

4. Next developments

The use of PRISMA in a “gas filled mode” (GFM) constitutes an important extension of its capabilities to the measurements of evaporation residues recoiling at or near to 0°. The GFM is characterized by high transmission efficiency (a very important feature in the case of low production cross sections) but the main drawback is the loss of mass and energy resolution. Then, PRISMA in GFM will be used as a separator rather than a spectrometer. In this configuration evaporation residues can be efficiently focused onto a reasonably small area at the exit of the magnetic dipole, where they can be implanted for decay studies (recoil- α tagging, α -decay studies, etc.).

Simulations for GFM operation of the PRISMA spectrometer are in progress. The first results seem to indicate that a suitable detection system for implanting the recoil nuclei could be composed of a matrix of 2x5 Si detectors with a thickness of 300 μm and an active area of 5x5 cm^2 . To get the position information Si strips will be used. A first prototype of this detection system is being assembled. The drift region existing downstream of the magnetic dipole was introduced mainly in order to increase the base for time of flight and ultimately to optimize the mass resolution in vacuum, but it is mostly useless in gas. Indeed the implantation system can be placed at only 60 cm of distance from the exit of the magnetic dipole.

5. Summary

The commissioning of the PRISMA+CLARA setup has been completed at the end of 2003. The in-beam tests and first experiments confirmed the performances foreseen for PRISMA and its detectors. Nine experiments have been already completed during 2004. The construction of the new detection system for the GFM operation of the PRISMA spectrometer is in progress.

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DESCRIPTION AND FIRST RESULTS OF THE CLARA-PRISMA SETUP

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AND THE CLARA AND PRISMA2 COLLABORATIONS.

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CLARA is an array of 25 Clover (EUROBALL type) Ge detectors, placed at the target position of the large acceptance magnetic spectrometer PRISMA. Due to the granularity of the CLARA array (100 crystals), the photopeak efficiency ($\approx 3\%$) and the PRISMA large acceptance, the setup is an excellent tool to investigate the structure of neutron rich nuclei, populated in multinucleon transfer reactions and deep inelastic collisions with stable beams. The setup is now fully operational, and the preliminary outcome of the firsts experiments will be discussed.

1. Introduction

Multinucleon-transfer reactions and deep-inelastic collisions have been used successfully in the last two decades to study the structure of nuclei far from stability in the neutron-rich side of the nuclear chart. Already in the 80s, Guidry and collaborators¹ suggested the possibility to populate high spin states in transfer reactions induced by heavy projectiles. Since then the use of these reactions in nuclear spectroscopy studies has increased, following the evolution of the γ -multidetector arrays, in some cases competing successfully with results from first generation radioactive beam facilities. A good example are the neutron-rich nuclei around ^{68}Ni , the structure of this nucleus has revealed the quasi-doubly-magic character of $N=40$ $Z=28$ ². Nuclei in this region has been investigated both with fragmentation and deep inelastic collision techniques^{2,3,4}.

Ancillary devices capable of identifying the reaction products or at least one of them, were already used in early works: PPAC counters in kinematic coincidences^{5,6,7} or Si telescopes to identify the light fragment⁸. Increasing the γ -ray efficiency in Compton-suppressed arrays allowed selection techniques purely based on the detection of γ - γ coincidences between unknown transitions from the neutron-rich nucleus and known ones from the reaction partner. The method was first used by Broda and coworkers⁹ and since then, the use of these kind of reactions in combination with modern γ -ray arrays (GASP, Gammasphere, Euroball, etc.) has increased substantially the amount of spectroscopic information of nuclei in the neutron-rich side of the nuclide chart.

Recent cross section measurements, for selected multinucleon transfer reactions, with neutron rich stable targets have shown the potentiality of this reaction mechanism to populate neutron rich nuclei with sizeable cross section values¹⁰.

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 corre-

sponding reaction product. Recently, a collaboration working at ANL and MSU, have used the information obtained from beta-decay to select γ -rays produced in deep-inelastic collisions and detected by the Gammasphere array¹¹. This technique is limited to nuclei where some states are populated both in the parent β -decay and in in-beam experiments with deep-inelastic collisions. The assignment of any other transition to the nucleus is done exclusively on the basis of γ -coincidences.

