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OSTIMULTI-NEUTRON TRANSFER REACTIONS AT
SUB-BARRIER ENERGIES

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The optimum conditions for multi-neutron transfer have been studied in the system $^{58}\text{Ni} + ^{124}\text{Sn}$ at bombarding energies at and below the Coulomb barrier. The experiments were performed in inverse kinematics with a ^{124}Sn beam bombarding a ^{58}Ni target. The particles were identified with respect to mass and Z in the split-pole spectrograph with a hybrid focal plane detector with mass and Z -resolutions of $A/\Delta A=150$ and $Z/\Delta Z=70$. At all energies the transfer of up to 6 neutrons was observed. The yields for these transfer reactions are found to decrease by about a factor of four for each transferred neutron.

1 Introduction

Heavy ion fusion followed by neutron evaporation has become the primary tool for the production of nuclei on the proton-rich side of the mass valley, allowing nuclear structure studies of isotopes ranging from the valley of stability to the proton drip line. Nuclei on the neutron-rich side of the mass valley, however, are much harder to reach. Most of the nuclear structure information in this region of the N - Z plane comes from fission reactions which produce nuclei in the mass range $A \sim 70$ - 150 ^{1,2}. While lighter nuclei ($A \leq 70$) on the neutron-rich side of the mass valley have recently been produced via projectile fragmentation reactions³, very little information is available for neutron-rich nuclei with masses $A \geq 160$.

Exotic multi-nucleon transfer reactions are presently the only way to investigate neutron-rich isotopes in this mass region. Deep-inelastic proton-pickup reactions induced by Xe, W and U beams have been used to study half-lives and decays of neutron-rich Lu, Yb and Tm isotopes⁴. Another method are pickup reactions induced by lighter heavy ions (e.g. $(^{18}\text{O}, ^{20}\text{Ne})$, $(^{18}\text{O}, ^{17}\text{F})$) on neutron-rich target nuclei⁵. The cross sections for these processes are typically only of the order of 1-10 μb , and thus require highly efficient detection techniques capable of separating the channel of interest from the other reaction products which are generated with considerably higher yields. In this contribution we will discuss the possibility of using multi-neutron transfer reactions on neutron-rich targets at bombarding energies in the vicinity of the Coulomb

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barrier for the production of nuclei on the neutron-rich side of the mass valley.

2 Theoretical Considerations

Spectroscopic studies of neutron-rich nuclei produced via multi-neutron transfer reactions have been performed for a few cases in the past^{6,7,8}. However, transfers of only one and two neutrons have been observed with reasonable cross sections so far. For the four-neutron transfer reaction $^{26}\text{Mg}(^{18}\text{O}, ^{14}\text{O})^{30}\text{Mg}$ cross sections of only 10 nb/sr have been measured⁹. These low transfer yields are caused by unfavorable kinematic matching conditions. As shown in Ref.10, these kinematic matching conditions are the controlling factor in heavy-ion induced transfer reactions. The maximum transfer yield is concentrated within a so-called Q-window, located to first order at a Q-value Q_{opt} , which, to first order, is given by:

$$Q_{opt} = Q_{gg} - E^* = E_i \cdot \left(\frac{z'Z'}{zZ} - 1 \right) \quad (1)$$

where Q_{gg} is the ground state Q value, E^* the total excitation energy, E_i the incident energy in the center-of-mass system, and zZ and $z'Z'$ the product of the nuclear charges in the entrance and exit channel, respectively. The width of the distribution can be calculated within the semiclassical model¹¹ and is typically ~ 8 MeV.

From eq. (1) one obtains for neutron transfer reactions (neglecting recoil corrections):

$$Q_{opt} = 0 \quad (2)$$

$$E^* = Q_{gg}. \quad (3)$$

A typical Q window for neutron transfer reactions is shown schematically in Fig. 1. For a positive ground state Q value a large range of excitation energies is located inside the Q window. A negative ground state Q value, on the other hand, results in strongly reduced yields.

