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First results of the CLARA-PRISMA setup installed at LNL

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Abstract. Spring 2004 has seen the first experiments performed with the CLARA-PRISMA setup installed at LNL (Legnaro). The setup consists of CLARA, an array of 25 Clover (EUROBALL type) Ge detectors, placed at the target position of the large acceptance PRISMA magnetic spectrometer. 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. PRISMA allows the identification of the reaction products opening the possibility to go further away from stability in comparison with previous experimental activities using the aforementioned reactions. The setup has been commissioned in the first three months of the year and since March is fully operational. Five experiments had been performed, with beams delivered by the LNL tandem and the ALPI linac. In this contribution the main features of the setup as well as the preliminary outcome of the first experiments will be described.

PACS. 29.40.Wk Solid-state detectors – 29.30.-h Spectrometers and spectroscopic techniques – 29.30.Kv X- and gamma-ray spectroscopy – 23.20.Lv Gamma transitions and level energies

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 collaborators [1] 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 gamma 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 fragment [8].

Increasing the gamma-ray efficiency in Compton-suppressed arrays allowed selection techniques purely based on the detection of gamma-gamma coincidences between unknown transitions from the neutron-rich nucleus and known ones from the reaction partner. The method was first used by Broda and coworkers [9] and since then it has been successfully applied up to the present day.

The increasing interest for going further away from the stability for neutron-rich medium mass or heavy nuclei, has created the necessity of new techniques to identify the gamma transitions belonging to the product of interest. Recently, a collaboration working at ANL and MSU, have used the information obtained from beta-decay to select γ-rays from deep inelastic collisions detected by the Gammasphere array [10]. 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.

The Clover array (CLARA) coupled to the PRISMA magnetic spectrometer is a step forward in the use of the multinucleon transfer and deep inelastic collisions in gamma spectroscopy. The setup aims to measure 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 unequivocally the transitions to the emitting nucleus by identifying the mass and Z of the product going into PRISMA. It will therefore lower the sensitivity limit in the measurements and consequently allow to study excited states of nuclei away from stability produced with low cross-section.

Recently, it has been proved the persistency of a sizable deep inelastic cross-section, populating neutron-rich nuclei, in peripheral reactions at Fermi energies [11,12].

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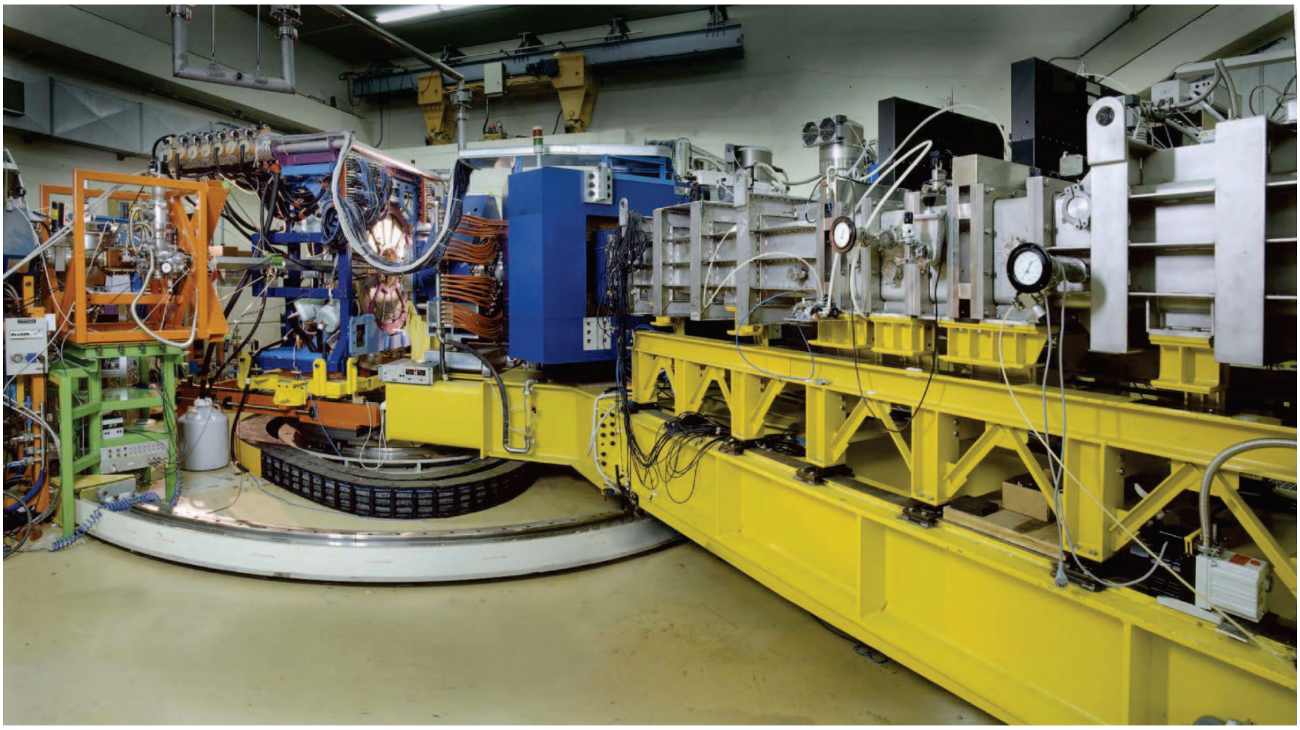

