CONF-880896--4

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DE89 000606

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Invited Paper
Presented at the

International Symposium

on

Heavy-Ion Reaction Dynamics

Hitachi, Japan 1-3 August, 1988

To be published by
Universal Academy Press, Tokyo

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ABSTRACT

The measurement of sub-barrier transfer reactions between heavy ions using a recoil mass separator is discussed. Data are presented for one and two particle transfer reactions of ^{58}Ni + ^{A}Sn and ^{58}Ni + ^{A}Sm over a range of bombarding energies from close to far below the interaction barrier. The data are analyzed in the framework of a semi-classical model of the transfer process. The results for one-nucleon transfer on the deformed targets show anomalous behavior.

I. Introduction

There is great interest[1)] in the study of the interaction of heavy nuclei at energies close to and below their mutual interaction barrier. The initial motivation for this interest came from the observation of the anomalous behavior of cross-sections for complete fusion in this energy region, the observed magnitude of this quantity frequently being orders of magnitude larger than predictions based on simple tunneling through a one-dimensional potential barrier. It is now generally agreed that the origin of the observed enhancement lies in the coupling of the entrance channel to other degrees of freedom of which inelastic scattering and transfer of particles to low-lying states are believed to be the most important. In addition, the study of quasi-elastic reactions in this energy region is of interest in its own right, due to the possibility that new aspects of these reactions might appear, such as phenomena associated with the tunneling of nucleons and nucleon pairs through the barrier which exists between the colliding ions at the closest point of the trajectory.

Despite these strong motivations, few data exist in the sub-barrier region for reaction channels other than fusion. This deficiency arises in part from experimental difficulties. Reactions between heavy ions are governed primarily by the closest approach of the colliding nuclei which, at low energies, results in a strong backward peaking of the reaction yield in the center-of-mass frame. For cases where the projectile has a significant fraction of the target mass, as is so in most cases of interest, the backscattered projectile-like fragment has such low energy that the usual techniques of measurement and identification are no longer operative. Here we report on a method which allows the systematic study of many aspects of these reactions in the energy regime of interest. We exploit the fact that associated with the backscattered projectile-like fragment is a complementary forward-scattered target-like fragment which recoils with a large fraction of the projectile energy. These fragments were detected and identified using a recoil mass separator (RMS) which allows the measurement of quasi-elastic transfer reactions in a hitherto almost unaccessible energy range.

2. Experiment

The experiments were performed using beams of ^{58}Ni ions of energies ranging from 180 to 260 MeV, provided by the Daresbury Nuclear Structure facility tandem accelerator. Targets of ^{116,118,120,122,124}Sn and ^{144,148,150,152,154}Sm were used and the recoiling target-like fragments were detected using a RMS.

The Daresbury RMS has been described[2)] in detail in the literature; a schematic layout is shown in Fig. 1. Briefly, it consists of a pair of ExB

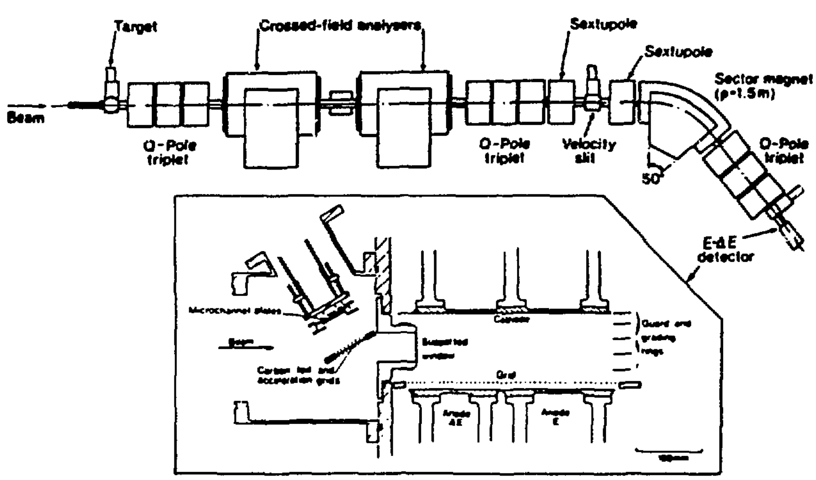


Fig. 1. Schematic layout of the Daresbury Recoil Mass Separator. The focal plane detector is illustrated in the inset.

velocity filters followed by a sector magnet which gives an image in the focal plane dispersed in A/q. Quadrupole and higher multipole elements serve to focus the beam and correct the main aberrations of the system.

