

4.1. Parallel Plate Avalanche Counter for light ions

The MWPPAC, presently installed at the focal plane of PRISMA, was designed for the detection of medium-heavy ions. As expected, low intrinsic efficiencies (below 1%) have been obtained in the detection of light ions. To overcome this limitation a more efficient Parallel Plate Avalanche Counter (PPAC) has been developed (figure 7). It has the same structure of the present MWPPAC. The main difference is the smaller diameter of wires (10 μm instead of 20 μm) used for the construction of the *X* anode plane. The position efficiency in this configuration is increased by the higher reduced electric field reached around the *X* wires that implies higher gas gains. In-beam tests were performed at LNL in December 2007. Different ion beams delivered by the XTU-Tandem (^{32}S at energies ranging from 100 MeV to 160 MeV and ^{16}O from 60 MeV to 90 MeV) were elastically scattered from a 200 μg/cm^2 thick ^{197}Au target. Cathode efficiency close to 100% has been measured for ^{32}S and ^{16}O ions over the whole explored energy range. The relative efficiency ε_r (shown in figure 8) of the *X* anode plane with respect to the cathode for ^{16}O at different energies has been estimated from the ratio between the number of counts in the *X* position spectra and the TOF (cathode) ones. The ε_r values for ^{12}C (and for the lowest ^{16}O energy) have been estimated from the measured efficiencies on the basis of the energy losses in the active volume of the detector. An increase in the relative efficiency ε_r up to ≈ 40% has been measured for 50 MeV ^{16}O ions.

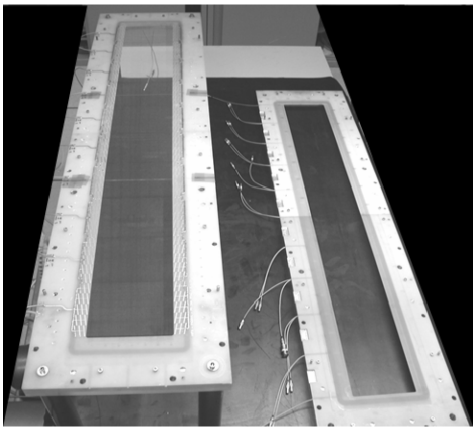

Figure 7. Electrodes of the new PPAC for light ions.

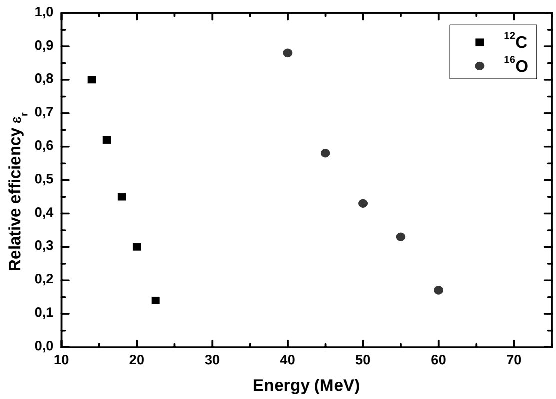

Figure 8. Relative efficiency ε_r for ^{12}C and ^{16}O ions as a function of their energy.

4.2. Secondary electron detector for low-energy heavy ions

The large thickness of the focal plane detector, mainly due to the MWPPAC windows (two mylar foils with a total thickness of 3 μm), limits its performance for low-energy heavy ions for which large energy losses and, consequently, large angular and energy straggling are expected. To overcome this limitation a large area Secondary Electron Detector (SED) is being developed. The working principle of this device is very similar to that of a Micro-Channel Plate. Heavy-ions passing through a thin (0.6 μm) plastic foil produce secondary electrons which are accelerated and transported, by means of electric and magnetic fields, toward the off-beam electron detector composed of a low pressure Multi-Wire Proportional Counter (MWPC). The installation of this new device at the focal plane of PRISMA will allow to decrease the detector thickness from ≈ 420 μg/cm^2 to ≈ 80 μg/cm^2. A small area (7x7 cm^2) prototype (shown in figure 9) has been designed and constructed by the University of Manchester. Gassiplex (GAS) based ASIC electronics has been developed at Daresbury Laboratory for the individual wire readout and data acquisition. The prototype was successfully tested in Manchester and Legnaro with two Saclay designed GAS32 (32 channels - embedding a preamplifier, a shaping time amplifier and a Track & Hold per channel) ASIC boards daisy chained together and coupled to a Daresbury designed V4FADC (fast analogic-to-digital converters) board (figure 10). Position resolutions of the order of 1 mm in the *X* and *Y* coordinates have been measured during the in-beam tests performed at LNL in October 2007 by using ^{80}Se ions at 250 MeV elastically scattered from a 100 μg/cm^2 thick ^{12}C target.

For the large area (1 m wide) SED design, a more size suitable ASIC board named GAS16 (16 channels) has been redesigned. The readout of all anode wires will require a total of 38 GAS16 boards. A new V4FADC module has been also designed to suit a wide range of ASIC electronics.

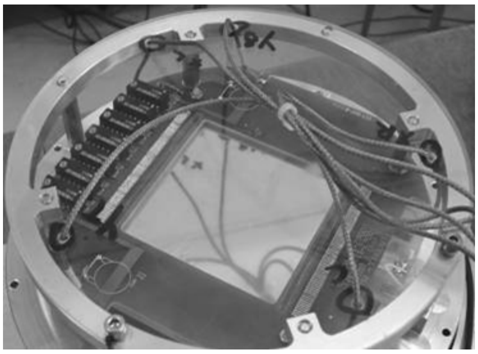

Figure 9. The small area SED based on a low pressure MWPC.

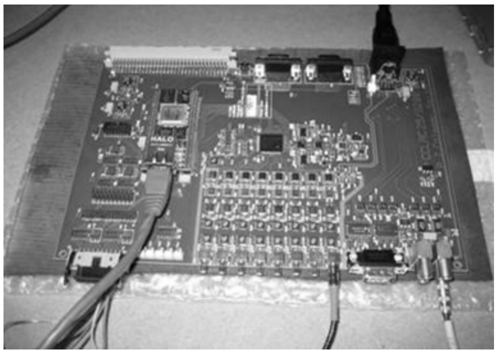

Figure 10. The V4FADC module which can control up to eight GAS16 boards.

5. Summary

The high efficiency and excellent mass resolving power of the PRISMA-CLARA set-up allowed to obtain new and significant information concerning the nuclear structure of neutron-rich nuclei in various regions of the nuclide chart. Moreover, the analysis of γ-γ coincidences from previous thick-target experiments performed with large γ arrays may benefit from the unambiguous attribution of new transitions to specific nuclei obtained with the PRISMA-CLARA set-up. The ongoing construction of new focal plane detectors for the PRISMA spectrometer will allow to overcome the limitations of the presently installed device for light ions and low-energy heavy ions.

Acknowledgments

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