INVESTIGATION OF NEUTRON-RICH NUCLEI WITH THE CLOVER ARRAY AND THE PRISMA MAGNETIC SPECTROMETER*

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(Received November 30, 2004)

A new experimental apparatus has been recently installed at the Legnaro National Laboratory (LNL). It combines a large acceptance magnetic spectrometer (PRISMA) with a powerful γ-detector array (CLARA) and is especially suited for spectroscopy of neutron-rich nuclei produced in deep-inelastic or multi-nucleon transfer reactions. In this talk the results of the first experiments will be presented.

PACS numbers: 21.10.–k, 23.20.–g, 25.70.Hi, 29.30.Aj

1. Introduction

Moderately neutron-rich nuclei can be populated, at relatively high angular momentum, by means of binary reactions such as multinucleon transfer and deep inelastic collisions [1, 2]. In recent years, the use of such reactions combined with modern γ-arrays has increased substantially the amount of information available on the structure of previously unaccessible nuclei far from stability. A good example is the neutron-rich nucleus ^{68}Ni, whose study with the GASP array in a thick target experiment has revealed the doubly magic character of $N = 40$, $Z = 28$ [3]. The combination of an efficient γ-array with a large-acceptance magnetic spectrometer for heavy ions detection is certainly a step forward with respect to the previous spectroscopic studies where the identification of the final nuclei was possible only through cross-coincidences between binary products. The Clover detectors of the Euroball spectrometer have been recently moved to Legnaro at the target position of the newly built PRISMA magnetic spectrometer [4, 5] and, after a commissioning phase, experiments have started in spring 2004. The high

* Presented at the XXXIX Zakopane School of Physics — International Symposium "Atomic Nuclei at Extreme Values of Temperature, Spin and Isospin", Zakopane, Poland, August 31–September 5, 2004.

resolving power of PRISMA gives, for most of the reaction products, the full identification of mass and Z allowing studying excited states of nuclei away from stability produced with low cross sections. In this talk I will present results of two of the experiments already performed, namely ^{82}Se+^{238}U and ^{64}Ni+^{238}U having, respectively, the goal of exploring the evolution of the $N = 50$ shell closure for large N/Z ratios and of characterizing a new region of nuclear deformation for $N \approx 40$ in neutron-rich Cr and Fe nuclei.

2. The PRISMA–CLARA set-up

PRISMA is a large acceptance magnetic spectrometer for heavy ions, which has been recently installed and commissioned at LNL [5]. It has been designed for detecting ions in the mass range $A = 100$–200 and for heavy-ion beams with energies $E = 5$–10 MeV/A from the XTU Tandem-ALPI-PIAVE accelerator complex. The optical design of PRISMA consists of a quadrupole singlet at 50 cm from the target and a dipole placed 60 cm further away. The most interesting features of PRISMA are its large solid angle of 80 msr; momentum acceptance $\pm 10\%$; mass resolution 1/300 via time of flight; energy resolution up to 1/1000 and rotation around the target in a large angular range (from -20° to 130°). These performances are achieved by software reconstruction of the ion tracks using the position, time and energy signals from the entrance (start) and focal-plane detectors. The active area of the micro-channel-plate start detector is $80 \times 100\,\mathrm{mm}^2$, covering the whole solid angle of PRISMA at a distance of 25 cm from the target. The focal plane detector consists of an array of multi-wire parallel-plate avalanche counters followed, downstream, by a second array of transverse field, multiparametric ionization chambers. This detector combination is the best compromise to fulfill the requirements for PRISMA which can be summarized as:

1. good nuclear charge resolution for ions with $Z \leq 60$ and low specific energies;
2. energy resolution $\leq 2\%$ for identification of the ion charge state, also using the time-of-flight information;
3. sensitivity to the position and angle of the incoming ions, which, in combination with the time signal, allows to obtain good mass resolution even for the heaviest ions delivered by the Tandem-ALPI-PIAVE accelerator complex;
4. timing at the sub-nanosecond level (≈ 300 ps);
5. capability of sustaining overall counting rates as high as 100–150 kHz.