The position of the transmitted ions in the focal plane is measured using a position sensitive channel plate detector which also provides timing information. The specific energy loss and total energy of the ions are measured using a gas ionization chamber.

A spectrum of energy loss versus total energy for recoils detected in the bombardment of ^{122}Sn with 214 MeV ^{58}Ni is shown in Fig. 2. The Sn-like

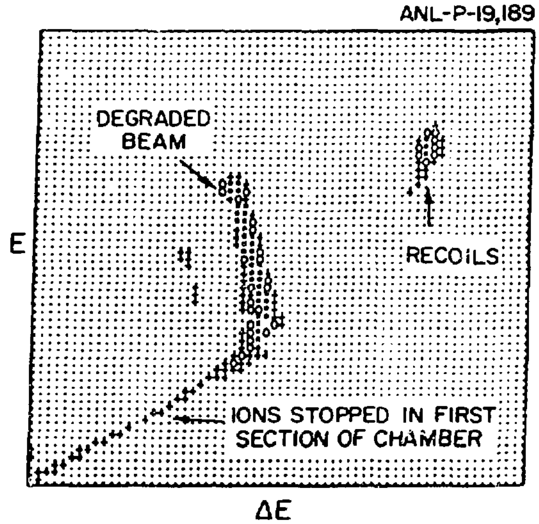


Fig. 2. Two-dimensional spectrum of energy loss versus total energy for recoils from 214 MeV ^{58}Ni + ^{122}Sn.

recoils are identified by their large energy loss and thus separated from a tail of beam particles originating from scattering of the beam from the electrostatic plates in the velocity filter.

The distribution of the Sn-like events as a function of energy and focal-plane position are shown in Fig. 3 together with the projections onto the two axes. The excellent mass resolution is evident in the position spectrum which, in this case, shows peaks corresponding to masses 122, 121 and 120 all of charge state 28^+. The energy spectrum shows a broad peak which falls within the acceptance of the RMS - the observed width of this peak is most likely dominated by energy straggling of the particles in the target, channel plate foil and ionization chamber entrance window. The complete acceptance of the events of interest was further checked by a scan of the recoil yields as a function of the central velocity setting of the RMS which results in a measured width equal to the expected acceptance of the device - consistent with a narrow spread in the velocities of the emitted fragments.

The present results provide no direct information on the nature of the transferred particles, although the reaction Q-values and systematics would favor neutron transfer. In a separate experiment[3,4] ^{58}Ni + ^{124}Sn at

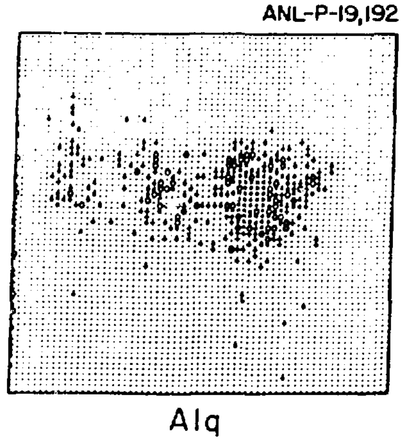
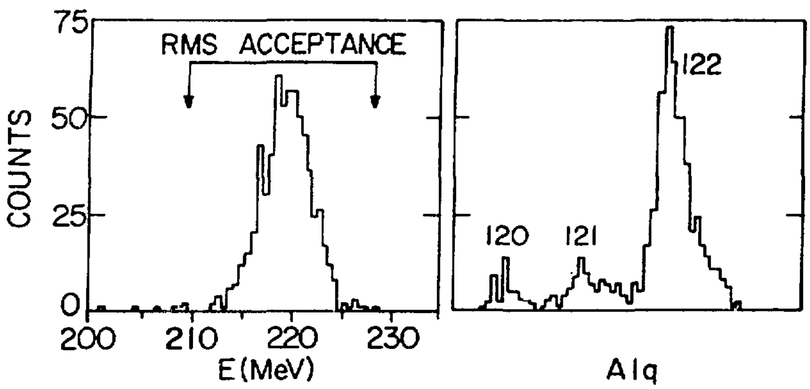


Fig. 3. Two-dimensional spectrum of position (A/q) versus total energy for Sn-like events. The projections onto the energy and position axes are also shown.