In a joint effort, γ -spectroscopy and reaction mechanisms groups belonging to INFN, in collaboration with several European institutes, have developed a new setup by coupling the array of Euroball Clover detectors CLARA¹² to the large acceptance magnetic spectrometer PRISMA¹³. This setup is a step forward in the use of the multinucleon transfer and deep inelastic collisions in γ spectroscopy, and aims at measuring in-beam prompt coincidences of γ -rays detected with CLARA and the reaction product seen by the PRISMA detectors. The setup allows in most cases to assign unambiguously the transitions to the emitting nucleus by identifying the mass (A) and atomic (Z) numbers of the product going into PRISMA. Therefore, it will lower the sensitivity limit in the measurements and consequently allow to study excited states of nuclei away from stability produced with low cross sections.

2. Description of the CLARA-PRISMA setup

PRISMA is a large acceptance magnetic spectrometer for heavy ions¹³. The optical design of PRISMA, consists of a quadrupole singlet and a dipole separated by 60 cm, and its most interesting features are: its large solid angle, approximately 80 msr; momentum acceptance $\pm 10\%$; mass resolution up to $\Delta A/A \approx 1/300$ achieved via TOF; Z resolution $\Delta Z/Z \approx 1/60$ using the segmented focal plane ionization chamber; energy resolution up to 1/1000 and rotation around the target in a large angular range ($-20^\circ \leq \theta \leq 130^\circ$). Some of these performance figures are achieved by software reconstruction of the ion tracks using the energy measured at the focal plane and the position and time of flight build with the MCP entrance¹⁴ and focal-plane multi wire parallel plate detector¹⁵. Within the mentioned Z and A resolutions, PRISMA allows for the unambiguous identification of the reaction products. A more detailed description of PRISMA is present in this volume in the contribution of Fioretto¹⁶.

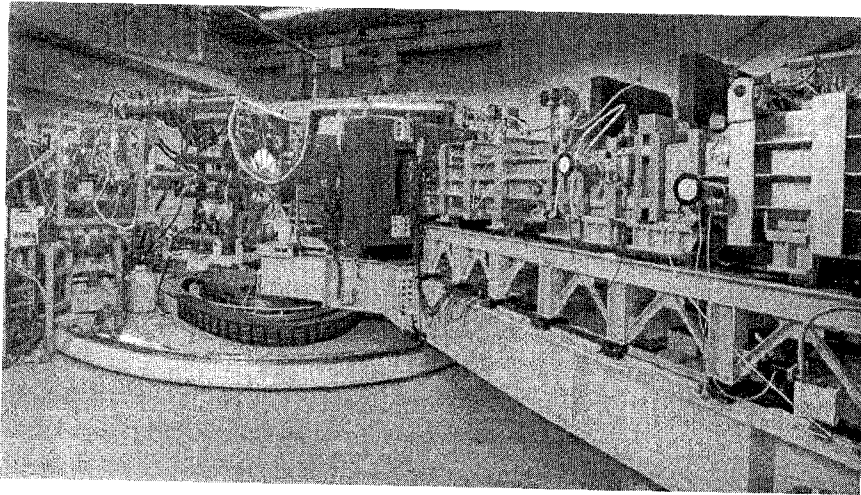


Figure 1. Photographic view of the CLARA-PRISMA setup. At the left of the picture is the CLARA array of Clover detectors followed by the quadrupole and dipole magnets of the PRISMA magnetic spectrometer. The picture ends at the right with the flight chamber and focal plane detector of the spectrometer.

At the target position of PRISMA is installed CLARA, an array of 25 composite EUROBALL Clover detectors¹⁷. These detectors are composed of four HP-Ge crystals mounted in a single cryostat and, to make use of the escape-suppression technique, the detectors are surrounded by a BGO anti-Compton shield.

CLARA is placed on a mobile platform which rotates together with the spectrometer, in such a way that the reaction products detected in the start and focal plane detectors of the spectrometer, in coincidence with the γ -rays, will have a forward trajectory with respect to the array. The PRISMA start detector (MCP)¹⁴ allows to determine the outgoing angle of the products with an angular resolution $\Delta\theta < 1^\circ$. The software reconstruction of the trajectory allows to determine accurately the velocity of the products. Therefore, the final Doppler broadening is due only to the angular aperture of the Ge crystals.

The main performance figures of the array are: efficiency $\approx 3\%$ for $E_\gamma = 1.3$ MeV, Peak/Total ratio $\approx 45\%$ and energy resolution $\approx 1\%$ for $v/c = 10\%$. CLARA is installed at the target position of PRISMA.

Clover composite detectors have an excellent sensitivity for measuring the degree of linear polarization of the γ -rays emitted by the products¹⁸. In nuclear reactions where the outgoing products have a preferential direction for the alignment of the angular momentum, the polarization coincidence measurements in oriented nuclei (PCO), together with the angular distributions or correlation (DCO) information, allows one to determine the character and multipolarity of the electromagnetic transitions and thus to obtain fundamental information on the angular momentum and parity of excited states.