The Euroball array in its standard configuration with all the 239 Ge detectors and the inner BGO ball has stopped operation at IReS Strasbourg in April 2003. As a part of a new physics program where the Euroball detectors are coupled to efficient recoil separators or spectrometers in different European laboratories (see Rising at GSI and Jurosphere at Jyvaskyla) the Euroball Clover detectors [6] have been moved to Legnaro and assembled in a new geometry around the PRISMA target position to form the CLARA array [7]. Fig. 1 shows a photograph of the completed set-up at the Tandem-ALPI accelerator of the Legnaro National Laboratory. The Ge-detectors are distributed in a hemisphere opposite to PRISMA with most of the Ge crystals placed at large azimuthal angles between $\theta = 104°$ and $180°$, with respect to the entrance direction of the spectrometer. The total photo-peak efficiency of the CLARA array is $\approx 3.3\%$, with a peak to total ratio (P/T) of $\approx 48\%$ and an energy resolution of $\approx 10\,\mathrm{keV}$ for a product velocity (v/c) of 10%.

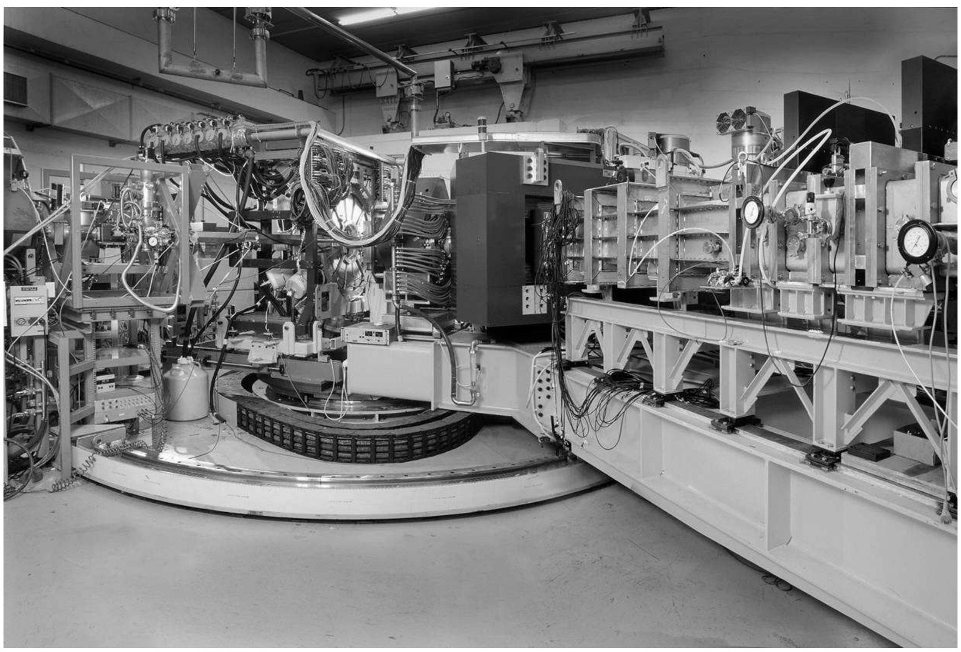

Fig. 1. View of the PRISMA–CLARA set-up at the Tandem-ALPI accelerator of Legnaro.

After a commissioning phase, experiments have started in spring 2004 with the physics program mainly devoted to spectroscopy of neutron-rich nuclei in different mass regions. Two of them will be described in the following.

3. Nuclear spectroscopy of neutron rich nuclei with $N = 50$

An important problem in nuclear structure physics is the determination of the extent to which the proton and neutron magic numbers, known from studies of nuclei near stability, remain valid for nuclei far away from the valley of stability. As an example, neutron-rich nuclei around the shell-model magic numbers $N = 20$ and $N = 28$ have exhibited properties inconsistent with shell closure, such as the experimentally observed onset of deformation which appear in such semi-magic nuclei with an higher N/Z ratio [8, 9]. These findings confirm predictions of various theoretical models on the quenching or disappearance of the classical shell gaps moving away from stability.

