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Population of heavy neutron-rich nuclei in multinucleon transfer reactions

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Abstract. Selected results recently obtained in studies of heavy ion transfer reactions at energies close to the Coulomb barrier are presented. In particular, the production of neutron-rich heavy nuclei via multinucleon transfer processes in ^{206}Pb+^{118}Sn, ^{197}Au+^{130}Te, and ^{94}Rb+^{208}Pb is discussed.

1 Introduction

In recent years transfer reactions between heavy ions at energies close to the Coulomb barrier have been recognized as a competitive tool for the production of exotic species, especially the heavy neutron-rich nuclei [1]. Different models [2–5] predict large primary cross sections for neutron-rich nuclei near the $N = 126$ shell closure.

Multinucleon transfer reactions are mainly governed by optimum Q-value considerations and nuclear form factors [1]. The balance of Q values is mostly controlled by the light partner, and with stable nuclei the dominant processes are neutron pick-up and proton stripping from the light reaction partner. At the same time, the heavy reaction partner gains charge while losing neutrons. With neutron-rich projectiles a change in the population pattern occurs, opening channels where the heavy partner of the reaction acquires neutrons while losing protons [2]. This path has been already studied in high-resolution experiments [6–9] using large solid-angle spectrometers. In the ^{136}Xe+^{198}Pt reaction [6] it was evidenced that the production of very neutron-rich heavy nuclei was associated with low kinetic-energy losses.

The recent progress in these studies was closely connected with the successful implementation of large solid angle magnetic spectrometers, which allow to identify the transfer products in mass, and charge with unprecedented efficiency [1, 9, 10]. A significant step forward has been achieved by the coincident detection of both binary partners [9, 11], or by the detection of the electromagnetic transitions [6, 7, 12, 13]. However, such studies are still limited to very few cases and an effort is required to explore a wider range of bombarding energies and masses.

Multinucleon transfer reactions constitute also a link between quasi-elastic processes, characterized by the transfer of few nucleons and small kinetic-energy losses, and deep-inelastic processes, where massive transfer and large kinetic-energy losses take place [9, 14–18]. This is particularly important for very heavy systems with the high Coulomb field, where processes with large energy loss components are expected. These effects are closely connected with secondary processes, like evaporation, which may significantly modify the primary cross sections.

2 The ^{206}Pb+^{118}Sn case

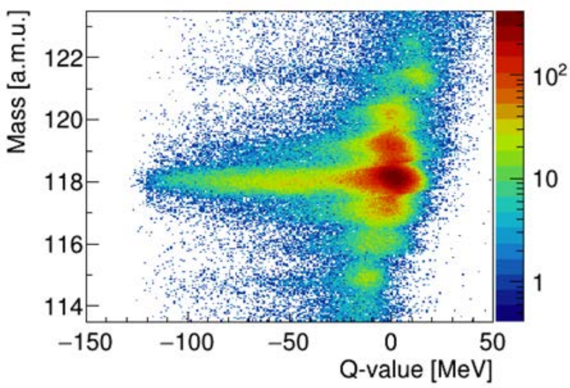

Figure 1. Mass vs Q-value matrix for Sn isotopes populated in the ^{206}Pb+^{118}Sn reaction at E_{lab} =1200 MeV and θ_{lab}=35°.

We studied very recently the ^{206}Pb+^{118}Sn system [10] at an energy high enough to get large mass and charge yields for multineutron and multiproton transfer channels. We have studied, in particular, how the main observables, cross sections and Q-value distributions, evolve as function of the number of transferred nucleons. We choose this specific system as the transfer of both neutron and proton pick-up and stripping channels (the terms pick-up and

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stripping are conventionally referred to the lighter partner of the reaction) is expected.

A ^{206}Pb beam was accelerated at the Legnaro National Laboratories (LNL) accelerator complex at E_{lab}=1200 MeV on the ^{118}Sn target. We detected target-like fragments in PRISMA [19–22], which was placed at θ_{lab}=35° (the grazing angle) and, in an additional short run, at 25°, an angular range sufficiently wide to consistently follow the drop in yield of the elastic+inelastic scattering and the main region of multinucleon transfers. Favorable experimental conditions were achieved by employing inverse kinematics, which allowed to get good A, Z and Q-value resolution, thanks to the high kinetic energy (6-8 MeV/A) of the detected ions. The identification of target-like products in PRISMA has been obtained on an event-by-event basis through the reconstruction of the trajectories of the ions [21] inside the magnetic elements. In Fig. 1 we show, as an example, the mass vs Q-value matrix for Sn (Z = 50) isotopes, demonstrating the good mass resolution, $\Delta A/A \approx 1/210$. In general, for these heavy masses, due to the overwhelming elastic yield, the atomic charge state resolution is not sufficient to remove the A/q repetitive pattern typical of magnetic spectrometers, which generates some degree of overlap for near-by masses.

