PIAVE-ALPI ACCELERATOR

Production yields of neutron-rich heavy nuclei in the ^{238}U+^{124}Sn multinucleon transfer reaction PRISMA + NOSE + AGATA experiment

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Abstract

In this experiment we intend to measure the ^{238}U+^{124}Sn multinucleon transfer reaction by using the PRISMA + NOSE + AGATA set-up to study the details of the A, Z, Q-value distributions and associated γ-rays. In addition, we will employ a high resolution kinematic coincidence to extract the light-heavy mass-mass correlation and the transfer induced fission probability of the heavy partner. By a cross comparison of these informations we will be able to define at best the yields of heavy partners. The results will provide precious inputs for a variety of experimental and theoretical studies whose developments require knowledge of the population yields of nuclear species produced via transfer mechanism that differ by a substantial amount of protons and neutrons from ^{238}U.

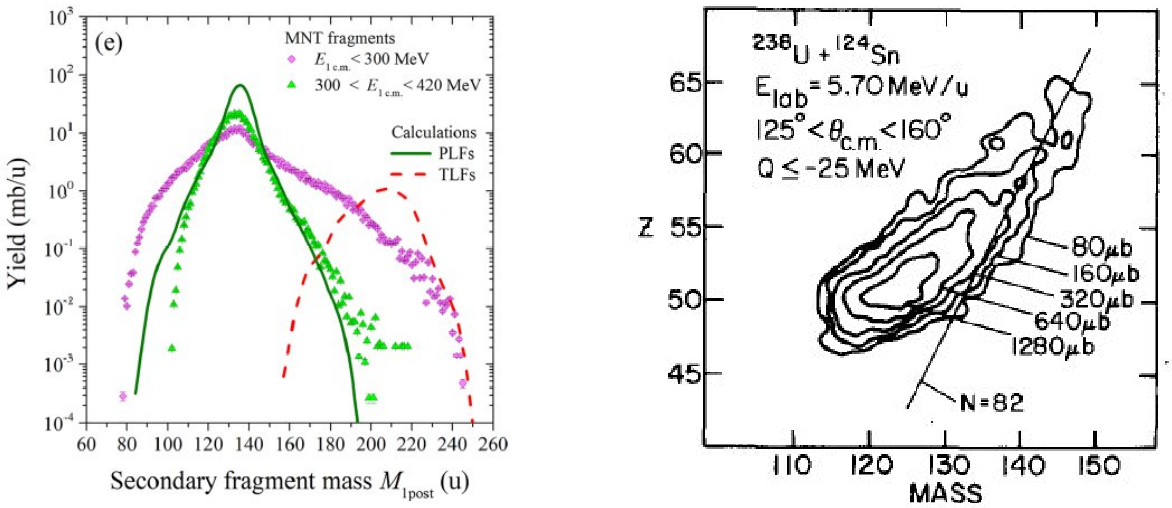

FIG. 1: Left: Mass distributions of fragments formed in the reaction ^{136}Xe+^{238}U at E_{lab} = 1.11 GeV (from Ref. [18]), together with calculations performed within the framework of the dynamic model based on Langevin equations. Right: Cross section contour lines for binary deep inelastic events in the reaction ^{238}U+^{124}Sn, plotted as a function of mass and nuclear charge Z of the target-like fragment (from Ref. [19]).