A new doubly magic region centered around ^{78}Ni will exist if the nucleon numbers $Z = 28$ and $N = 50$ continue to be magic on the very neutron-rich side of stability. Various theoretical calculations exist that come to different conclusions with respect to quenching or not of the $N = 50$ shell closure. Those using mass predictions from the infinite nuclear matter model, point to the quenching of the $N = 50$ shell gap already at $Z \approx 32$ [10]. Hartree–Fock–Bogoliubov (HFB) calculations based on Gogny's two-body effective interaction [11] and shell model calculations [12] predict on the other side a persistence of the shell closure for the $N = 50$ nuclei close to ^{78}Ni. In contrast, a more recent HFB calculation [13], in which pairing is treated on the same footing as particle–hole interactions, predict a significant reduction of the shell gap.

Information about the evolution of the $N = 50$ shell when moving away from stability can be extracted, in a model dependent way, by the study of the medium- and high-spin states of the $N = 50$ nuclei. Here low-lying excitations involve mainly proton configurations whereas, with increasing spin and excitation energy the breaking of the $N = 50$ core becomes more important. The knowledge of the excitation energy of such medium- and high-spin states can then be used for extracting the shell gap through the comparison with shell-model calculations.

Deep-inelastic heavy-ion reactions with stable beams have proved to be an excellent method to populate medium or high-spin states in neutron rich nuclei not accessible in fusion–evaporation reaction. With the goal to reach the $N = 50$ nuclei with lower Z numbers, we have chosen the stable $N = 48$ projectile ^{82}Se to bombard an heavy target such as ^{238}U. The energy of the ^{82}Se beam was 505 MeV with a current of $6p$ nA. The thickness of the ^{238}U target was $\approx$ 400 μg/cm^2. Of the total 25 Clover detectors which could be mounted, 22 were available for this experiment. The efficiency of the array with only 22 detectors is closed to 2.6% with a measured P/T of $\approx$ 44%. The PRISMA spectrometer has been rotated at an angle of 64°

which corresponds approximately to the grazing angle of the reaction used. In Fig. 2, the mass distributions for each Z, from Kr to Ni, produced in this reaction are shown. Other isotopic chains are also observed with PRISMA which are not plotted in Fig. 2. For example we have also detected the extreme case of 24 nucleons transfer from ^{82}Se to ^{58}Cr (removal of 10 protons and 14 neutrons from the beam). By gating on the mass of a specific

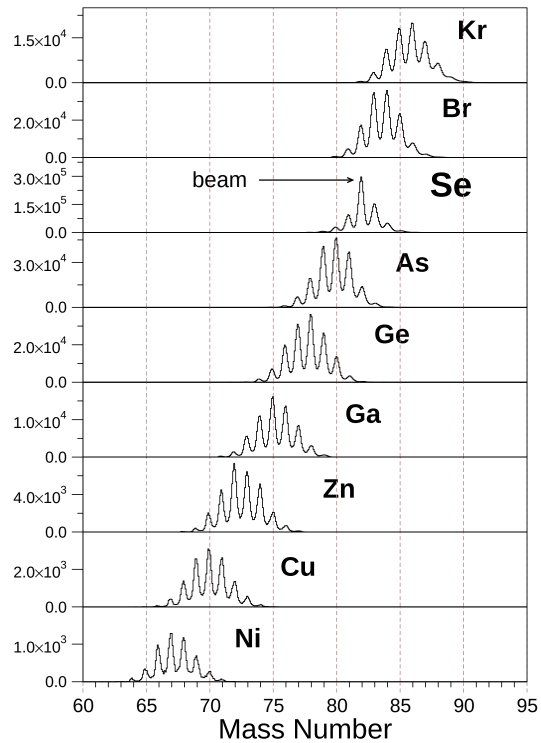

Fig. 2. Mass distribution for the different isotopes detected by the PRISMA spectrometer and populated in the ^{82}Se $+^{238}$U reaction at 505 MeV of beam energy.