The large acceptance of PRISMA gives an excellent opportunity to follow the details of the energy dissipated and the evolution of the reaction from the quasi-elastic to the deep-inelastic regimes. To this aim, we studied the evolution of Q-value, constructed by assuming a binary reaction, as a function of the scattering angle. One observes that, for pure neutron transfer channels, these distributions are dominated by a quasi-elastic peak at more forward scattering angles. Moving to angles more backward than the grazing one, the region close to the ground-to-ground state becomes progressively unpopulated while large energy-loss components become dominant. Such behavior is even more pronounced for the proton transfer channels, indicating that evaporation of neutrons may be expected. This study clearly shows that the ^{206}Pb+^{118}Sn reaction is dominated by the high Coulomb field and one can observe the progressive increase of the large energy-loss components towards backward angles [14, 15], at variance with the reactions with medium-mass projectiles on heavy targets [8, 17, 23].

The estimated total cross sections have been compared with the GRAZING calculation [24, 25]. This model calculates how the total reaction cross section is distributed amongst the different reaction channels by treating quasi-elastic and deep-inelastic processes on the same footing. The GRAZING model takes into account, besides the relative motion variables, the intrinsic degrees of freedom of projectile and target. These are the surface degrees of freedom and particle transfer. The exchange of many nucleons proceeds via a multi-step mechanism of single nucleons. One observes how the pure neutron transfer channels are well reproduced by calculations. The same holds for the pure $(-1p)$ channel. GRAZING progressively underestimates yields as more nucleons are transferred, implying that more complicated processes than a direct transfer are present. For proton transfer channels, the experimental cross sections tend to shift toward lower masses than GRAZING calculated ones. We remind that the primary cross sections for channels involving neutron stripping may be significantly modified by the evaporation of neutrons from the close-by larger masses. This leads to a reshuffling of the final mass distribution, which indeed affects more significantly the lower mass region of the populated isotopes. The comparison of experimental cross sections with the recent calculations by using microscopic models based on relativistic density functional [5], shows a good agreement for transfers of many nucleons in the presently studied ^{206}Pb+^{118}Sn heavy system, where large energy losses have been observed. An improved understanding will be particularly relevant for the proton pick-up channels since they pave the path towards the population of the neutron-rich heavy nuclei.

3 The ^{197}Au+^{130}Te case

In order to understand the production of neutron-rich heavy nuclei, and in particular the effect of evaporation, we performed an experiment with a simultaneous detection of light and heavy transfer products in the ^{197}Au+^{130}Te reaction [9], by using a dedicated set-up [11] specifically built and coupled to the PRISMA spectrometer [21]. The required resolutions of the NOSE detector [11] had to match those of PRISMA, in particular ∼1 mm for the positions, ∼350 ps for timing measurements, and about 1% for energy. By using the most neutron-rich stable ^{130}Te target we populated channels involving both neutron pick-up and neutron stripping. To obtain the best possible ion identification, we used inverse kinematics, where both binary partners have high kinetic energy at quite forward angles. We used a ^{197}Au beam, at E_{lab}=1.07 GeV, delivered by the PIAVE-ALPI complex of LNL. Te-like ions were identified in the PRISMA, while the Au-like ions were detected in a coincident gas-detector system (NOSE) [11]. By employing the kinematic coincidence between the two detector systems we constructed the mass distribution of the heavy transfer products, by assuming a pure binary process. Such coincidences allowed to construct a mass-mass correlation matrix, displayed in Fig. 2, where the mass of Au-like ions in NOSE could be correlated with that of the Te-like ions in PRISMA.

