Insights from multinucleon transfer reactions in ^{206}Pb+^{118}Sn

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Abstract. Multinucleon transfer reactions for the ^{206}Pb +^{118} Sn system were measured at E_{lab} = 1200 MeV using the PRISMA large solid-angle magnetic spectrometer. The experiment was conducted at laboratory angles around the grazing angle, covering an angular range of approximately 20°. The resulting differential and total cross sections, along with Q-value distributions for various neutron and proton pick-up and stripping channels, are presented. The Q-value distributions suggest a transition from quasi-elastic to deep inelastic collision processes, particularly in channels involving nucleon transfers. The experimental results have been compared with GRAZING code calculations, showing good agreement for few-nucleon transfer channels, while channels with large nucleon transfers are underestimated, indicating the involvement of more complex processes.

1 Introduction

In this proceeding findings published in Ref. [1] will be briefly introduced. In the publication we discussed the results from the ^{206}Pb + ^{118}Sn system measured around the Coulomb barrier, where our focus was on multinucleon transfer reactions. Such reactions are interesting because they connect quasielastic (QE) processes, where few nucleons are transferred with small kinetic-energy losses, to deep-inelastic collisions (DIC), where more nucleons are exchanged and large energy losses are observed. Despite decades of study, the detailed understanding of the transition between QE and DIC, influenced by nuclear structure and dynamics, remains challenging [2, 3].

Recent advances in multinucleon transfer reactions have highlighted their potential for producing exotic, heavy neutron-rich nuclei [4] and for studying nucleon-nucleon correlations at low energies dominated by quasielastic processes [5, 6]. The implementation of large-angle magnetic spectrometers has enabled efficient identification of transfer products [7–15], improving theoretical models [16–21], but further exploration is needed, particularly in heavy systems affected by high Coulomb fields.

In this study, we investigated the ^{206}Pb + ^{118}Sn system at an energy high enough to produce large mass and charge yields, allowing us to examine how cross sections and Q-value distributions evolve with the number of transferred nucleons. By selecting the ^{206}Pb + ^{118}Sn system, due to Q-value matching, we were able to observe both neutron and proton pick-up and stripping channels.

Additionally, we focused on neutron-stripping and proton pick-up channels, which are relevant for producing heavy neutron-rich nuclei [12, 13, 15, 22], and explored how mass and charge yields depend on energy losses as reactions transition from quasielastic (QE) to deep-inelastic (DIC) regimes, testing the description of neutron- and proton-transfer channels.

2 The experiment

In this experiment, a ^{206}Pb beam was accelerated to 1200 MeV using the PIAVE-ALPI accelerator at Legnaro National Laboratories into ^{118}Sn target. We used inverse kinematics where target-like fragments were detected using the PRISMA spectrometer [11] at two detecting angles θ_{lab} = 25° and 35°. High-resolution for A, Z, and Q-values are achieved. Monitor detectors enable to follow beam

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conditions throughout the experiment. After conducting an in-depth, event-by-event analysis of the reaction products, we successfully identified each ion [24, 25]. More details can be found in Ref. [1].

3 Results

The large acceptance of PRISMA allowed us to follow the evolution from quasielastic to deep-inelastic regimes, represented through Wilczynski plots [27]. We constructed this plot for all observed transfer channels, with Q-values calculated assuming binary reactions. As an example, in Fig. 1, the Wilczynski plot for (+1n) channel is shown, together with the projections onto the Q-value axis at selected center of mass angles. It can be observed that the distribution peak is near the ground-to-ground state Q-value (Q_{gs}) for the angle around the grazing one (θ_{cm} $\approx$109), while for more forward angles peak shifts at larger energy-loss region. The spectrometer's angular and energy acceptance may slightly affect these shapes [28, 29]. The data reveal the strong influence of the Coulomb field, with large energy-loss components increasing at backward angles, unlike reactions involving medium-mass projectiles [8, 14, 30–36]. These high-resolution measurements provide insight into more details, in such a heavy system, than previously observed.

