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Modeling multi-nucleon transfer in symmetric collisions of massive nuclei

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ABSTRACT

Symmetric collisions of massive nuclei, such as ^{238}U + ^{248}Cm, have been proposed as ways to make new n-rich heavy nuclei via multi-nucleon transfer (MNT) reactions. We have measured the yields of several projectile-like and target-like fragments from the reaction of 1360 MeV ^{204}Hg + ^{198}Pt. We find that current models for this symmetric collision (GRAZING, DNS, ImQMD) significantly underestimate the yields of these transfer products, even for small transfers.

1. Introduction

Multi-nucleon transfer reactions have long been used to make heavy nuclei for nuclear spectroscopic studies. Recently attention has been focused on the use of these reactions to study nuclei with N = 126 and to synthesize new neutron-rich heavy nuclei. (Regarding this last point, we note that all trans-uranium nuclei synthesized in hot fusion reactions are neutron-deficient relative to the line of beta stability.)

One of the motivations for the study of multi-nucleon transfer reactions in the heavy nuclei is the recent work of Zagrebaev and Greiner [1]. These authors have pointed out several promising examples of opportunities to make new neutron rich actinide nuclei using multi-nucleon transfer reactions such as ^{238}U + ^{248}Cm. In these reactions, they postulate a mass transfer from the projectile to the target nucleus driven by shell effects in the multidimensional potential energy surface that governs the dynamics of such collisions at low excitation energies (so-called inverse quasi-fission). These reactions are difficult to study due to low beam intensities, low cross-sections (picobarn–nanobarn) and the difficulty of detecting the most neutron rich products, which are β-emitters.

Because of these limits on experimental verification of these exciting possibilities, people have recognized the utility and necessity of comparing measurements of multi-nucleon transfer reactions with appropriate models in simpler systems. A well-known model for predicting the cross sections for transfer products is GRAZING, a semi-classical model due to Pollarolo and Winther [2,3]. GRAZING uses a semi-classical model of the reacting ions moving on classical trajectories with quantum calculations of the probability of excitation of collective states and nucleon transfer. This model describes few nucleon transfers [4] well. It has been employed to describe the production of projectile like fragments (PLFs) involving transfers of 4–5 nucleons in the asymmetric reaction of ^{136}Xe with ^{238}U, where the predictions of this model "agree well" with measurements [5]. (A modification of the GRAZING code to calculate the decay of primary products by fission and neutron emission has been published [6].)

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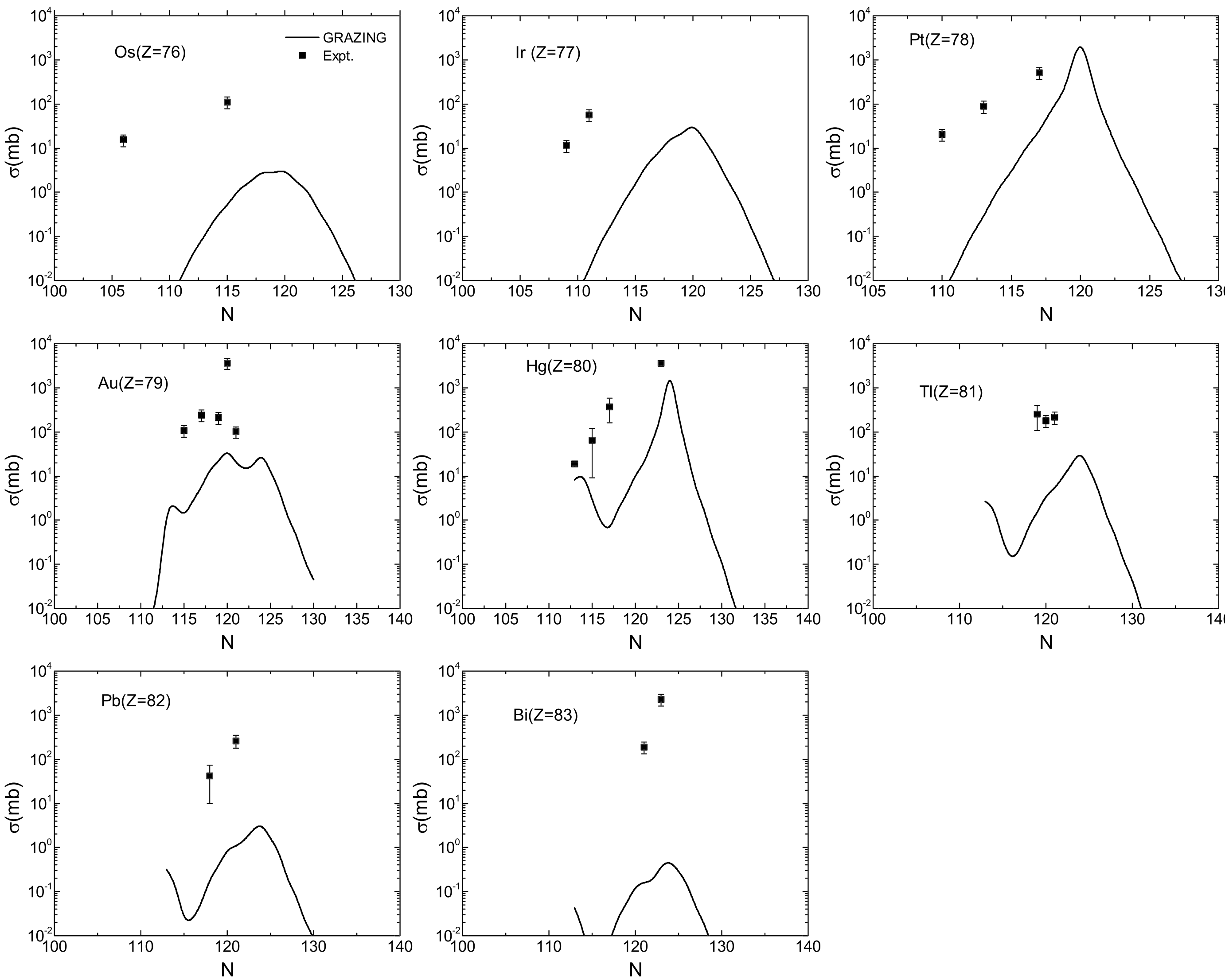