One can see that to each Te isotope is associated the correct centroid of the mass of the corresponding binary partner. Even if we cannot separate the Au isotopes, we can infer that the masses of the detected heavy products do not differ significantly from those of the primary ones. On the basis of these findings, the experimental mass distributions clearly demonstrates the population of neutron-rich heavy nuclei in the vicinity of ^{197}Au. From the mass-mass correlation matrix of Fig. 2 we integrated the yields for each isotope of Te and attributed them to the single mass of the Au isotope determined by the centroid of the mass distributions. These yields have been compared with the GRAZING calculations (see Fig. 3), where the slope of the experimental data is well reproduced. The obtained agreement between data and calculations allows us to conclude that evaporation is not altering significantly

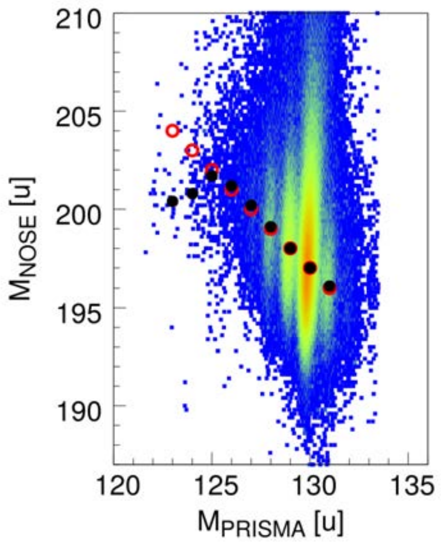

Figure 2. Mass-mass correlation matrix of Te isotopes detected in PRISMA and the heavy partner detected in coincidence in NOSE for ^{197}Au+^{130}Te. The red circles indicate the centroids of the primary binary partner while the black dots indicate the actual centroids of the distribution.

the primary mass distributions at these bombarding energies quite close to the Coulomb barrier, at least for few neutron transfer channels.

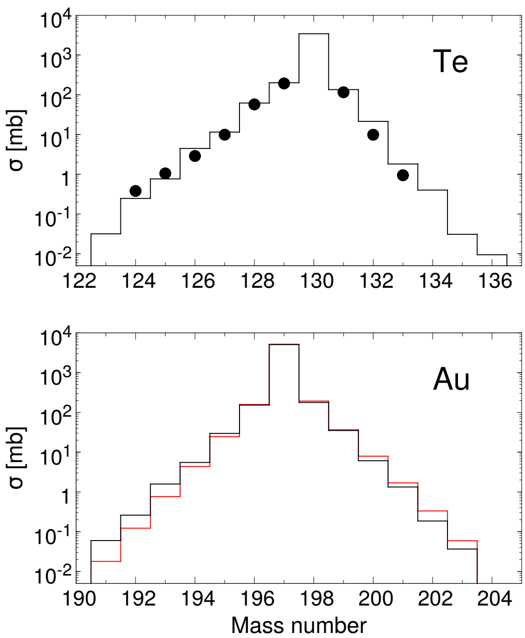

Figure 3. Total experimental cross section of Te isotopes (points) and the GRAZING calculations with (red line) and without (black line) neutron evaporation for ^{197}Au+^{130}Te.

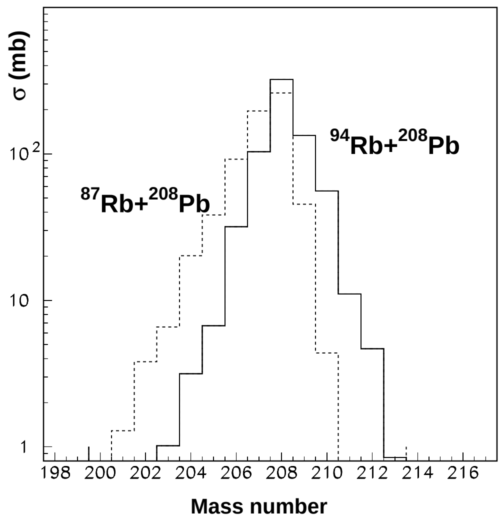

Figure 4. GRAZING calculated total cross sections for Pb isotopes in ^{94}Rb+^{208}Pb (full line) and ^{87}Rb+^{208}Pb (dashed line) reactions at E_{lab} = 575 MeV.

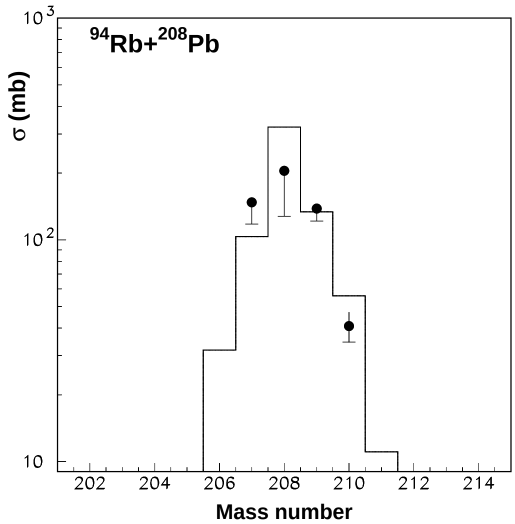

Figure 5. Total cross sections of Pb isotopes in the ^{94}Rb+^{208}Pb reaction. The measured cross sections are indicated as lower limits, while those which include the estimated values for the ground states are indicated with full points. The histogram is the GRAZING prediction for E_{lab} = 575 MeV.