Fig. 1. Photographic view of the CLARA-PRISMA setup. At the left of the picture is the CLARA array of Clover detectors followed by the quadrupole and dipole magnets of the PRISMA magnetic spectrometer. The picture ends at the right with the flight and focal plane detector chambers of the spectrometer.

This finding will open the perspective of using such mechanism, in appropriate facilities, with the advantage of the product forward focusing, for the overall efficiency of the magnetic spectrometers.

2 The CLARA-PRISMA setup

PRISMA is a large acceptance magnetic spectrometer for heavy ions, installed at LNL. It has been designed for the heavy-ion beams of the XTU Tandem-ALPI-PIAVE accelerator complex [13]. The most interesting features of the spectrometer are its large angular acceptance (80 msr), momentum acceptance $\pm 10\%$; measured mass (via TOF) and Z resolutions $\Delta M/M \approx 1/190$ and $\Delta Z/Z \approx 1/60$ respectively; and energy resolution up to 1/1000 and rotation around the target in a large angular range ($-20^\circ \leq \theta \leq 130^\circ$).

The mass resolution performance is achieved by software reconstruction of the ion trajectory, using the position, time and energy signals from the entrance position sensitive Micro-Channel-Plate (MCP) and the Multi-Wire Parallel Plate Avalanche (MWPPAC) focal-plane detectors [14]. The Z identification is provided by the Ionization Chamber (IC) installed after the MWPPAC.

The project of coupling an array of Compton suppressed γ-ray detectors to the PRISMA spectrometer has been developed in the framework of a series of campaigns using EUROBALL detectors for specific research programs in few European facilities.

The array CLARA, working in conjunction with PRISMA aims at using binary reactions (quasi-elastic, multinucleon transfer or deep inelastic scattering) in order to populate excited states in the reaction products. In many cases it is compulsory to use stable heavy n-rich targets. The use of binary reactions implies in most cases large velocities for the products of interest. Therefore the design of the γ-ray detector array has been done to optimize the sensitivity, taking under consideration the kinematics of the aforementioned reactions and the mechanical constrains imposed by the spectrometer. PRISMA prevents the use of more than 1π of the forward solid angle, and to keep the resolution at a sensible level (1% at $v/c \approx 0.1$) at large product velocity, high granularity and a large Ge-crystal to target distances are fundamental. The adopted solution uses 25 EUROBALL Clover detectors [15], taking advantage of the reduced dimensions of each of the four crystals composing the detector, being the granularity guaranteed by the large number of detectors (hundred crystals) building up the array. This solution, with a target-crystal distance of about 29.5 cm, leads to an array efficiency above 3% for 1.3 MeV γ-rays.

