Measurement of Subbarrier Transfer Reactions for ^{58}Ni +Sn Using a Recoil Mass Separator

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Measurements have been made of the $\theta_{\text{c.m.}} = 180°$ cross sections for the transfer reactions of ^{58}Ni+^{116,118,120,122,124}Sn at energies below the Coulomb barrier using a recoil mass separator. The largest single channel is for one-nucleon pickup, the cross section for which shows a strong dependence on target isotope. This dependence is correlated with the ground-state Q values for one-neutron pickup and is the same as that observed for a subbarrier fusion for these systems.

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Considerable recent experimental and theoretical effort[1] has been directed towards a characterization and understanding of the enhancement of subbarrier fusion of heavy ions over the predictions of simple models. The current understanding of this phenomenon involves the coupling of the entrance channel to other degrees of freedom, which, at energies below the one-channel fusion barrier, results in an effective increase in the probability of barrier penetration over the no-coupling situation, thus increasing the fusion cross section. In principle the framework thus exists for a complete description of not only the fusion channel, but also all reaction channels in the subbarrier region. For a quantitative test of such calculations it is therefore essential to measure, in addition to the fusion cross section itself, all possible reaction channels at subbarrier energies.

Comparatively little information exists on subbarrier reactions of heavy systems other than for the fusion channel itself and for those reactions induced by the long-range Coulomb interaction. For the systems considered in this Letter, transfer cross sections at near-barrier energies have been reported[2] for ^{58}Ni+^{112,124}Sn as well as more complete measurements[3] for ^{58}Ni+^{112,116,120,124}Sn at much higher energies. Subbarrier transfer cross sections for selected transitions in ^{64}Ni+^{58,64}Ni reactions have been obtained[4] from measurements of their decay gamma rays. Here we report, for the first time, a complete set of measurements for ^{58}Ni+^{116,118,120,122,124}Sn transfer reactions over a range of energies from the vicinity of the Coulomb barrier to far below this energy. These data, in combination with the previous measurements, now provide a unique set of information for a quantitative test of any calculation of fusion and reaction channels in the barrier region.

Measurements of reactions at subbarrier energies are made difficult by the fact that the yields are inherently backward peaked in the center-of-mass frame, the nuclear interactions resulting only from the closest encounters of the target and projectile. In the case of a projectile such as Ni incident on a Sn target, the backscattered projectilelike ion has such a small fraction of the initial kinetic energy that detection and identification are essentially impossible. Associated with the low-energy backscattered projectile, however, is a relatively high-energy, targetlike recoil particle which in principle can also be detected. In the present work this was accomplished with use of a recoil mass separator (RMS). This is the first time that such a device has been used in this manner and although in this Letter we concentrate on data relevant to the question of subbarrier fusion enhancement, we note that the technique will also be applicable to other physics questions such as that of nucleon pair and multiple pair transfer at sub-Coulomb energies.

The experiments were performed at the Daresbury Laboratory Nuclear Structure Facility with a beam of ^{58}Ni ions of energy ranging from 183 to 220 MeV, the nominal Coulomb barrier for Ni+Sn corresponding to an energy of 230 MeV. The beam was incident on 100-μg/cm^2 targets of enriched ^{116,118,120,122,124}Sn. The targetlike recoils were detected at $\theta = (0 \pm 3)°$ with use of the Daresbury RMS which consists[5] of a pair of crossedfield velocity filters followed by a magnetic dipole to give mass dispersion, interspersed by a number of magnetic multipole focusing elements. The detector in the focal plane of the RMS consists of a position-sensitive, channel-plate detector followed by a ΔE-E gas ionization detector. The beam intensity and target quality were monitored with the elastic scattering measured with a surface-barrier detector mounted in the RMS target chamber.

The recoiling targetlike fragments were identified according to their energy loss in the ΔE counter, which distinguished them from a tail of beam particles which originated from beam scattered within the separator. A spectrum of total energy (E) versus position for such targetlike events for the ^{58}Ni+^{124}Sn system is shown in the upper portion of Fig. 1(a), where the three groups of events correspond to elastic and inelastic scattering, one-nucleon $(1N)$ pickup, and two-nucleon $(2N)$ pickup reactions, all of charge state 28. The projection of these events onto the position axis is shown in the lower part of Fig. 1(b), displaying the clear separation obtained between the different mass peaks. The settings of the RMS were scanned to check the variation of the relative yields of the different masses with respect to charge state and with respect to the velocity acceptance $(\Delta V/V = 3\%)$ of the RMS. For the former, no significant variation was observed and for the latter, provided the center of the velocity bite was close to that expected for quasielastic scattering, the yields also remained stable.