Differential cross sections shown in Fig. 2 were extracted from measurements with large angular acceptance, which enable to follow the reaction evolution. For neutron-transfer channels, whole 40-degree acceptance, in center of mass system, is shown for the quasielastic peaks obtained by the cut in Q-value distribution (see more in Ref. [1]) and indicated with empty points in the Fig. 2. Differential cross sections for proton channels, are constructed by integrating whole Q-value spectra, shown with full points, while, only full Q-value distributions were used at θ_{lab} = 35°.

The angular distributions, shown in Fig. 2 and total cross sections in Fig. 3, were compared to GRAZING calculations [37, 38]. In the GRAZING model, two ions interact through both Coulomb and nuclear forces, allowing for nucleon exchange. The system's relative motion is computed within a combined nuclear and Coulomb field. Each nucleus is treated as a collection of independent nucleons, with the key degrees of freedom being surface vibrations and single-particle degree of freedom. For surface mode excitations, the model uses a macroscopic approximation, where the form factors are proportional to the derivative of the ion-ion potential with respect to distance, and their strengths are determined by the experimental $B(E\lambda)$ values. The model, for each nucleon transfer, uses a representative form factor. The exchange of many nucleons is treated independently and in the successive approximation. By comparing the calculations with the experimental angular distribution data shown in Fig. 2, a good agreement can be observed for the elastic+inelastic, and one-nucleon transfer channels. However, the experimental proton pick-up channels were underestimated, likely due to underestimating of the form factor strength. Additionally, neutron evaporation affected the neutron-stripping channels, leading to a progressive underestimation of the calculated cross sections.

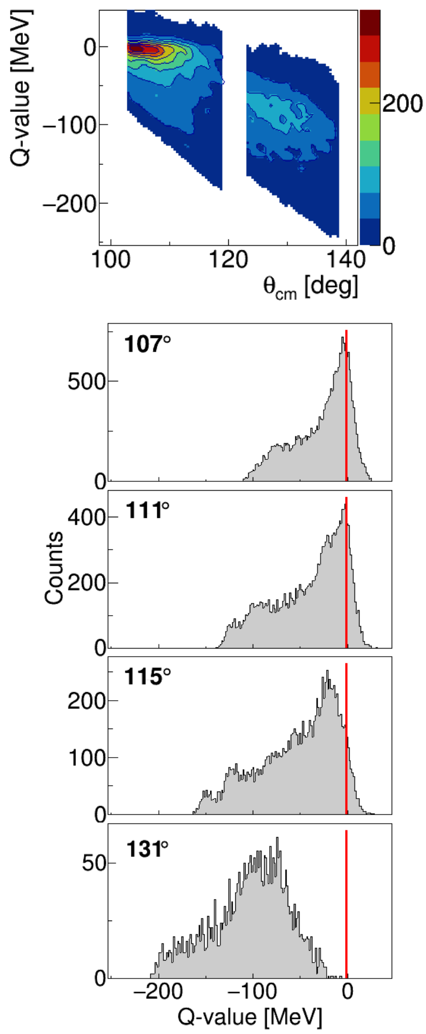

Figure 1. Matrix of Q-value vs center-of-mass angle θ_{cm} for the (+1n) channel (top). The matrix is displayed by matching the measured events at the two PRISMA angular and magnetic settings. The panels below show the projections onto the Q-value axis at the indicated center-of-mass angles (corresponding to θ_{lab} = 36.5°, 34.5°, 32.5°, and 24.5° starting from top to bottom, with $\Delta\theta_{\text{lab}} \approx 2°$). The vertical (red) lines represent the ground-to-ground state Q-value. Figure from [1].