The MCP entrance detector covers a small fraction (below 1%) of the total solid angle, but taking into account the kinematics and the angular distribution of the cross-section, efficiencies of the order of 3 to 5% are expected, at the grazing angle, for a typical reaction. A picture of the experimental setup is shown in fig. 1. The CLARA array rotates with PRISMA and therefore, the angle between the Clover detectors and the trajectory of the outcoming products are kept within the PRISMA acceptance.

The characteristics of the setup allowed not only the assignment of gamma transitions to moderately exotic nuclear species, but also the investigation of the character and multipolarity of the radiation through angular distributions and linear polarization measurements [16]. It is possible as well to measure lifetime of excited states by using the techniques described in ref. [16].

The setup is presently fully functional and the experimental program is in progress. In the following section some preliminary results from the first experiments will be described.

3 Experimental activity

The experimental program of the CLARA-PRISMA setup, started in March 2004, is focused mainly on the nuclear structure in neutron-rich nuclei and on the investigation of "non-yrast" states populated by quasi-elastic reactions.

A consistent fraction of the experimental activity is connected to the study of the magic numbers in neutron-rich nuclei. Concerning this subject 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 the collectivity in nuclei beyond this new magicity, in particular in n-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 neutron-rich nuclei

Nuclei in the neighborhood of the neutron-rich doubly magic nucleus ^{78}Ni has concentrated experimental efforts on stable and radioactive beam facilities in the last few years. Several reasons justify the interest in this area of the nuclear chart. Firstly the large N/Z ratio, much larger than any other known n-rich heavy doubly magic nucleus. This large ratio qualifies the region for searching for shell effects connected with nuclei with large neutron excess. In recent works it has been extensively discussed the effect of the difference between the proton and neutron root mean square radius in neutron-rich nuclei [17,18,19,20], in particular on the nuclear potential. The reduction of the spin-orbit term of the potential at the neutron drip-line, reduces the energy splitting between the spin-orbit partners, and thus the energy gap.

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 nuclei [21].

The spectroscopic information provided by experiments in this region can be compared with shell model calculations, and from the comparison it is expected to infer

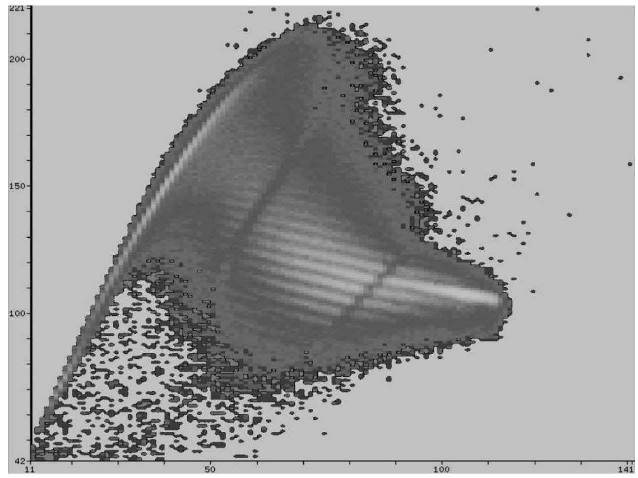

Fig. 2. ΔE-E matrix from the ionization chamber of the PRISMA focal plane. The matrix belongs to the ^{82}Se 505 MeV + ^{238}U experiment.

possible changes in the $N = 50$ shell gap. It is of particular interest to check if the modification of the gap starts as early on Z as in ^{82}Ge as predicted by Nayak and collaborators [22] or on the contrary, if it does not appear at all before ^{78}Ni as deduced from the relativistic mean field calculations performed by Geng and collaborators [23].