The combination of the CLARA Clover array with the PRISMA spectrometer allows to perform lifetime measurements with several techniques. For short lifetimes, below ≈ 1 ps, a technique based on the lineshape analysis can be used. This technique, developed at the EUROBALL Recoil Filter Detector¹⁹, is based on the straggling of the ions in the target. Since the PRISMA start MCP detector can give an accurate trajectory of the outgoing ion and therefore a precise Doppler correction, it is possible to distinguish between the fraction of events emitted in the target where the ion can still change the trajectory (imprecise Doppler correction) and the fraction emitted outside the target for which the Doppler correction is right. The lifetime range covered by this technique, strongly dependent on the product velocity, goes from ≈ 50 fs to ≈ 0.5 ps using different target thicknesses.

A lifetime technique covering the range from ≈ 1 ps to ≈ 1 ns is based on the differential recoil distance method. The idea is to place a thin metallic foil at certain distances after the production target. This foil will act as energy degrader, and the velocity will be changed for the projectile-like reaction products going towards PRISMA. Depending on the velocity distribution of the projectile-like nuclei and on the desired lifetime range, the target-degrader distance will vary from few microns to hundreds of microns. This technique will be tested during the next semester with differential plunger targets consisting on a thin production target and an energy degrader foil placed at fixed distance, in a single mechanical setup. Several plunger targets, corresponding to different fixed distances, will be placed in the normal target holder inside the reaction chamber. The angular straggling of 2-3 degrees due to the degrader does not influence significantly the geometrical acceptance of the spectrometer and the velocity distribution shift can be compensated with proper magnetic field settings.

Finally, for long lifetimes, the Recoil Shadow Method, developed at EUROBALL with the Clover detectors²⁰, can measure up to several ns, again depending on the product velocity. This technique is based on the shadowing of the Clover detector crystals by the heavy metal collimator. It allows to measure the average distance from the target to the point where the radiation has been emitted.

3. Experimental activity

As it has been mentioned before the CLARA-PRISMA setup is an ideal tool to study the structure of moderately neutron-rich nuclei using multi-nucleon transfer and deep-inelastic collisions. In this sense, the spectroscopic information provided by the setup is complementary to that provided by first generation radioactive beam facilities. Therefore, several topics are common to the mentioned facilities and our setup, i.e. shell evolution at $N=20$, 28 and 50 and the onset of collectivity for the Cr and Fe isotopes towards $N=40$.

The experimental program of the CLARA-PRISMA setup started on March 2004. During this experimental campaign only 22 Clover detectors were used and therefore the efficiency of CLARA was $\approx 2.6\%$.

A consistent fraction of the experimental activity is connected to the study of the magic numbers in neutron-rich nuclei. Regarding this topic, nuclei in the vicinity of $N=50$ have been studied and some preliminary results will be described.

The appearance of unexpected magic numbers and the onset of collectivity in nuclei beyond this new magicity, in particular in neutron-rich nuclei with $A \approx 60$ and $N \approx 34$ have also concentrated experimental efforts and some preliminary results obtained with CLARA-PRISMA in this region will be also shown.

3.1. The $N=50$ shell closure in the vicinity of ^{78}Ni

The large N/Z ratio of the neutron-rich doubly magic nucleus ^{78}Ni qualifies the region around this nucleus for searching for shell effects connected with nuclei with large neutron excess.

Recent works extensively discussed the changes of the nuclear potential due to the difference between the proton and neutron root mean square radius in neutron rich nuclei^{21,22,23,24}. The vicinity to the drip-line is not

the only effect that can modify the shell structure in neutron-rich nuclei. It has been suggested recently that the attractive tensor interaction between spin-flip orbitals (repulsive between non spin-flip) may contribute to the weakening of the shell gaps in neutron-rich nuclei²⁵.

The spectroscopic information provided by experiments in the ^{78}Ni region can be compared with shell model calculations, and from the comparison it is expected to infer possible changes in the $N=50$ shell gap. This comparison will as well provide fundamental information to extract the contribution of the tensor interaction in the evolution of the shell gaps.

The calculations performed in the Infinite Nuclear Matter framework by Nayak and collaborators²⁶ predicted that changes in the shell gap at $N=50$ start in ^{82}Ge ($Z = 34$). On the contrary, the relativistic mean field calculations performed by Geng and collaborators²⁷ predict observable effects on the $N=50$ shell gap only for nuclei bellow $Z=28-26$.