220 MeV - transfers were measured in coincidence with gamma rays. These data conclusively identify the reactions as neutron transfer which, together with systematics, makes it likely that in all cases studied the transferred particles are neutrons.

Cross-sections were obtained by assuming that the total yield observed corresponds to the $\theta_{cm} = 180^{\circ}$ Rutherford scattering cross-section; the cross-sections for the individual masses then being given by the ratio of their yields to the total. Fusion is either known or expected to be negligibly small at these energies. The validity of the above procedure was checked in a number of cases where the yields were measured for all strong charge states and a cross-section calculated using the ratios of the solid angles of the RMS and a monitor detector at a fixed forward angle. These values agreed to within 15%.

3. Results and Analysis

Cross-sections for one-neutron pickup from Sn are shown as a function of center-of-mass bombarding energy in Fig. 4. The Coulomb barrier for these

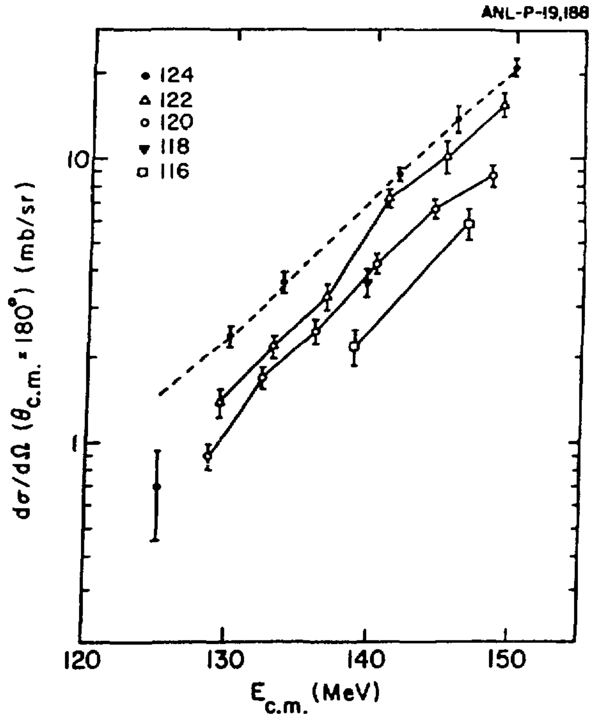


Fig. 4. Cross-sections for one neutron pickup in ^{58}Ni + Sn reactions plotted versus center-of-mass bombarding energy. The dashed line shows the DWBA prediction for ^{124}Sn. The solid lines join the data point.

systems is at approximately 150 MeV. The data for each isotopes fall with decreasing bombarding energy with slopes which are independent of target mass. The absolute magnitudes, however, depend strongly on the target, varying by a factor of three from the heaviest to the lightest isotope.

The general features of these data can be understood using a simple semi-classical model[4,5] of sub-Coulomb neutron transfer. On the basis of this model, we expect the dependence of the θ_{cm} = 180° cross-section to be given by:

$$\frac{d\sigma}{d\Omega} \propto \frac{e^{-2\kappa_n d}}{\kappa_n} \frac{d\sigma}{d\Omega}\Big|_{RUTH} , \quad \text{where } d = \frac{Z_1 Z_2 e^2}{E_{cm}} , \tag{1}$$

is the distance of closest approach in a head-on collision. This dependence on κ_n and d, coupled with the almost unchanging single-particle and collective behavior of the Sn isotopes (Table I), results in the rather simple behavior observed.