In the following we will consider as a test case the production of neutron-rich Gd isotopes through multi-neutron transfer reactions on a ^{160}Gd target. The solid lines in Figure 2a give the ground state Q values for the one- to six-neutron transfer reactions induced by several stable projectiles ranging from

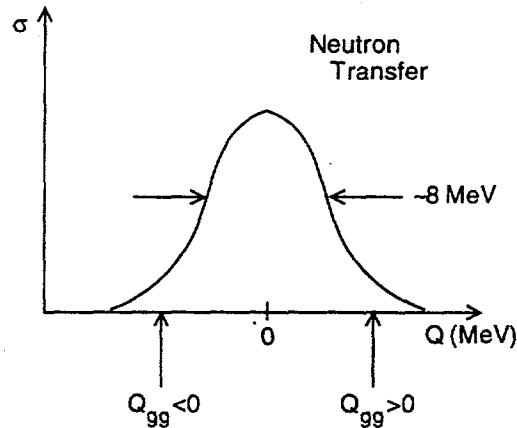


Figure 1: Schematic of a Q window for neutron transfer reactions.

^{18}O to ^{208}Pb on ^{160}Gd . Q values for other target nuclei show a similar behaviour.

The fact that the ground state Q values for the three- to six neutron transfer reactions leading to $^{163-166}\text{Gd}$ are less than -5 MeV and thus not within the optimum Q window explains the observation that in experiments with stable beams only one- and two-neutron transfer reactions could be studied so far.

The dashed line in Fig. 2a represents the ground state Q values calculated for the one- to six neutron transfer reactions induced by a radioactive ^{142}Xe beam on ^{160}Gd . Contrary to the Q_{gg} values that are available with stable beams, the Q values for neutron transfers in the $^{142}\text{Xe} + ^{160}\text{Gd}$ system are positive and thus the transfer yields should not be suppressed due to unfavourable matching conditions.

Exotic beams such as ^{142}Xe will be available at the next generation radioactive beam facilities. In order to study the reaction mechanism for Q-matched multi-neutron transfer reactions we have performed pilot experiments for the system $^{58}\text{Ni} + ^{124}\text{Sn}$ using stable ^{124}Sn beams. The ground state Q values for the one- to six neutron transfer reactions are shown in Fig. 2b. The Q values for these multi-neutron transfer reactions are all positive, similar to the $^{142}\text{Xe} + ^{160}\text{Gd}$ case.

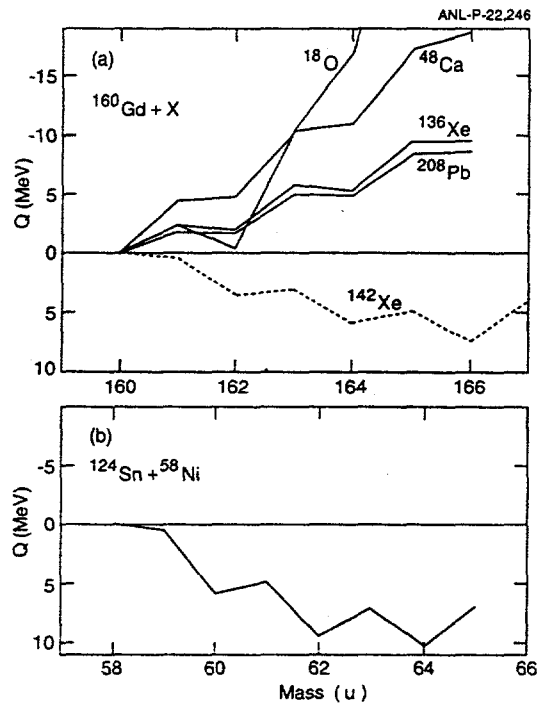


Figure 2: (a) Ground state Q values for producing $^{161-166}\text{Gd}$ nuclei via multi-neutron transfer reactions induced by different projectiles on a ^{160}Gd target. (b) Ground state Q values for the system $^{58}\text{Ni} + ^{124}\text{Sn}$ producing $^{59-65}\text{Ni}$ isotopes.

3 Experimental Details

The experiment was performed at Argonne National Laboratory's ATLAS accelerator by bombarding a ^{58}Ni target with ^{124}Sn beams at energies between 480 - 512 MeV. In order to keep the excitation energy in the final system, and thus neutron evaporation effects to a minimum, the experiments were performed at incident energies in the vicinity of the Coulomb barrier. The choice of inverse kinematics, i.e. bombarding a lighter target (^{58}Ni) with a heavy (^{124}Sn) beam is essential at low center-of-mass energies since under these conditions the Ni-like reaction products are emitted with high energies at forward angles, which strongly simplifies their mass and Z-identification. The Ni and Sn like particles were momentum analyzed in the Enge Split-Pole spectrograph

and detected in the focal plane with a hybrid focal plane detector¹² which measured mass, charge and Q value with resolutions of $A/\Delta A=150$, $Z/\Delta Z=70$ and $\Delta Q \sim 3$ MeV. Due to the large dynamic range of the spectrograph 60-80 % of the total charge-state distributions for quasi-elastic Sn and Ni-like reaction products could be measured with a single magnetic field setting. A mass spectrum for Ni- isotopes measured at a scattering angle of $\Theta_{lab}=20^\circ$ at an energy of $E_{c.m.}=153$ MeV is shown in Fig.3. Ni isotopes in the mass range $A=58-65$, originating from the one- to seven neutron transfer reactions are observed.