Total cross sections in Fig. 3 are constructed by integrating differential cross sections, and similar conclusions can be made. We can observe good agreement with GRAZING in neutron-transfer channels. The discrepancies for proton-transfer channels suggest additional degrees of freedom, such as a stronger evaporation effect than GRAZING suggested, especially in proton striping channels, where the peaks of distributions are sifted towards lower masses. Pair-transfer modes may be also necessary to explain the results [10, 40]. The influence of charge transfer further affects proton-stripping channels, stressing the need for more detailed theoretical models, particularly for the proton pick-up side, which is crucial for accessing neutron-rich heavy nuclei.

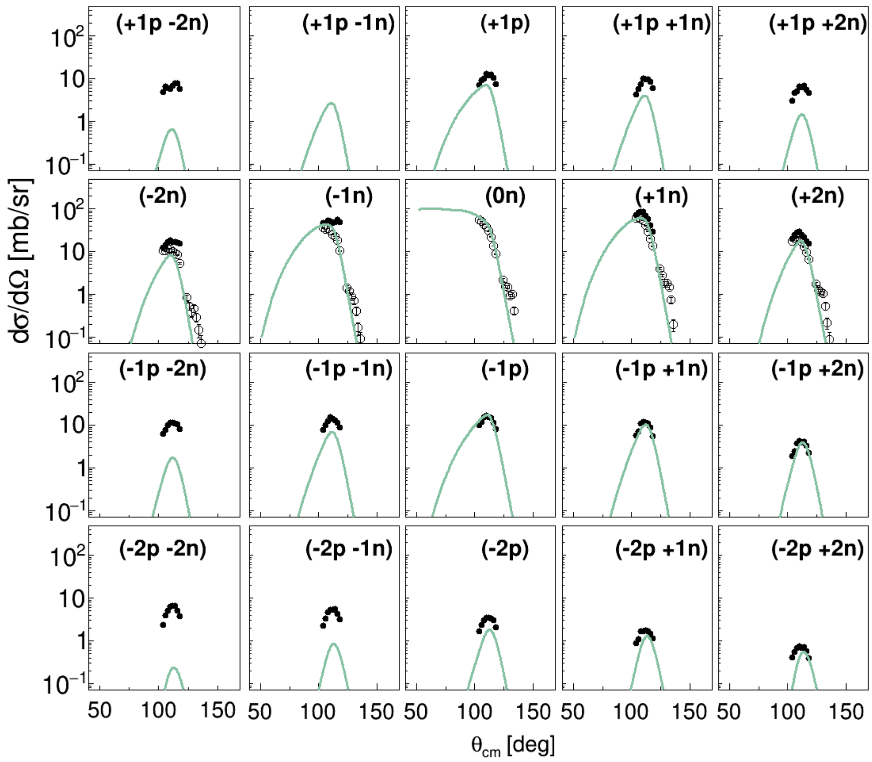

Figure 2. Experimental differential cross sections (points) compared with GRAZING calculations (lines). The filled circles correspond to the integration of the full Q-values, while the empty circles correspond to the quasielastic part only. The elastic + inelastic channel is plotted as a ratio over the Rutherford cross section (multiplied by 100). The experimental cross section for the (+1p − 1n) channel could not be safely extracted due to partial overlap with the ^{118}Sn yield. Experimental errors are statistical only. The relative normalization between the different PRISMA settings at $\theta_{\mathrm{lab}} = 25°$ and 35° was obtained by using the elastically scattered ^{118}Sn ions in the monitor detector placed at 58°. Figure from [1].