Table 1
Properties of the Even Sn Isotopes

A	B_n MeV	Q_n MeV	κ_n fm^{-1}	β_2 [a]	β_3 [a]
116	9.57	-0.56	0.681	0.120	0.046
118	9.33	-0.33	0.672	0.110	0.035
120	9.10	-0.11	0.664	0.108	0.031
122	8.80	0.18	0.653	0.104	0.035
124	8.49	0.51	0.641	0.095	0.041

[a] Deformation associated with the collective inelastic excitation of the lowest 2^+ and 3^- states

The cross-sections calculated using the semi-classical model are shown together with the data in Fig. 5. The calculated curves are normalized at one

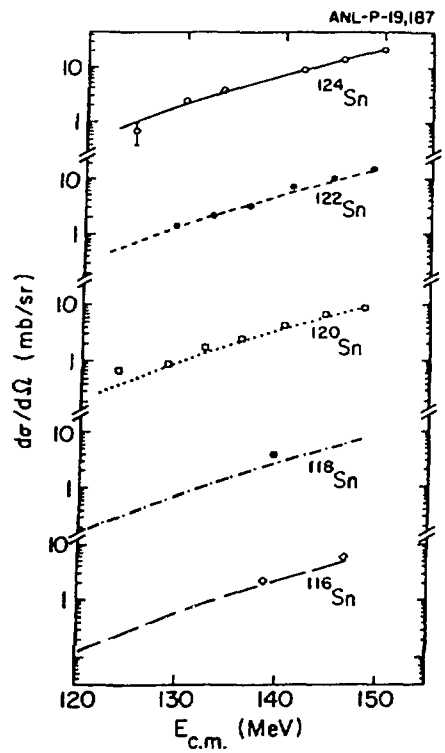


Fig. 5. Cross-sections for one-neutron pickup in ^{58}Ni + Sn reactions together with cross-sections calculated using the semi-classical expression given in the text. The curves are normalized to the highest energy point for ^{124}Sn.

point, ^{124}Sn at the highest energy. The overall agreement is remarkable. The near constancy of the observed slopes comes from the form of the semi-classical expression which has a logarithmic slope which depends linearly on κ_n - and remains constant within a few percent across the isotopic sequence. The magnitude of the cross-section, however, depends exponentially on $2\kappa_n d$ which results in the observed factor of three differences between the lightest and heaviest isotopes studied. It would not have been expected that the simple semi-classical treatment would give such a good account of the variation of the cross-section magnitudes. This has the additional requirement that the dependence of the overall magnitude of the valence neutron wavefunctions at the nuclear surface vary only weakly from isotope to isotope such that its magnitude at large distances is governed only by κ_n, the binding energy parameter.

An analysis within the framework of DWBA using spectroscopic factors from light ion work together with the code PTOLEMY[6)] is in similarly good agreement with the data. The DWBA energy dependence, which depends on the same long-range behavior of the neutron wavefunction, is shown as a dashed line for ^{124}Sn in Fig. 4. The calculated isotopic dependence is shown together with the data and semi-classical expectations in Fig. 6. Note

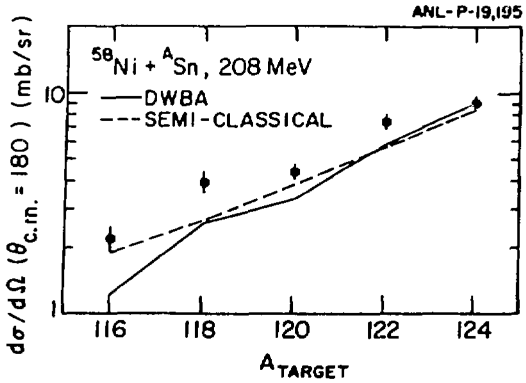


Fig. 6. Cross-sections for one neutron pickup in ^{58}Ni + ^{A}Sn at 208 MeV bombarding energy, together with the predictions of the semi-classical model and the results of DWBA calculations.

that the DWBA predictions are absolute. The conclusion is therefore that the sub-barrier neutron transfer of ^{58}Ni + Sn is quite well accounted for in all respects by both semi-classical and quantum mechanical theories of the transfer process.