isotope we then obtain from CLARA the associated γ-spectrum: those corresponding to the series of As isotopes are shown in Fig. 3. In this way we can unambiguously assign new γ-transitions to all nuclei populated in the reaction. The example of ^{80}As, a completely unknown odd–odd nucleus, is further displayed in the upper part of Fig. 4. From that spectrum one can assign unambiguously many new γ-transitions which de-excite levels in ^{80}As. From the PRISMA–CLARA data it is not possible to place them in a level scheme, since γ–γ coincidence data are missing. We went, therefore, back to the γ–γ coincidence data of a previous GASP experiment [14] where the same ^{82}Se beam at an energy of 460 MeV was impinging a ^{192}Os thick

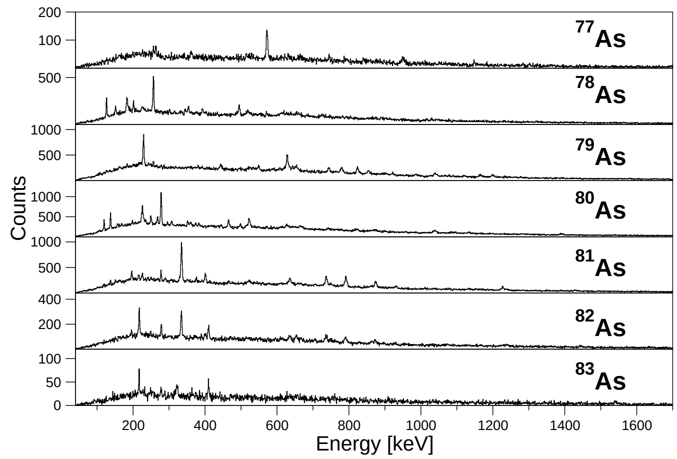

Fig. 3. Doppler corrected γ-ray spectra measured with the CLARA Ge-detector array in coincidence with the $Z = 33$ As nuclei.

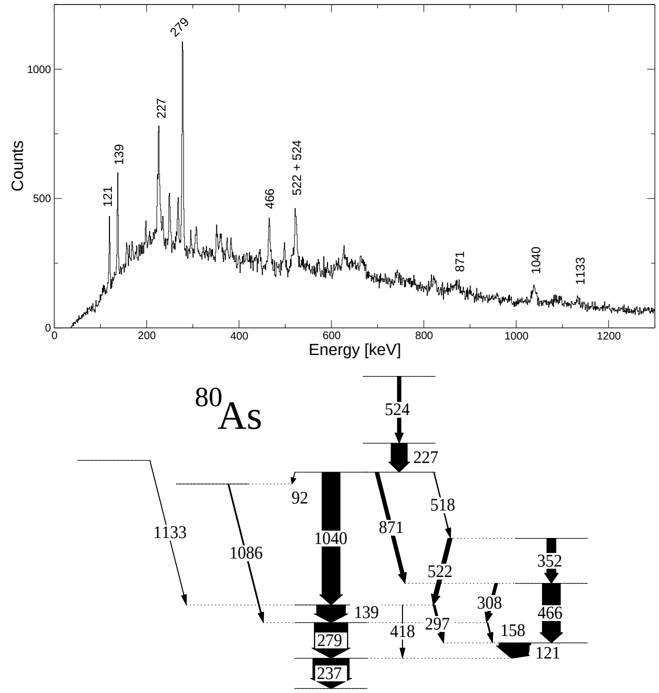

Fig. 4. Above: Doppler corrected γ-ray spectrum measured with the CLARA Ge-detector array in coincidence with $Z = 33$ and $A = 80$ selected with the PRISMA spectrometer. Below: The level scheme of the nucleus ^{80}As built from the GASP data (see text).