The experimental activity of CLARA-PRISMA in this region²⁸ has been performed using a ^{82}Se beam at 505 MeV, delivered by the Tandem-ALPI complex, impinging on a $^{238}\text{UO}_2$ 400 $\mu\text{gr}/\text{cm}^2$ target. In order to select mainly the quasi-elastic projectile-like reaction products from the multi-nucleon transfer process, the spectrometer was placed at the grazing angle ($\theta_g = 64^\circ$). Spectra from more than 50 nuclear species, from Kr to Cr isotopes, were obtained in a 4-days experiment, with a beam intensity of 5 to 6 pA.

The limited CLARA and PRISMA efficiencies and the short beamtime, prevented the measurement of $\gamma-\gamma$ -product coincidences, for many of the measured nuclei. Therefore, to build the level scheme it was necessary to resort to a previous GASP experiment²⁹ performed again with ^{82}Se beam at an energy of 460 MeV bombarding a thick ^{192}Os target.

For the more exotic $N=50$ isotones, due to the low population cross-section and the limited duration of the experiment, it was only possible to identify a candidate for the 4^+ state in ^{82}Ge ²⁸. In Fig. 3.1 the confirmed 4^+ in ^{84}Se and the candidate for the 4^+ in ^{82}Ge are shown together with the systematics and shell model calculation performed by Lisetskiy and collaborators³⁰. These calculations are done with a new effective interaction based in a G-matrix Bonn-C Hamiltonian fitted to the experimental data available in the region, and takes into account the changes in the effective single particle energies due to evolution of the monopole interactions, between ^{56}Ni and ^{78}Ni ($Z=28$ isotopes) and between ^{78}Ni and ^{100}Sn ($N=50$ isotones), for the proton and neutron orbitals respectively.

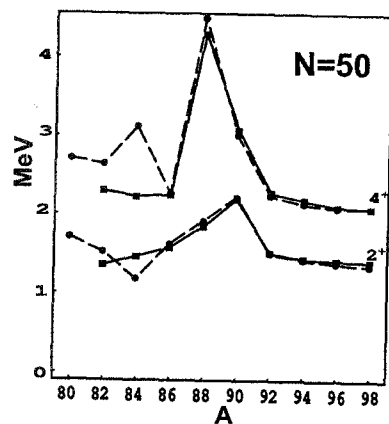


Figure 2. Calculated 30 (circles) and experimental (squares) 2^+ and 4^+ excitation energies for the even-even $N=50$ isotones from ^{98}Cd to ^{82}Ge . The excitation energy of the 4^+ in ^{84}Se has been confirmed and a preliminary value for ^{82}Ge is also reported.

3.2. The onset of deformation in neutron rich $A=60$ nuclei

The excitation energy of the first 2^+ states in even-even Cr isotopes 31 is decreasing very fast when going from the $N=32$ to the $N=40$ Cr isotope. The 2^+ states in ^{58}Cr , ^{60}Cr and ^{62}Cr are placed at 880, 646 and 446 keV respectively, suggesting the possible onset of deformation towards $N=40$.

Neutron-rich nuclei in the $A=60$ mass region, where protons are partially filling the $1f_{7/2}$ shell and the neutrons are filling the other pf orbitals, are predicted to develop deformation. In particular, recent shell-model calculations 32 predict the decrease of the excitation energy of the first 2^+ state and large $E2$ transition probabilities for its decay to the ground state, for even mass Cr and Fe isotopes with neutron number approaching $N=40$, a magic number at stability, due to the $g_{9/2}$ and $d_{5/2}$ orbitals entering into play.

An experiment aimed at studying the structure of Cr and Fe isotopes in this region 33 , has been performed at CLARA-PRISMA setup. In this experiment it has been identified for the first time the ground state band in the nucleus ^{58}Cr ($Z=24; N=34$). The nucleus ^{58}Cr has been populated in the reaction $^{64}\text{Ni} + ^{238}\text{U}$. The ^{64}Ni beam, with the energy of 400 MeV was delivered by the Tandem-ALPI accelerator complex. The thickness of the