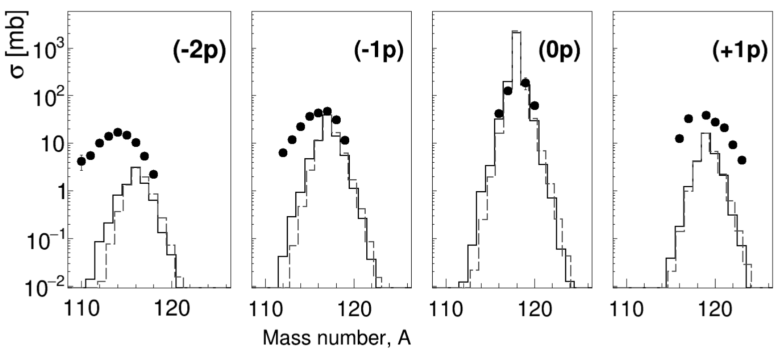

Figure 3. Experimental (points) and GRAZING calculated (histograms) total angle and Q-value integrated cross sections for the various transfer channels populated in the ^{206}Pb + ^{118}Sn reaction at E_{lab} = 1200 MeV. Experimental errors are only statistical ones and are almost all within the size of the symbols. The solid and dashed histograms represent the calculations performed with and without evaporation, respectively. The experimental cross sections for the pure neutron transfers have been extracted only for the ($\pm 1n$) and ($\pm 2n$) channels and only for the quasielastic part of the Q-values (see text for details). Due to the overwhelming elastic yield, the cross section for (+1p − 1n), corresponding to ^{118}Sb, is not included. Figure from [1].

4 Conclusion

Multineutron and multiproton transfer channels were successfully measured with high resolution in the ^{206}Pb + ^{118}Sn system at E_{lab} = 1200 MeV for nuclei around $A \approx 120$, utilizing the large solid-angle magnetic spectrometer PRISMA. By examining the Q-value distributions as a function of the scattering angle, mass, and charge of the transfer products, we tracked the evolution from quasielastic to deep-inelastic processes. For few-nucleon transfer channels, these observables, such as Q-values and cross sections, largely retain the characteristics of direct processes. However, in channels involving many nucleons, the large energy loss leads to significant reshuffling in the final yield distributions.

Comparing the experimental cross sections with those predicted by the GRAZING code shows an overall good agreement for most few-nucleon transfer channels. This agreement demonstrates the validity of the nuclear potential and the range of partial waves used in the calculations, even for this heavy system. However, the progressive underestimation of the yields for channels with more nucleon transfers suggests that more complex processes, not fully captured by current theory, may be at play. The different behavior between proton stripping and proton pick-up channels, particularly significant for producing neutron-rich heavy nuclei, remains an open question, indicating the need for further studies and improvement in the theoretical description of proton transfers.