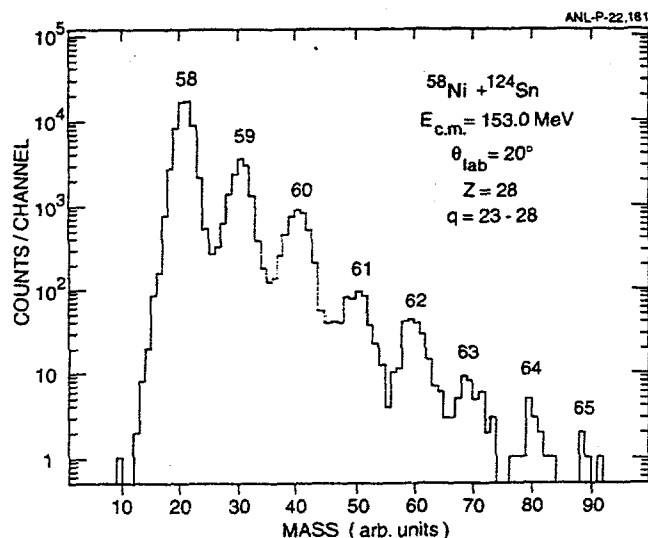


Figure 3: Mass spectrum for Ni ($Z=28$) isotopes measured at $E_{c.m.} = 153$ MeV in the system $^{58}\text{Ni} + ^{124}\text{Sn}$.

4 Experimental Results

The angular distributions for elastic scattering (including inelastic excitations up to 4 MeV) are shown in Fig.4. The solid lines are coupled-channel calculations performed with the code PTOLEMY¹³ including the ground state and the first excited 2^+ states in ^{58}Ni and ^{124}Sn , with coupling matrix elements taken from the literature¹⁴. Deviations from Rutherford scattering occur only at backward angles with the ratio $\sigma_{el}/\sigma_{Rutherford}$ reaching values between 0.5 and 0.1 at $\Theta_{c.m.}=180^\circ$.

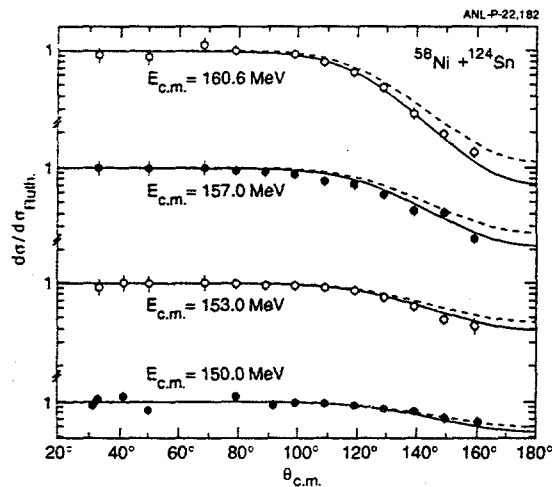


Figure 4: Angular distributions for elastic scattering (including inelastic excitations up to $E^* = 4$ MeV) for the system $^{58}\text{Ni} + ^{124}\text{Sn}$. The solid lines are coupled-channels calculations with different optical potentials.

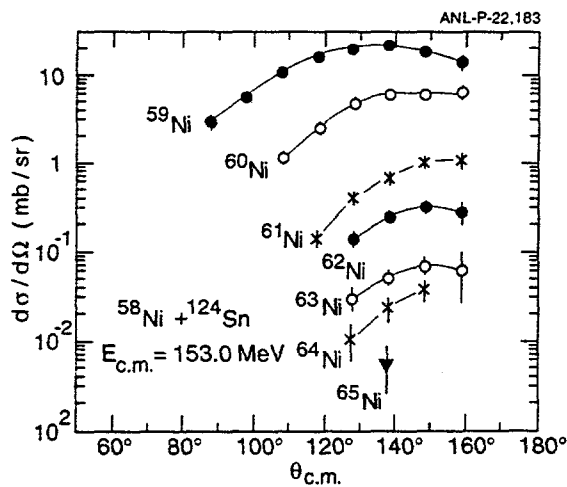


Figure 5: Angular distributions for neutron transfer reactions measured in the system $^{58}\text{Ni} + ^{124}\text{Sn}$ at $E_{c.m.} = 153$ MeV. The lines serve to guide the eye.