Data for ^{58}Ni + ^{144,148,150,152,154}Sm are shown in Fig. 7 - for both

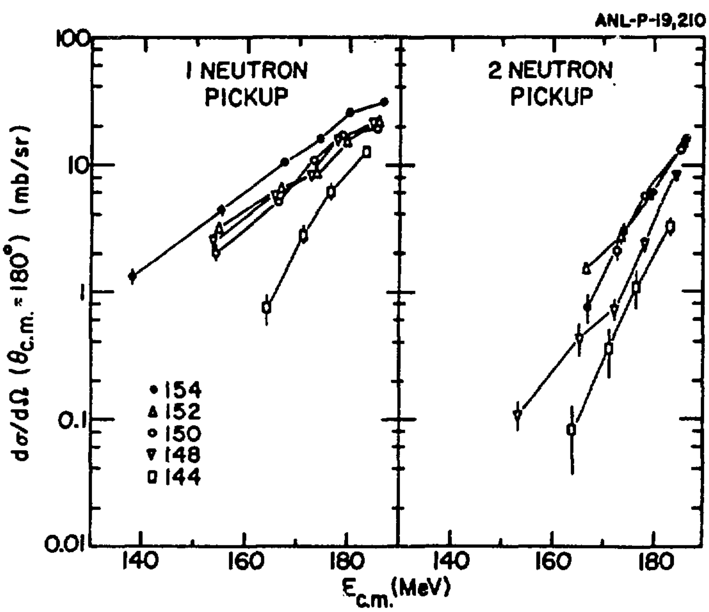


Fig. 7. Cross-sections for one- and two-neutron pickup in ^{58}Ni + ^{A}Sm reactions plotted versus center-of-mass bombarding energy.

one and two nucleon pickup reactions. The major difference in this set of data when compared to ^{58}Ni + Sn are the apparent changes in the energy dependence of the one neutron transfer for ^{144}Sm and the heavier isotopes. The structure of the Sm isotopes is changing from the spherical ^{144}Sm to well-deformed, prolate ^{154}Sm as shown in Table II

A	B_n MeV	Q_n MeV	κ_n fm^{-1}	B_{2n} MeV	Q_{2n} MeV	κ_{2n} fm^{-1}	β_2 [a]
144	10.55	-1.56	0.715	16.39	1.26	1.254	0.
148	8.14	0.86	0.628	14.51	5.90	1.180	0.11
150	7.99	1.01	0.622	13.86	6.53	1.153	0.19
152	8.27	0.73	0.633	13.86	6.53	1.153	0.25
154	7.98	1.02	0.622	13.85	6.55	1.153	0.27

[a] Static ground-state deformation

Nevertheless, the general behavior of the slopes for one-neutron transfer on ^{144}Sm and all the two neutron transfer are well reproduced by the semi-classical model, as illustrated in Fig. 8 for ^{144}Sm and ^{154}Sm.

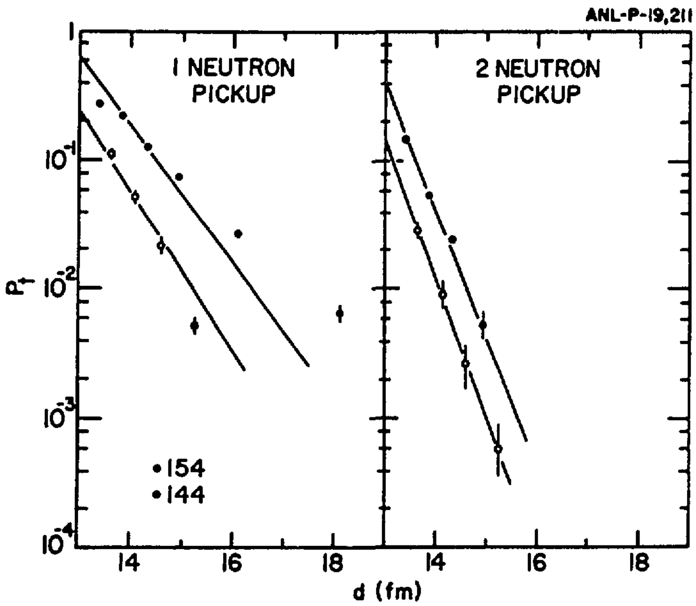


Fig. 8. Cross-sections for one and two-neutron pickup in ^{58}Ni + ^{144,154}Sm plotted versus distance of closest approach. The straight lines are the predictions of the semi-classical model using ground-state binding energies. The curves are normalized to the data.