The experimental activity in this region [24] has been performed with a ^{82}Se beam at 505 MeV, delivered by the Tandem-ALPI complex, bombarding a $^{238}UO_2$ 400 μgr/cm^2 target. The spectrometer was placed at the grazing angle ($\theta_G = 64°$), in order to select mainly the quasi-elastic projectile-like reaction products from the multi-nucleon transfer process. Spectra from more than 50 nuclear species, from Kr to Cr isotopes, were obtained in 4 days of experiment with a beam intensity of 5 to 6 pnA. The ΔE-E matrix coming from the focal plane ionization chamber had enough resolution to have a good Z identification (see fig. 2). The mass distributions for the nuclides ranging from Kr to Ni are shown in fig. 3.

For this experiment only 22 Clover detectors were used and the efficiency of CLARA in this case was $\approx 2.6\%$. The described experimental conditions prevented the measurement of $\gamma-\gamma-$PRISMA coincidences for many of the measured nuclei and therefore, to build the level scheme it was necessary to resort to a previous GASP experiment [25] performed again with ^{82}Se beam at an energy of 460 MeV bombarding a thick ^{192}Os target. An example of the quality of the data is shown in fig. 4, the spectrum and level scheme correspond to the odd-odd ^{80}As nucleus (one-proton and one-neutron stripping reaction channel). The transitions placed in the preliminary level scheme are marked also in the spectrum, and several other transitions are still under investigation [24]. The ground-state transition of 237 keV is hardly present in the CLARA spectrum shown in the figure, this suggests a relatively large lifetime (in the order of ns) for the state de-excited by this transition in ^{80}As. The transition was identified and placed in the level scheme with the help of the already mentioned GASP data set.

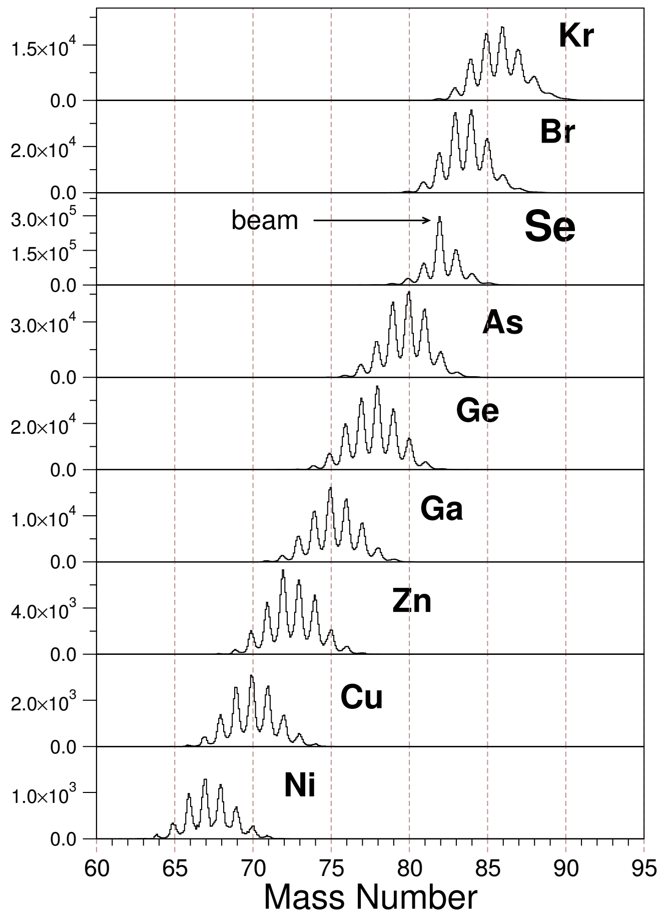

Fig. 3. Mass distribution for the Kr to Ni isotopes populated in the ^{82}Se 505 MeV + ^{238}U experiment. It has been observed population up to Cr isotopes.

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 [24]. In fig. 5 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 collaborators [26]. This calculation is 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. The above-mentioned picture reflects how important is to have information on the excited states for nuclei in the vicinity of ^{78}Ni.