I. THE PHYSICS FRAME

The ^{238}U nucleus is the most neutron-rich stable element with the highest Z and therefore represents a crucial starting point for the population of very neutron-rich nuclei in suitable reactions at near barrier energies. Current interest is for both Z larger and lower than 92. In the former cases one may get access to the transactinides, where nowadays peculiar emphasis is on the study of fission processes [1]. In the latter case one may reach the Ra-Fr region, relevant for the spectroscopy of octupole deformed shapes [2, 3] and studies of fundamental interactions like electric dipole moments [4] or parity violation [5]. For the production of these nuclei a suitable mechanism is provided by multinucleon transfer reactions between heavy ions [6–10], for which nuclear reaction models [7–9, 11–16] predict primary cross sections that are comparable, or even larger, than those of other reactions like fragmentation at intermediate energies or low-energy fusion with radioactive beams. Major issues challenge both theorists and experimentalists. The various reaction models, which started to be developed some decades ago and which are being continuously improved, predict cross sections differing even by orders of magnitudes on the very neutron-rich side, due to the complexity of the treatment of the relevant degrees of freedom and the need to incorporate on the same footing quasi-elastic and deep inelastic components. The primary yields can be in fact significantly modified by secondary processes (nucleon evaporation and fission), with the reaction Q values getting more and more negative as the number of transferred nucleons increases. The influence of secondary processes is particularly important for the heavy reaction partner, which in general keeps a larger fraction of excitation energy. Experimentally, the investigation of nuclei in these regions is hampered by the difficulty of direct A, Z identification and by the presence of an overwhelming fission yields. In low resolution experiments one employed radiochemical methods [17] to measure cross sections down to nb level, but with this technique one cannot get any information on the reaction process. More frequently one makes use of multi-detector systems in kinematic coincidence [18] where the average mass is reconstructed by assuming binary or ternary kinematic, with typical results shown in the left part of Fig. 1. In some cases nuclear charge could be measured with gas chambers [19, 20], for example in the ^{238}U+^{124}Sn reaction, whose average mass and charge distribution is shown in the right part of Fig. 1. Gamma-gamma coincidence techniques have been also employed with large γ arrays [21, 22], both for in-beam and off-beam spectroscopy, but on a general basis absolute cross section determination turns out to be difficult due to the complexity of the decay pattern and, especially for heavy nuclei, due to the presence of isomers [23]. Very recent experiments have been also carried out by employing velocity filters and α detection techniques [24].

The coming into operation of large acceptance magnetic spectrometers made it possible to perform measurements on multinucleon transfer reactions [6] with full ion identification. Numerous experiments have been carried out by coupling PRISMA to CLARA [25] and AGATA γ arrays [26] for γ spectroscopic studies, detecting the lighter partner of the reaction and getting information on the associated heavy partner assuming binary kinematics. Mass and charge yields and corresponding cross sections have been extracted for studies of reaction dynamics and comparisons have been made with calculations based on different theories, whose developments is at the focus of growing interest [9, 16]. One also successfully demonstrated the powerful method of using PRISMA for studies of nucleon-nucleon correlations, exploiting its unique performance in terms of both resolution and efficiency. Making use of inverse kinematics, target recoils have been detected in multinucleon transfer reactions for the systems ^{96}Zr+^{40}Ca [27], ^{116}Sn+^{60}Ni [28, 29], ^{92}Mo+^{54}Fe [30], ^{197}Au+^{130}Te [31] and ^{206}Pb+^{118}Sn [32, 33], spanning up to four orders of magnitudes in cross sections.

Exploiting the achieved experience in the field we here propose to use the PRISMA + AGATA set-up to study the details of the A, Z, Q-value distributions and associated γ-rays of the reaction products in the ^{238}U+^{124}Sn reaction. The set-up will be also equipped with a second arm detector (NOSE) for high resolution kinematic coincidences to get light-heavy mass-mass correlations and to extract additional observables that characterize the heavy partners, like the transfer induced fission probability.