target. The analysis of such data has proven the coincidence relationship among the new γ-rays assigned to ^{80}As allowing to build the level scheme shown in Fig. 4. One notices immediately that the strongest transition of this nucleus, the one of 237 keV collecting all the intensity, barely appears, if at all, in the spectrum in coincidence with PRISMA. This can be understood if the 237 keV γ-ray de-excites an isomeric state, even of a few nanoseconds, sufficient to escape detection in CLARA where a thin target (300–400μg/cm^2) has to be used. In the GASP experiment the target thickness was 60 mg/cm^2, sufficient to stop all reaction fragments. One can, therefore, conclude that, in order to do spectroscopy of the exotic nuclei populated in deep-inelastic reactions, both thin target (where the γ-ray identification is made with the help of a heavy ion spectrometer) and thick target (with an efficient Ge-array for γ–γ coincidences) experiments are necessary.

In the above mentioned reaction we could identify also new γ-rays that could be assigned to the $N = 50$ neutron-rich nuclei that were the main aim of this experiment. Going then back to the GASP thick target data, level schemes could be built for the $N = 50$ nuclei ^{87}Rb, ^{85}Br, ^{84}Se and ^{82}Ge. Those of ^{87}Rb and ^{84}Se are shown in Figs. 5 and 6, respectively. Spins have been assigned, on the basis of angular distributions, up to a maximum of $23/2^+$ in a odd–even case (^{87}Rb) and of 7^+ in a even–even one (^{84}Se).

As stated previously, shell model calculations have been performed for the newly observed states of the $N = 50$ nuclei in order to investigate the role of the neutron-core breaking excitations and, therefore, of the $N = 50$ shell gap. This has been achieved by carrying out two sets of calculations, one allowing (SM2) particle–hole excitation across the $N = 50$ neutron core and the other (SM1) not. Details on the selected active proton and neutron orbitals and on the effective interactions used are given in Ref. [14]. A comparison of the experimental and calculated levels of ^{87}Rb and ^{84}Se is shown in Figs. 5 and 6, respectively. In both cases one observes that all experimentally known levels are well reproduced using the proton configuration space (SM1) but only up to a certain spin ($17/2^+$ for ^{87}Rb and 6^+ for ^{84}Se). In both nuclei, above ≈ 4 MeV, the agreement between experimental levels and the shell-model calculations performed in the proton space become rather poor. It is likely that at this point particle–hole excitations across the $N = 50$ neutron core begin to be important. In fact, by comparing the measured values with the excited levels calculated using both the proton and neutron spaces (SM2) the agreement between experimental and calculated energies above 4 MeV improves significantly. A closer inspection of the wave functions involved shows that the dominant contribution for the high spin states in the two nuclei result from coupling the neutron cluster $\nu(0\,g_{9/2}^{-1},\ 1d_{5/2}^{1})_j$ to the proton particle excitations. Similar results have been

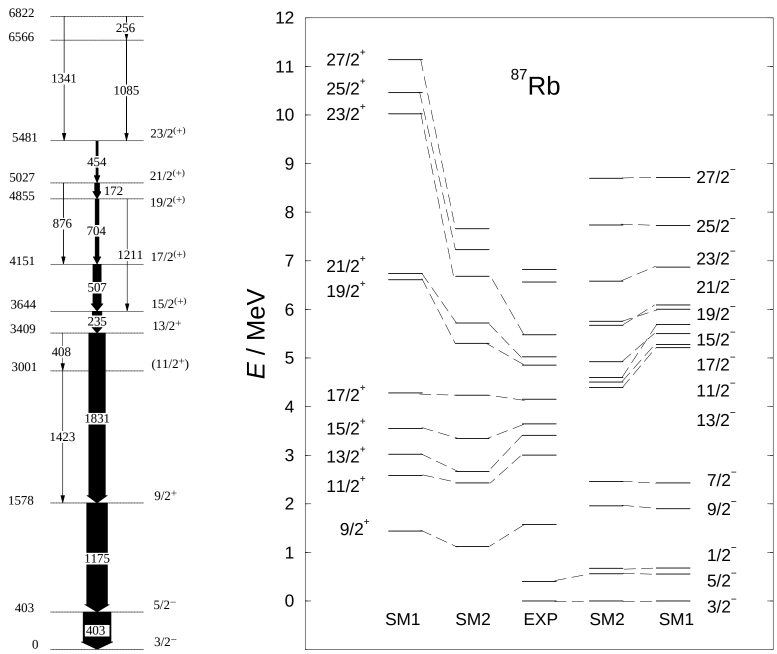

Fig. 5. Level scheme of ^{87}Rb (left) and shell model calculations for ^{87}Rb. The calculations are performed using either a proton space (SM1) or allowing also neutron particle–hole excitations across the $N = 50$ shell gap (SM2).