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

Recently, a new shell closure at $N = 32$ has been identified for Ca isotopes [27]. The presence of this shell gap has been explained by Otsuka and collaborators as coming from

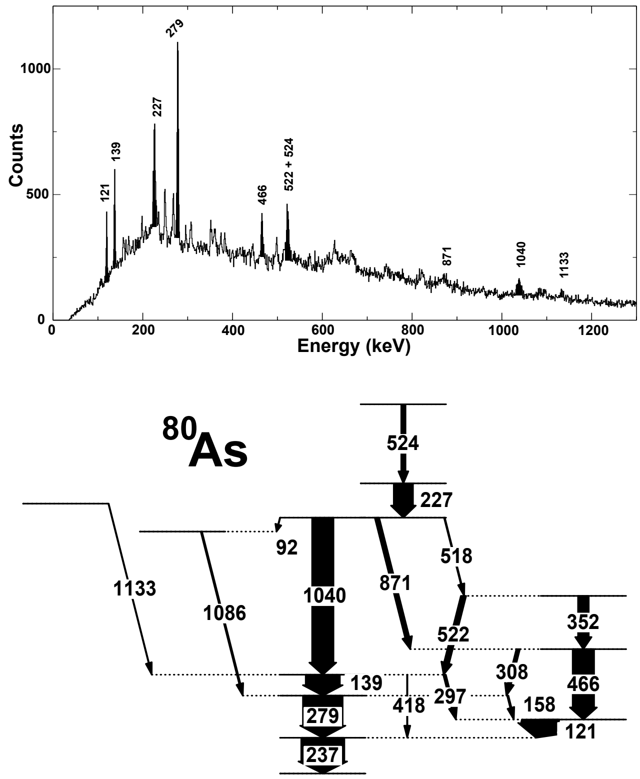

Fig. 4. Spectrum (upper panel) and level scheme (lower panel) for the odd-odd nucleus ^{80}As corresponding to the 1-proton stripping – 1-neutron stripping channel in the ^{82}Se beam experiment.

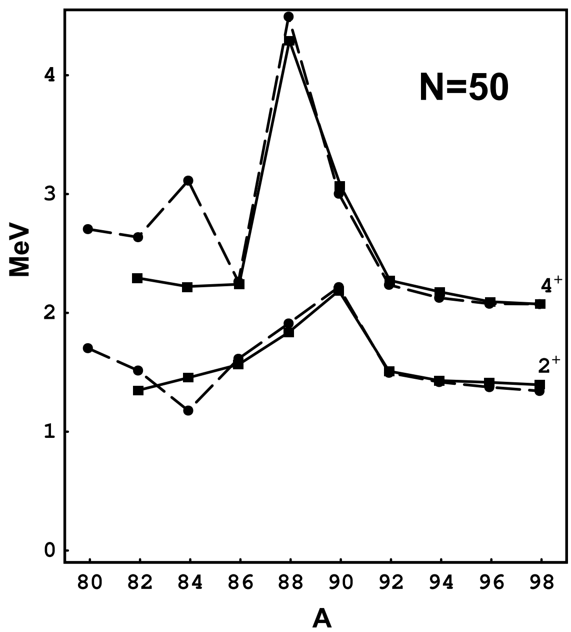

Fig. 5. Calculated [26] (circles) and experimental (squares) 2^+ and 4^+ excitation energies for the even-even $N = 50$ isotones from ^{98}Cd to ^{82}Ge. The excitation energy of the 4^+ in ^{84}Se has been confirmed and a preliminary value for ^{82}Ge is also reported.