II. THE PROPOSED EXPERIMENT

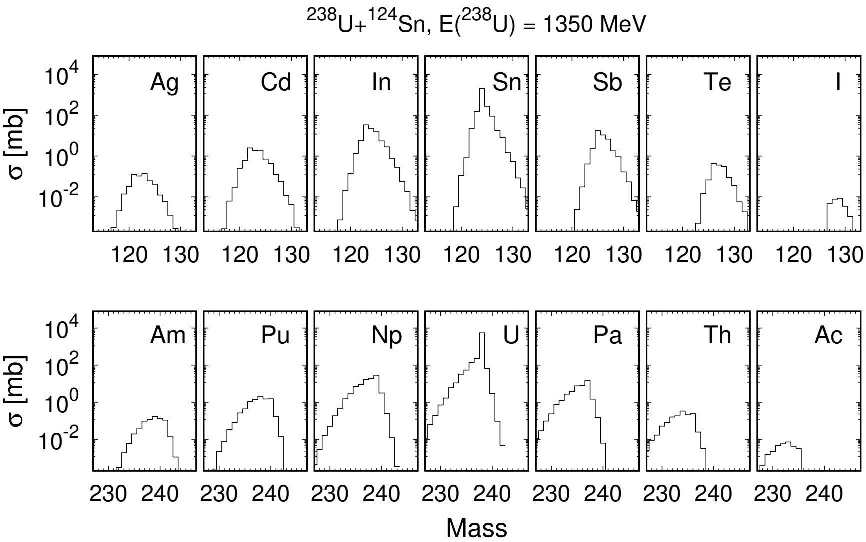

FIG. 2: The GRAZING calculated total cross section for various transfer channels, from $(-3p)$ to $(+3p)$, populated in the ^{238}U+^{124}Sn reaction at a bombarding energy of E_{lab} = 1350 MeV. In these calculation fission following transfer is not taken into account.

The proposed reaction is ^{238}U+^{124}Sn at a bombarding energy of E_{lab} = 1350 MeV, where inverse kinematics conditions guarantee the highest achievable A, Z, Q resolutions and detection

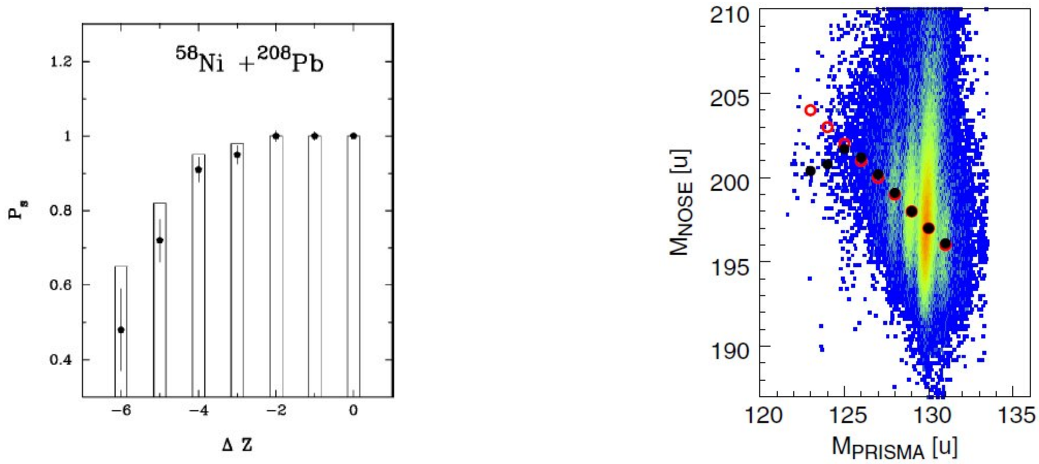

FIG. 3: Left: survival probability against fission P_s for the heavy target-like fragments in the ^{58}Ni+^{208}Pb multinucleon transfer reaction as a function of the number of transferred protons ΔZ averaged over neutron numbers. Points and histograms are the experimental and theoretical values, respectively (from [36]). Right: Mass-mass correlation matrix of Te isotopes detected in PRISMA and the heavy partner detected in coincidence with NOSE for the ^{197}Au+^{130}Te reaction (from Ref. [31]).

efficiency. Large cross sections for multinucleon transfer channels are predicted by the GRAZING model [12, 13], as shown in Fig. 2. Since transfer processes are governed by form factors and optimum Q-value considerations, with the ^{238}U projectile and ^{124}Sn target, besides proton stripping and neutron pick-up channels (the terms stripping and pick-up are referred to the lighter partner of the reaction), proton pick-up and neutron stripping channels open up, as experimentally shown in different heavy ion reactions by directly detecting in Z and A the light partner products [34, 35]. The path corresponding to proton pick-up leads to the very neutron-rich Th-Ra-Fr region, with predicted cross sections dropping off more rapidly than those of the proton stripping channels. These predictions do not agree with the results [19] shown in the right part of Fig. 1, where proton pick-up channels are favourite. On the other hand, TDHF calculations [9, 16], where large energy loss components should be better taken into account, seem to follow the experimental trends. One has to keep in mind that in low resolution experiments one has a poor knowledge of the detailed A, Z and Q-value distributions, consequently mixing up quasi-elastic, deep inelastic and fission contributions (including transfer induced fission). That the situation is in general unclear is seen for example from the left part of Fig. 1, where the experimental yields with masses below ^{238}U strongly differ from other models based on transport or diffusion processes [14].