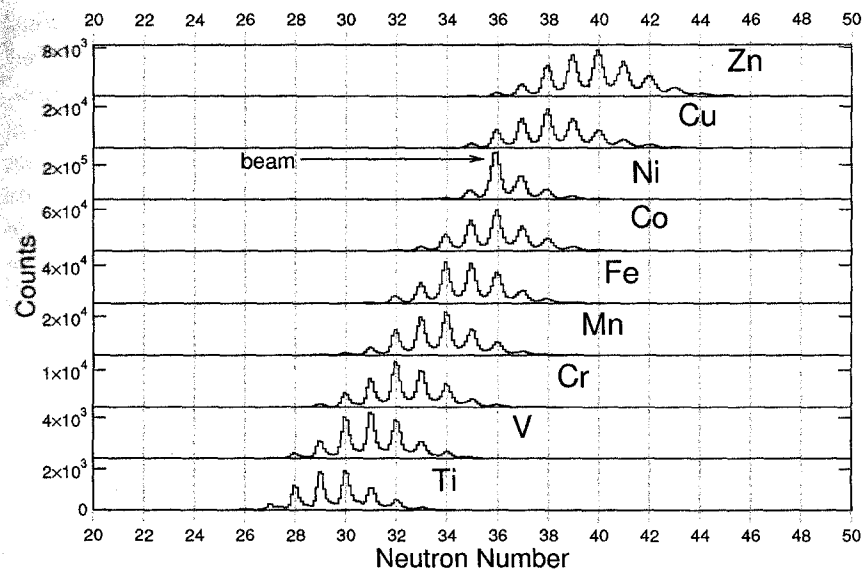


Figure 3. Mass distribution for isotopes from Zn to Ti, measured with the PRISMA spectrometer following the ^{64}Ni 400 MeV + ^{238}U reaction. In the axis the neutron number has been plotted.

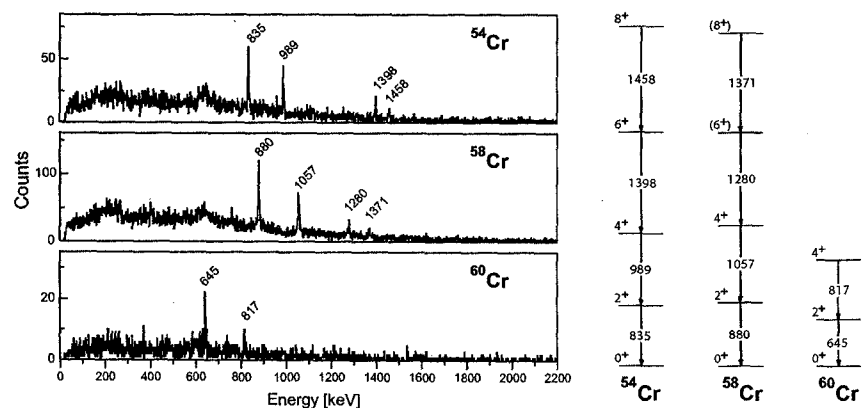


Figure 4. CLARA γ -ray spectrum and level scheme obtained for few Cr even-even isotopes in the ^{64}Ni beam experiment.

Uranium target was $400 \mu\text{g}/\text{cm}^2$. Projectile-like nuclei produced following multinucleon transfer were detected with the PRISMA spectrometer placed at 64° , which corresponds to the grazing angle of the quasi-elastic reaction.

The mass spectrum obtained in the analysis of for Zn to Ti isotopes is shown in Fig. 3. A CLARA γ -ray spectrum is obtained for this nucleus setting a condition on the ^{58}Cr in the PRISMA data. The spectrum for ^{58}Cr together with close by Cr isotopes, are shown in Fig. 4³³. Only the 2^+ level at 880 keV, was previously known from β -decay data³⁴. The tentative location of the (4^+) state at 1937 keV excitation energy, ratio $E(4^+)/E(2^+) = 2.2$, characterizes the ^{58}Cr as a transitional nucleus. The excitation energy of the (6^+) state is preliminary assigned to 3217 keV and therefore, the ratio between the excitation energy of the 6^+ and 2^+ states is equal to 3.65. The two aforementioned ratios are very closed to the expected values for a nucleus described by the E(5) critical point symmetry³⁵, i.e. a nucleus at the U(5)-0(6) shape phase transition.

4. Conclusions

This contribution describes the CLARA-PRISMA setup and shows the preliminary results of two of the seven experiments already performed at the setup. CLARA-PRISMA is now fully operational and the results obtained show the high potential of the multinucleon-transfer and deep-inelastic reactions with stable beams in populating neutron-rich nuclei. The upgrades realized for the LNL accelerators (low beta cavities for the ALPI linac and the new PIAVE injector) open new perspectives concerning the variety of nuclear species that will be available for the users in 2005.

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