4 The ^{94}Rb+^{208}Pb case

As already discussed in Introduction, at energies close to the Coulomb barrier, multinucleon transfer reactions are mainly governed by optimum *Q*-value considerations and nuclear form factors [1, 2]. Such ingredients allow to understand how nucleons are exchanged between projectile and target and how energy and angular momentum are transferred from the relative motion to the intrinsic degrees of freedom. On this basis one understands why, with stable nuclei, the dominant channels are the neutron pick-up and the proton stripping, so the reaction tends to populate heavy partner products that are neutron poor. With neutron-rich projectiles a change in the population pattern occurs, opening the path which leads to primary neutron-rich heavy partners. This is illustrated in Fig. 4 where we compared the GRAZING calculated cross sections for Pb isotopes for the reaction using ^{87}Rb, the most neutron-rich stable isotopes of Rb, which differs by seven neutrons from the radioactive ^{94}Rb. One clearly observes much larger cross sections for the neutron-rich Pb isotopes by using the radioactive ^{94}Rb beam, highlighting the importance of the use of neutron-rich projectiles significantly far from the stability.

In this context we performed an experiment aiming at the direct identification of lead isotopes and their absolute cross sections determination employing the high efficiency MINIBALL γ array [26] coupled to an annular position sensitive silicon detector [27] combined with a radioactive ^{94}Rb beam in the ^{94}Rb+^{208}Pb reaction. A ^{94}Rb ion beam at E_{lab} = 583 MeV was delivered by the HIE-ISOLDE facility [28] in CERN onto a ^{208}Pb. The bombarding energy corresponds, to a value $\sim$ 30% higher than the Coulomb barrier, as a compromise between having rather large primary cross sections and limiting secondary processes. The used detector set-up allowed the identification of reaction products via their associated γ rays.

To get the absolute value of the cross sections, we have taken as a reference the lowest 3^- octupole state of ^{208}Pb and normalized its intensity at forward angles to a Distorted Wave Born Approximation calculation. This normalization was used to convert the γ yields into cross sections for all observed Pb isotopes. Of course, by integrating all γ intensity associated with each specific isotope we extract a lower limit for the cross sections. We estimated the ground state cross sections by making use of the previously measured ^{40}Ar+^{208}Pb reaction [8] by employing the PRISMA magnetic spectrometer coupled to the CLARA γ-array [29]. The comparison of the cross sections measured with CLARA with the total absolute cross section measured with PRISMA determines the proportion of the ground states cross sections with respect to the total ones.

The experimental and GRAZING calculated cross sections for the Pb isotopes are reported in Fig. 5. In that figure we quote both the values corresponding to the γ yields directly extracted from the experiment (lower bars) and those where the estimated cross sections to the ground states of Pb isotopes have been added (points). One sees clearly the sizeable cross sections in the neutron-rich mass region, which confirms the predicted change of population pattern. One also finds a rather fair agreement between the data and calculations. In the higher mass region, the experimental cross section for ^{209}Pb is particularly well reproduced.

5 Outlook

The advent of the last generation large solid angle magnetic spectrometers, especially when coupled to large γ arrays, allowed to make significant advances in the field of multinucleon transfer reactions at energies close to the Coulomb barrier. Via multiple transfers of neutrons and protons one can populate nuclei moderately far from stability, especially in the neutron-rich region. One can thus study into more detail the behaviour of the yield distribution (important for the reaction mechanism) and perform gamma spectroscopy of yet unexplored nuclear levels (important for nuclear structure). Via transfer of multiple pairs valuable information on nucleon-nucleon correlations can also be derived, especially if measurements are performed below the Coulomb barrier [30]. Present focus is also in the study of the properties of the heavy binary partner. Via proton pick-up and neutron stripping channels one may get access to neutron-rich heavy nuclei, important also for astrophysics. The presence of secondary effects, namely nucleon evaporation and transfer induced fission, lower the final yield. Those effects, especially for large masses, need to be more carefully investigated, especially near the Pb and in the actinides regions, where other production methods, like fission or fragmentation, have severe limitations or cannot be used at all.

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