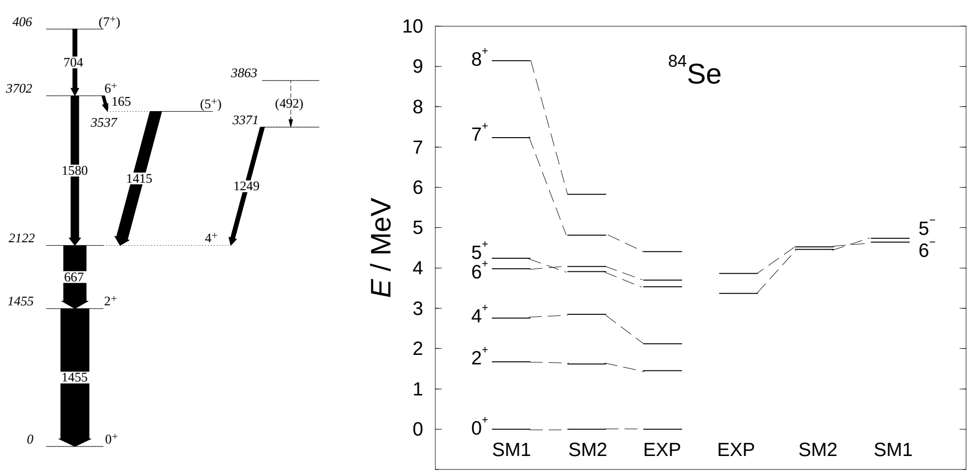

Fig. 6. Level scheme of ^{84}Se (left) and shell model calculations for ^{84}Se. The calculations are performed using either a proton space (SM1) or allowing also neutron particle–hole excitations across the $N = 50$ shell gap (SM2).

obtained also for the other $N = 50$ nuclei ^{85}Br and ^{82}Ge. One can, therefore, conclude that, in order to reasonably reproduce the excited levels above $I^\pi = 17/2^+$ and 6^+ (for odd–even and even–even systems, respectively), it is necessary to introduce particle–hole excitations across the $N = 50$ gap. The size of the gap (≈ 4 MeV for ^{78}Ni) has been kept constant in the calculations. The general agreement observed between the measured and calculated excitation energies of the levels can, therefore, be considered a strong indication that, when moving away from the stability line down to $Z = 32$, the $N = 50$ gap remains constant.

4. Spectroscopy of deformed neutron rich $A \approx 60$ nuclei

Another neutron-rich region, where new magic numbers may appear and others disappear, is the one bounded by $N = 28$–40 and $Z = 20$–28. As a matter of fact, it has been shown that a new subshell closure is present at $N = 32$ but only for $Z \approx 20$ [15]. The appearance of this new shell gap has been explained [16] in terms of a strong spin-flip $\pi 1f_{7/2} - \nu 1f_{5/2}$ proton–neutron monopole interaction. On the other side it has been predicted that in the middle of this nuclear region nuclear deformation sets in, and that the subshell closure at $N = 40$ disappears. The chromium isotopes lie in the middle of the proton shell where the greatest collective effects in this region are expected. In fact, recent β-decay studies in fragmentation reactions [17] have located the 2^+ energies in ^{60}Cr and ^{62}Cr at 646 and 446 keV respectively, *i.e.* steeply decreasing when approaching $N = 40$. This indicates that these isotopes are strongly deformed with $\beta_2 \approx 0.3$. Shell model calculations reproduce well this trend [18] by taking into account the intruder $g_{9/2}$ and $d_{5/2}$ orbitals. In fact, in the nuclei where the $1f_{7/2}$ shell is not filled, the neutron excited to the *sdg*-shell couple to the *pf*-protons and deformation appears. The removal of two or four protons from the spherical ^{68}Ni drives the $N = 40$ nuclei ^{66}Fe and ^{64}Cr into prolate shapes generating a new region of deformation [18].