References

[1] J. Diklić et al., Phys. Rev. C **107**, 014619 (2023).
[2] W. von Oertzen and A. Vitturi, Rep. Prog. Phys. **64**, 1247 (2001).
[3] L. Corradi, G. Pollarolo, and S. Szilner, J. Phys. G: Nucl. Part. Phys. **36**, 113101 (2009).
[4] C. H. Dasso, G. Pollarolo, and A. Winther, Phys. Rev. Lett. **73**, 1907 (1994).
[5] D. Montanari, L. Corradi, S. Szilner, G. Pollarolo, E. Fioretto, G. Montagnoli *et al.*, Phys. Rev. Lett. **113**, 052501 (2014).
[6] L. Corradi, S. Szilner, G. Pollarolo, T. Mijatović, D. Montanari, E. Fioretto, A. Goasduff, D. Jelavić Malenica, G. Montagnoli, and A. M. Stefanini, Phys. Lett. B **834**, 137477 (2022).
[7] C. L. Jiang, K. E. Rehm, H. Esbensen, D. J. Blumenthal, B. Crowell, J. Gehring, B. Glagola, J. P. Schiffer, and A. H. Wuosmaa, Phys. Rev. C **57**, 2393 (1998).
[8] L. Corradi, A. M. Stefanini, C. J. Lin, S. Beghini, G. Montagnoli, F. Scarlassara, G. Pollarolo, and A. Winther, Phys. Rev. C **59**, 261 (1999).
[9] L. Corradi *et al.*, Phys. Rev. C **63**, 021601(R) (2001).
[10] S. Szilner *et al.*, Phys. Rev. C **71**, 044610 (2005).
[11] S. Szilner, C. A. Ur, L. Corradi, N. Marginean, G. Pollarolo, A. M. Stefanini *et al.*, Phys. Rev. C **76**, 024604 (2007).
[12] Y. X. Watanabe, Y. H. Kim, S. C. Jeong, Y. Hirayama, N. Imai, H. Ishiyama *et al.*, Phys. Rev. Lett. **115**, 172503 (2015).
[13] A. Vogt *et al.*, Phys. Rev. C **92**, 024619 (2015).
[14] T. Mijatović, S. Szilner, L. Corradi, D. Montanari, G. Pollarolo, E. Fioretto *et al.*, Phys. Rev. C **94**, 064616 (2016).
[15] F. Galtarossa, L. Corradi, S. Szilner, E. Fioretto, G. Pollarolo, T. Mijatović *et al.*, Phys. Rev. C **97**, 054606 (2018).
[16] V. Zagrebaev and W. Greiner, Phys. Rev. Lett. **101**, 122701 (2008).
[17] K. Sekizawa and S. Ayik, Phys. Rev. C **102**, 014620 (2020).
[18] K. Sekizawa, Front. Phys. **7**, 20 (2019).
[19] C. Li, J. Tian, and F. S. Zhang, Phys. Lett. B **809**, 135697 (2020).
[20] C. Simenel and A. Umar, Prog. Part. Nucl. Phys. **103**, 19 (2018).
[21] T. Mijatović, Front. Phys. **10**, 965198 (2022).
[22] D. M. Brink, Phys. Lett. B **40**, 37 (1972).
[23] P. Čolović, S. Szilner, A. Illana, J. J. Valiente-Dobón, L. Corradi, G. Pollarolo *et al.*, Phys. Rev. C **102**, 054609 (2020).
[24] G. Montagnoli *et al.*, Nucl. Instrum. Methods Phys. Res. A **547**, 455 (2005).
[25] S. Beghini *et al.*, Nucl. Instrum. Methods Phys. Res. A **551**, 364 (2005).
[26] F. Galtarossa, Multinucleon transfer in the 197Au + 130Te reaction studied with a high-resolution kinematic coincidence, Ph.D. thesis, University of Ferrara, 2018.
[27] J. Wilczynski, Phys. Lett. B **47**, 484 (1973).
[28] D. Montanari *et al.*, Eur. Phys. J. A **47**, 4 (2011).
[29] T. Mijatović *et al.*, Eur. Phys. J. A **52**, 113 (2016).
[30] A. Gobbi and W. Norenberg, in Heavy Ion Collisions, Vol. 2, edited by R. Bock (North-Holland, Amsterdam, 1980).
[31] W. U. Schroder and J. R. Huizenga, Annu. Rev. Nucl. Sci. **27**, 465 (1977).
[32] D. H. E. Gross and H. Kalinowski, Phys. Rep. **45**, 175 (1978).
[33] S. Pontoppidan *et al.*, Phys. Rev. C **28**, 2299 (1983).
[34] W. Mayer, G. Beier, J. Friese, W. Henning, P. Kienle, H. J. Körner, W. A. Mayer, L. Müller, G. Rosner, and W. Wagner, Phys. Lett. B **152**, 162 (1985).
[35] K. E. Rehm, A. M. van den Berg, J. J. Kolata, D. G. Kovar, W. Kutschera, G. Rosner, G. S. F. Stephans, and J. L. Yntema, Phys. Rev. C **37**, 2629 (1988).
[36] R. Płaneta, K. Kwiatkowski, S. H. Zhou, V. E. Viola, H. Breuer, M. A. McMahan, W. Kehoe, and A. C. Mignerey, Phys. Rev. C **41**, 942 (1990).
[37] A. Winther, Nucl. Phys. A **572**, 191 (1994).
[38] A. Winther, Nucl. Phys. A **594**, 203 (1995).
[39] J. M. Quesada, G. Pollarolo, R. A. Broglia, and A. Winther, Nucl. Phys. A **442**, 381 (1985).
[40] L. Corradi *et al.*, Phys. Rev. C **66**, 024606 (2002).