Fig. 1. The observed fragment yields for the $E_{c.m.} = 619$ MeV ^{204}Hg + ^{198}Pt reaction compared to the predictions of the GRAZING model.

Barrett et al. [7] compared quantitatively the predictions of the GRAZING model and the calculations of Zagrebaev and Greiner to describe the yields of the PLFs and the target-like fragments (TLFs) for the reaction of $E_{c.m.} = 450$ MeV ^{136}Xe with ^{208}Pb. They found that the GRAZING model worked well to describe transfers of $\Delta Z = -1$ to $+2$, but failed to describe larger transfers while the model of Zagrebaev and Greiner reproduced the observed distributions for $\Delta Z = -8$ to $+4$. Li et al. [8] reviewing the same data, came to similar conclusions about the GRAZING model.

Wen et al. [9] and Zhu et al. [10] have pointed out that significant improvements can be made by combining a dinuclear system (DNS) approach with the GRAZING model. (Zhu et al. [10] also predict, using the DNS model, the possibility of making n-rich nuclei with Z = 99–104 in the symmetric collisions of massive nuclei.) Feng [11] also shows the predictions of the DNS model for the data of Barrett et al. [7]. The DNS model treats the more central collisions neglected in the GRAZING model leading to significantly better predictions for large transfers in the $E_{c.m.} = 450$ MeV ^{136}Xe + ^{208}Pb reaction and the $E_{c.m.} = 307.5$ MeV ^{64}Ni with ^{238}U reactions. The GRAZING model describes transfer in peripheral collisions where no capture has occurred while the DNS model describes transfer in more central collisions after capture. The two approaches are thus complementary.

Li et al. [8] did find excellent agreement between the data for the $E_{c.m.} = 450$ MeV ^{136}Xe + ^{208}Pb reaction and the predictions of the improved Quantum Molecular Dynamics model [12].

In this paper, we report the measurement of the yields of the TLFs and PLFs from the **symmetric** reaction of $E_{c.m.} = 619$ MeV $^{204}_{80}$Hg with $^{198}_{78}$Pt. We find that the GRAZING/DNS model underestimates the yields of the smallest transfers (and the larger transfers) by an order of magnitude or more while the ImQMD model does a better (but not adequate) job of representing the data.

2. Experimental methods

This experiment was performed at the ATLAS facility of the Argonne National Laboratory. A beam of 1360 MeV ^{204}Hg^{31+} ions struck a thick (47 mg/cm^2) ^{198}Pt target (91.63% ^{198}Pt). The beam stopped in the thick target and the center of target beam energy was 1257 MeV ($E_{c.m.} = 619$ MeV). The effective target thickness was 4.8 mg/cm^2. The irradiation lasted 1661 minutes with an average beam intensity of 1.3×10^9 particles/s. Counting of the irradiated sample using a well-calibrated Ge detector (in the ATLAS hot chemistry laboratory) commenced about 22 hours after the end of the irradiation and continued for about 3 days. (Nine sequential measurements of the target radioactivity were made.)