It should be noted that the experimental evidence for deformation effects in this region so far has been drawn from the systematics of a single-excited state, deduced from the most intense γ-ray transition following β-decay [17]. The extent and type of deformation can be established more firmly with the observation of further members of the yrast structure. In particular, the energy ratio $R = E(4^+)/E(2^+)$ can provide crucial additional evidence in this regard. The reaction ^{64}Ni + ^{238}U, at an energy of 400 MeV has been, therefore, chosen io order to populate medium-high spin states in nuclei produced by multi-nucleon transfer or deep-inelastic reactions. The goal was to extend the spectroscopy of Cr and Fe nuclei for which, at present, only single excited states are known. The PRISMA spectrometer has been placed at an angle of 64°, *i.e.* the grazing angle for the ^{64}Ni + ^{238}U reaction. Fig. 7 shows a preliminary mass spectrum for the Cr isotopes detected with PRISMA. By gating on mass $A = 58$ one obtains from CLARA a γ-spectrum with 4–5 prominent lines which can be associated to the yrast decay of ^{58}Cr, where only the 2^+ level was known before from β-decay studies [15, 19]. In particular, the location of the 4^+ state at 1936 keV characterizes ^{58}Cr as a transitional nucleus with $E(4^+)/E(2^+) = 2.2$. The data analysis is going on and will provide new information on many new isotopes of this poorly known nuclear region.

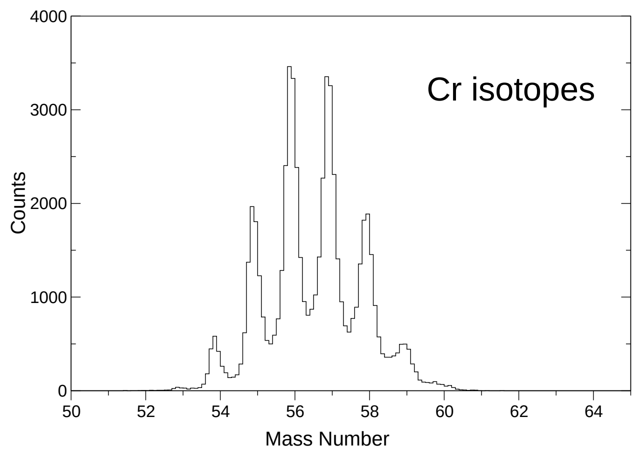

Fig. 7. Mass distributions for the Cr isotopes detected by the PRISMA spectrometer and populated in the ^{64}Ni + ^{238}U reaction at 400 MeV of beam energy.

5. Conclusions

The first successful experiments with the new PRISMA–CLARA setup of the Legnaro Laboratory has been performed in spring 2004. In the majority of the cases the goal was to explore and understand the behavior of neutron-rich nuclei which are still unaccessible with traditional fusion–evaporation reactions and by using stable beams. In particular, the study of neutron rich nuclei with $N = 50$, performed also in a thick target experiment with the GASP spectrometer, has allowed to extend their high spin knowledge down to $Z = 32$ and to conclude that the $N = 50$ shell closure does not weaken when going further from the stability line. The exploration of neutron-rich Cr and Fe isotopes is also progressing and the new data that are emerging will be important in defining the onset and the type of a new region of nuclear deformation in light nuclei.

I would like to thank all the members of the PRISMA–CLARA collaboration for the hard work of setting up the complex apparatus, of the data taking and of the analysis. Special thanks, for helping me in preparing the talk and the manuscript, go to Andres Gadea, Nicu Marginean, Alberto Stefanini, Giovanna Montagnoli and Giacomo de Angelis.

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