Angular distributions for multi-neutron transfer reactions measured at $E_{c.m.} = 153$ MeV are given in Fig. 5. These distributions are all backward peaked with maxima that shift to larger scattering angles with increasing number of transferred neutrons. Proton transfer reactions yielding Co, Fe, Mn and Cr isotopes are also observed with cross sections which are smaller than the neutron transfer yields by factors of 5 - 100. The energy and angle-integrated neutron transfer cross sections measured at the four bombarding energies are presented in Fig.6. It can be seen that the cross sections fall off exponentially with increasing number of transferred neutrons. At energies in the vicinity of the Coulomb barrier ($E_{c.m.} = 157, 160.6$ MeV) the angle-integrated cross sections for the six-neutron transfer reactions are in the 100-200 μb range: i.e. considerably larger than the yields obtained for deep-inelastic proton-pickup reactions ^{4,5}.

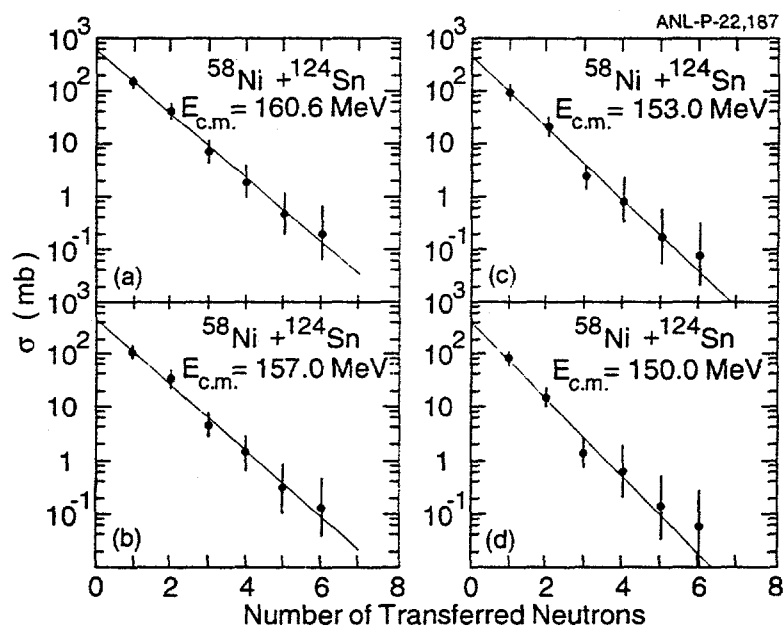


Figure 6: Angle- and energy integrated cross sections as function of the number of transferred neutrons for the system $^{58}\text{Ni} + ^{124}\text{Sn}$ at four incident energies. The solid lines are least-squares fits to the data.

A similar behaviour has been observed in other Q-matched multi-neutron transfer reactions which have been studied previously, including $^{112}\text{Sn} + ^{120}\text{Sn}$ ¹¹,

$^{58}\text{Sn} + ^{100}\text{Mo}^{15}$ and $^{40}\text{Ca} + ^{124}\text{Sn}^{16}$.

The ratio of the transfer cross sections between the n and $n+1$ neutron transfer reaction σ_n/σ_{n+1} measured in the system $^{58}\text{Ni} + ^{124}\text{Sn}$ at the highest bombarding energy is plotted in Fig.7.

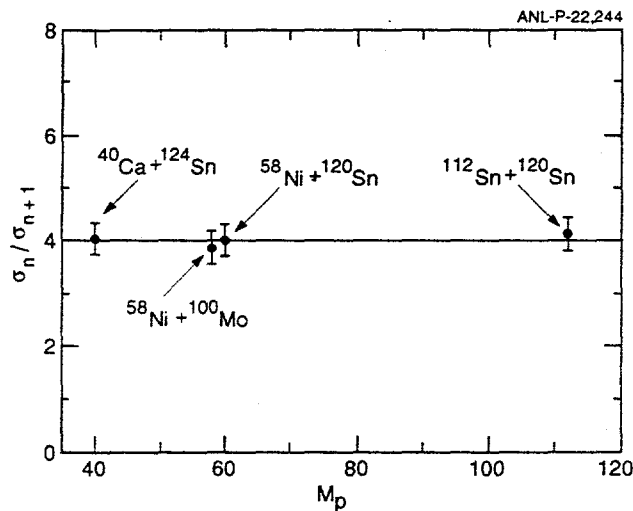


Figure 7: Ratio of the angle- and energy-integrated cross sections σ_n/σ_{n+1} for multi-neutron transfer reactions measured in several systems.