The origin of the anomalous slopes for one neutron transfer on ^{148,150,152,154}Sm is unknown at present. It is unlikely be purely a deformation effect as then surely a similar anomalous behavior would appear for the two-neutron transfer on the deformed targets. One possibility is that it is a combination of the effects of deformation and excitation energies of the final fragments. This comes about in the following way. The optimum Q-value for the neutron transfer reactions is Q = 0 and thus, for the case of the one-neutron transfer reactions, the ground-state Q-values (Table II) favor population of relatively low-lying states in the residual nuclei. In contrast, for the two-neutron transfer, the large positive ground-state Q-values favor the population of quite highly excited states in the final nuclei. If there were then some mechanism involving only low-lying states and which also involves deformation producing an anomalous energy dependence, we would then be able to account for the observations.

This hypothesis is consistent with the results[7,8] of studies of transfer reactions at higher bombarding energies where the transfer probability was extracted from the angular distribution of the emitted particles. In these experiments, information on the excitation energy and angular momentum of the final fragments was obtained from measurements of the coincident gamma-ray sum energy and multiplicity. It was observed that the anomalous slope, in this case for two-particle transfer, resulted from processes leaving the fragments at relatively low excitation energy and spin. The systematic behavior of this phenomenon is still, however, far from clear.

Despite the above, possibly correct, statement of the conditions required for the slope anomaly, no theoretical explanation of the responsible mechanism exists. It is relatively straightforward to incorporate the effects of deformation in the semi-classical model used in the derivation of Equation 1. Some results of this procedure are shown in Fig. 9. It can be seen that, for an ensemble

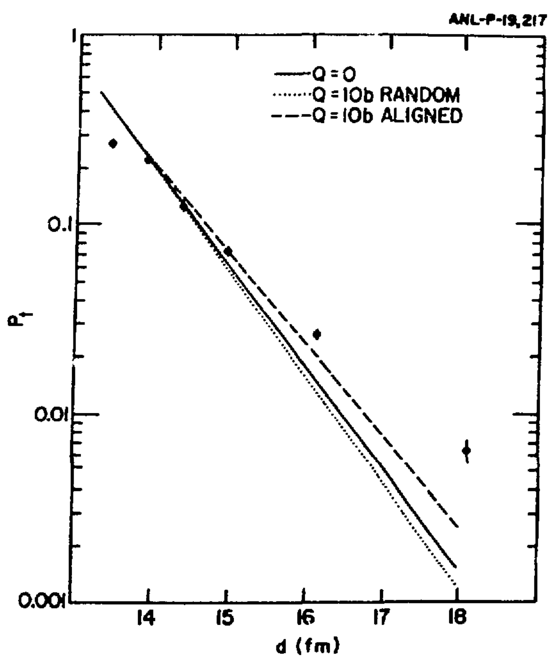


Fig. 9. Predictions of the semi-classical model including the effects of deformation - the normalizations are arbitrary.

of randomly oriented target nuclei whose orientations are frozen during the collision, the effect of including deformation has little effect on the predicted slopes. It is possible to produce a slope closer to those observed in the data by requiring that all the target nuclei be oriented with their deformation axes along the beam direction - without, however, specifying how this comes about. The detailed origin of this phenomenon therefore remains an open question.

4. Summary

The utilization of a RMS in the measurement of sub-barrier transfer reactions has been described and data for one and two neutron transfer of $^{58}Ni + {}^{A}Sn$ and $^{58}Ni + {}^{A}Sm$ presented. These data are well accounted for by both DWBA and semi-classical model calculations with the exception of the one-neutron transfer reactions on the deformed Sm targets which show a less steep energy dependence than expected. This so-called "slope anomaly" has been previously observed in other systems at higher energies but no consistent explanation of its phenomenology or origin exists at present.

5. Acknowledgements

This work was performed in collaboration with C.N. Pass, P.M. Evans, A.E. Smith (Oxford), J.S. Lilley, J. Simpson, J.R. Smith (Daresbury), A.N. James (Liverpool) and B.R. Fulton (Birmingham). Support from NATO Collaborative Research Grant 0076/87 is gratefully acknowledged. This research was supported by the U.S. Department of Energy, Nuclear Physics Division, under contract W-31-109-ENG-38.

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