The main aim of the proposed experiment is to make a major step forward in the understanding of these processes by measuring with significant statistics the complete yields of stripping and pick-up of neutrons and protons and their dependence on angles and Q values, with cross sections down to sub-μbarn. PRISMA will detect target-like recoils. The coupling to AGATA will be essential to measure the inelastic channel (important for reaction models), to quantify the transfer strength to excited states and to directly identify evaporative processes. AGATA will be important also to associate the reconstructed masses with the correct γ transitions and to help in the Z determination of heavy nuclei via detection of their characteristic X rays [37]. PRISMA will be employed also in a high resolution kinematic coincidence with the NOSE gas detector (see later) to extract the transfer induced fission probability of the heavy partner. This kind of measurement, based essentially on the determination of the ratio of binary coincident to single events has been already successfully employed in the ^{58}Ni+^{208}Pb reaction, as seen in the left panel of Fig. 3 (see Ref. [36] for details). The measurement of the transfer induced fission is important for testing into more detail the various reaction models, since the fission channel represents a substantial component of the total reaction cross section and is the main source of depletion from quasi-elastic processes. The PRISMA + NOSE coincidences allows at the same time to disentangle true binary processes from processes involving fission and to construct a light vs heavy mass-mass correlation matrix. Such a correlation was clearly demonstrated in the ^{197}Au+^{130}Te reaction [31], as reported in the right panel of Fig. 3, where the mass distribution of the heavy partner is shown to be located in well-defined bands. The black dots indicate the centroids of the projections of each band, showing how they slightly bend toward lower masses in comparison to those expected for the corresponding primary neutron transfer channels (red circles), directly indicating the effect of evaporation.

III. THE EXPERIMENT

The measurement will be performed in inverse kinematics by using a ^{238}U beam at the bombarding energy of E_{lab}= 1.35 GeV, with an average current of $\sim$ 1 pnA onto a 300 μg/cm^2 strip ^{124}Sn target, employing the superconducting PIAVE-ALPI accelerator complex of LNL. Target isotopic purity will be 99.81%. To avoid frequent replacement of targets due to heat dissipation of ^{238}U beam we are constructing a step-rotating target, based on a wheel driven by a mini-motor synchronized with a beam wobbled at a properly chosen frequency (presumably a few Hz). We will detect Sn-like recoils in PRISMA at θ_{lab}=35°, close to the grazing angle of the reaction, and the associated U-like ions in NOSE, which will be placed also at θ_{lab}=35° on the opposite side of the beam axis. For these kind of reactions in inverse kinematics and with this kind of entrance channel mass asymmetry, the grazing angles of the binary partners turn out to be quite similar. This situation is very useful since one can interchange the detection of the projectile-like and target-like ions to cross check the consistency of the yields determination. By detecting U-like ions in PRISMA we can take the opportunity to attempt a mass identification, at least for the transfer channels with large cross sections. Promising results have been already obtained in the analysis of the recent experiments [38], where AGATA turned out to be fundamental to guarantee the correct mass identification. For absolute normalizations, two monitor silicon detectors will be placed at proper angles to get pure Rutherford scattered ^{124}Sn ions.

NOSE [39] is a composite gas detector equipped with a Bragg ionization chamber, providing total energy and nuclear charge information, and a MWPPAC in front of it, providing X,Y position and timing signals. Resolutions are similar as those of the focal plane detectors in PRISMA. Such a detector has been already successfully employed in a high resolution kinematic coincidence experiment for the ^{197}Au+^{130}Te reaction [31]. It has recently been reassembled, upgraded and equipped with a new mechanical structure to be adapted for the PRISMA + AGATA scattering chamber. The geometrical solid angle is similar to the PRISMA's one. From cross section calculations performed with the GRAZING code and taking into account PRISMA detector efficiencies, we estimate to collect with PRISMA about 25 counts/day for primary cross sections of 1 μb/sr, corresponding to the $(+4p)$ channels (i.e. Xe isotopes), which will allow to well probe the predictive power of the different theoretical models. A 20% statistical error for cross sections averaged over 8-10 mass partitions for the same $(+4p)$ channels can be reached in 10 days of run. This fixes the request of beam time. Within this limit, assuming a 1% probability of survival against fission of the heavy partner, the binary kinematics coincidences with NOSE will be then measurable for $(+2p)$ channels, leading to a rate compatible for coincidences with AGATA.