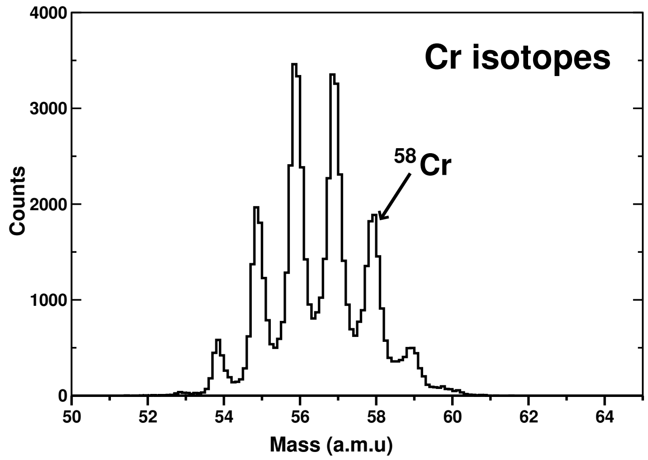

Fig. 6. Mass distribution for the Cr isotopes measured with the PRISMA spectrometer following the ^{64}Ni 400 MeV + ^{238}U reaction. The ^{58}Cr peak has been marked.

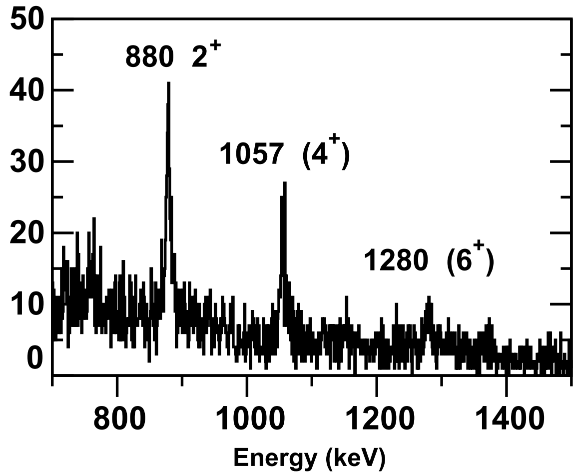

Fig. 7. CLARA γ-ray spectrum obtained with the ^{58}Cr condition in the PRISMA spectrometer in the ^{64}Ni beam experiment. Spin parity assignment are preliminary above the already known 2^+.

the strong spin-flip proton-neutron monopole interaction between the $\pi f_{7/2}$ and the $\nu f_{5/2}$ orbitals [28]. This shell closure gets progressively weaker, in Ti and Cr isotopes, as Z increases.

β-decay studies of even-even Cr isotopes produced by fragmentation reactions have allowed the identification of the first 2^+ states [29]. The excitation energy of these states 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 $N = 40$. Shell model calculations are able to reproduce this behavior only when the model space includes the intruder $g_{9/2}$ and $d_{5/2}$ orbitals [30].

An experiment, aiming to study the structure of Cr and Fe isotopes in this region [31], has been performed at CLARA-PRISMA setup with a ^{64}Ni beam impinging in a $^{238}UO_2$ 400 μgr/cm^2 target. The PRISMA spectrometer was placed at the grazing angle for this reaction ($\theta_G = 64$). With this PRISMA detection angle and beam energy ($\approx 17\%$ above the Coulomb barrier), it is expected to detect mainly products of the multi-nucleon transfer channels. The preliminary mass spectrum obtained in a partial analysis of the data set obtained in the experiment is shown in fig. 6. A CLARA γ-ray spectrum is obtained for this nucleus setting a condition on the ^{58}Cr in the PRISMA data. The spectrum is shown in fig. 7 [31], even with a partial analysis of the data, several peaks are easily seen in it. Only the 2^+ level at 880 keV, was previously known from β-decay data [27]. Our assignment for the transition de-exciting the (4^+) has the same energy as a temptatively assigned $0^+ \to 2^+$ transition in ref. [27]. If, as expected, the two transitions are the same, the direct population of the (4^+) state in β-decay would suggests a 3^+ assignment for the spin and parity of the ^{58}V ground state.

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 symmetry [32], *i.e.* a nucleus at the $U(5)$-$O(6)$ shape phase transition.

4 Conclusions

This contribution describes the preliminary results of two experiments of the seven already performed at the CLARA-PRISMA setup installed at LNL. The setup 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 the next years.

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