Also included are the ratios σ_n/σ_{n+1} obtained for other systems measured in Refs.11,15,16. It is interesting to note that for incident energies at and above the Coulomb barrier all of them exhibit the same σ_n/σ_{n+1} ratios of about 4. Since the cross sections for Q -matched one-neutron transfer reactions are typically around 200 mb¹⁷, we expect cross sections for the six-neutron transfer reactions around 200 μb . Calculations performed with the multi-nucleon transfer code of Ref.18 are in good agreement with these observations¹⁴.

5 Summary

Although the target-projectile combination for this first pilot experiment with stable beams was not selected to produce nuclei on the neutron-rich side of the mass valley, the results have some bearing on the production of exotic neutron-rich nuclei in future experiments with radioactive beams. In order not

to experience a suppression of the production yields due to the underlying kinematic matching conditions, positive ground-state Q values for multi-neutron transfer reactions are essential. In reactions with stable ion beams this is generally difficult to achieve and, therefore, only one- and two-neutron transfer reactions have been observed in first experiments studying neutron-rich heavy nuclei. By selecting projectile-target combinations with the best ground state Q values using radioactive ion beams a strong enhancement in the production yields can be expected. Experiments with stable beams as well as calculations with a newly developed multi-particle transfer code¹⁸ predict cross sections of 1-2 mb for the four-neutron transfer and 100-200 μb for the six-neutron transfer reactions. These yields are considerably larger than the ones observed for exotic proton-pickup reactions which are typically in the μb range. Using a γ detector array with a 10 % overall efficiency, a 0.1 pA beam intensity, a 500 $\mu\text{g}/\text{cm}^2$ target, a γ multiplicity of 5 and a 100 μb cross section a reaction rate of ~ 200 events/hour can be expected. Angular momentum transfers up to $\sim 14 \hbar$ for a two-neutron transfer reaction have been observed⁸ at energies which are ~ 20 % above the Coulomb barrier. At lower incident energies even higher angular momentum transfers can be expected for multi-neutron transfer reactions due to the increased momentum mismatch. Multi-neutron transfer reactions induced by radioactive ion beams will thus open up a region of the N-Z plane for nuclear structure studies which is at present inaccessible.

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References

1. I. Ahmad and W. R. Phillips, *Rep. Prog. Phys.* **58**, 1415 (1995).
2. J. H. Hamilton *et al.* *Prog. Part. Nucl. Phys.* **35** 635, (1995).
3. K. Rykaczewski, contribution to this conference.
4. K. Rykaczewski *et al.* *Nucl. Phys. A* **499**, 529 (1989).
5. C. T. Zhang, contribution to this conference.
6. J. Koenig *et al.* *Phys. Rev. C* **24**, 2076 (1981).
7. R. Broda *et al.* *Phys. Rev. Lett.* **74**, 868 (1995).
8. I. Y. Lee *et al.* *Phys. Rev. C* **56**, 753 (1997).

9. I. Paschopoulos *et al*, *Phys. Rev. C* **18**, 1277 (1978).
10. P. J. A. Buttle and L. J. B. Goldfarb, *Nucl. Phys. A* **176**, 299 (1971).
11. W. von Oertzen *et al*, *Z. Phys. A* **326**, 463 (1987).
12. K. E. Rehm and F. L. H. Wolfs, *Nucl. Instrum. Methods A* **273**, 262 (1988).
13. M. H. Macfarlane and S. C. Pieper, Argonne National Laboratory Report No. ANL-76-11(Rev.1), 1978.
14. C. L. Jiang *et al*, submitted to *Phys. Rev. C*.
15. C. L. Jiang *et al*, *Phys. Lett. B* **337**, 59 (1994).
16. L. Corradi *et al*, *Phys. Rev. C* **54**, 201 (1996).
17. K. E. Rehm *et al*, *Phys. Rev. C* **42**, 2497 (1990).
18. C. Dasso *et al*, *Phys. Rev. Lett.* **73**, 1907 (1993).