For the proposed experiment we need to carefully set a complex set-up, requiring initial 2 days for PRISMA and NOSE. For PRISMA, additional 2 days for a Bρ scanning of the magnetic field in order to measure the possible cuts in the transmission of the spectrometer for the large deep inelastic components is also mandatory. So, we need a total of **14 days** of beam time.

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[1] A. N. Andreyev et al., Reports on Progr. in Phys., **81**, 016301 (2018).
[2] P. A. Butler, J. Phys. G **43** 073002 (2016).
[3] P. A. Butler et al., Phys. Rev. Lett. **124**, 042503 (2020).
[4] J. Dobaczewski et al., Phys. Rev. Lett. **121**, 232501 (2018).
[5] S. Agustsson et al., Scientific Reports **7**: 4207 (DOI:10.1038/s41598-017-04397-y).
[6] L. Corradi, G. Pollarolo and S. Szilner, J. of Phys. G: Nucl. Part. Phys. **36**, 113101 (2009).
[7] C. H. Dasso, G. Pollarolo, and A. Winther, Phys. Rev. Lett. **73**, 1907 (1994).
[8] V. Zagrebaev and W. Greiner, Phys. Rev. Lett. **101**, 122701 (2008).
[9] K. Sezikawa, Phys.. Rev. C **96**, 041601(R) (2017.)
[10] Y. X. Watanabe et al., Phys. Rev. Lett. 115, 172503 (2015).
[11] R. A. Broglia and A. Winther, Heavy Ion Reactions (Addison-Wesley, Redwood City, CA, 1991).
[12] A. Winther, Nucl. Phys. A **572**, 191 (1994).
[13] A. Winther, Nucl. Phys. A **594**, 2023 (1995).
[14] F. C. Dai et al., Phys. Rev. C **109**, 024617 (2024).
[15] C. Li et al, Phys. Lett. B **776**, 278 (2018).
[16] D. D. Zhang, D. Vretenar, T. Nikšić, P. W. Zhao, and J. Meng, Phys. Rev. C **109**, 024614 (2024).
[17] M. Schadel et al., Phys. Rev. Lett. **48**, 852 (1982).
[18] E. M. Kozulin et al., Phys. Rev. C **109**, 034616 (2024).
[19] W. Mayer et al, Phys. Lett. B **152**, 162 (1985).
[20] W von Oertzen, and A Vitturi, Rep. Prog. Phys. **64**, 1247 (2001).
[21] W. Krolas et al., Nucl. Phys. A **724**, 289 (2003).
[22] J. S. Barrett et al., Phys. Rev. C **91**, 064615 (2015).
[23] P. Colovic et al., Phys. Rev. C **102**, 054609 (2020).
[24] H. M. Devaraja et al., Phys. Lett. B **862**, 139353 (2025).
[25] S. Szilner et al., Phys. Rev. C **76**, 024604 (2007).
[26] The Advanced GAmma Tracking Array (AGATA), https://www.agata.org/
[27] L. Corradi et al., Phys. Rev. C **84**, 034603 (2011).
[28] D. Montanari et al., Phys. Rev. Lett. **113**, 052501 (2014).
[29] L. Corradi et al., Phys. Lett. B **834**, 137477 (2022).
[30] T. Mijatović et al., Journal of physics, Conference series **1643**, 012097 (2020).
[31] F. Galtarossa et al., Phys. Rev. C **97**, 054606 (2018).
[32] J. Diklic et al., Phys. Rev. C **107**, 014619 (2023).
[33] S. Szilner et al., Phys. Rev. Lett. **133**, 202501 (2024).
[34] T. Mijatovic et al., Phys. Rev. C **94**, 064616 (2016).
[35] T. Mijatovic, Frontiers in Phys. 965198 (2022).
[36] L. Corradi et al., Phys. Rev. C **66**, 024606 (2002).
[37] A. Vogt et al., Phys. Rev. C **92**, 024619 (2015).
[38] F. Galtarossa, T. Mijatovic et al., PAC Proposal LNL February 2024.
[39] E. Fioretto et al., Nucl. Instr. and Methods in Phys. Res. A **899**, 73 (2018).