The cross sections were obtained by the assumption that, for each target and bombarding energy, the total measured yield of elastic, inelastic, and transfer reactions corresponded to the Rutherford elastic-scattering value. The cross sections for each mass then follow the ratios of these yields. The validity of this procedure was checked in the one case by use of the monitor detector yield together with the known solid angles of the monitor and RMS and the measured charge-state distribution of the recoils. Where necessary, the measured cross sections were corrected for the presence of isotopic impurities in the target by use of the quoted isotopic compositions of

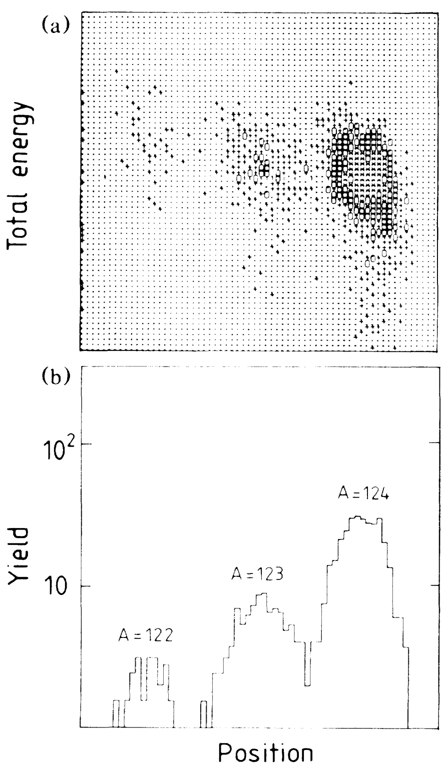

FIG. 1. (a) E vs focal-plane position spectrum for events identified as targetlike products in the ^{58}Ni+^{124}Sn reaction at 213 MeV. (b) Projection of (a) onto the position axis. The peaks correspond to masses 124, 123, and 122 all with charge state 28.

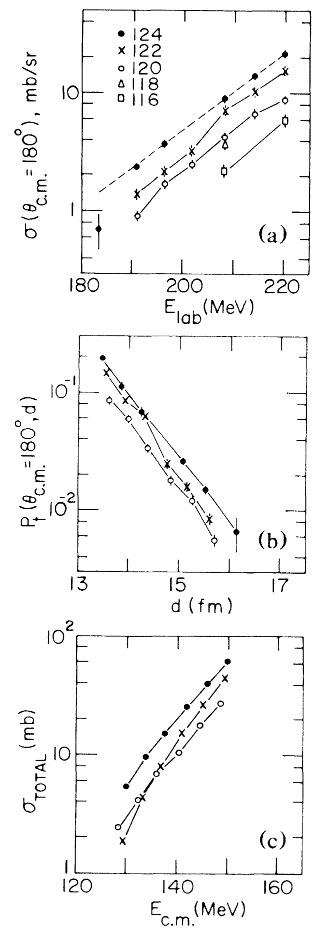

FIG. 2. (a) $\theta_{c.m.}=180°$ differential cross sections for $1N$ pickup reactions on ^{124,122,120,118,116}Sn plotted as a function of laboratory bombarding energy. The dashed line is the result of DWBA calculations for the ^{124}Sn target. The solid lines simply connect the data points for the other isotopes. (b) Transfer probability plotted vs distance of closest approach for these reactions. (c) Total cross sections for $1N$ pickup, deduced as described in the text, plotted vs center-of-mass bombarding energy.

the target material. For the $1N$ pickup reactions this was always a small correction. For the $2N$ pickup, however, this correction was larger because of the intrinsically smaller cross section for this channel. In the case of the ^{122}Sn target, the 3.8% admixture of ^{120}Sn prevented any reliable determination of the $2N$ pickup cross section.

In this Letter we concentrate on the target and energy dependence of the $1N$ pickup reactions which are by far the largest transfer channel. The $2N$ pickup channel is on the average a factor of 5 weaker than the corresponding $1N$ pickup. No yield was observed for stripping reactions at the level of sensitivity of this experiment (0.05 mb/sr). The 180° cross sections for the $1N$ pickup are shown in Fig. 2(a) and are listed in Table I. The data for the various isotopes all fall with decreasing bombarding energy with a slope which does not depend significantly on the specific target isotope. The absolute magnitudes of the cross sections, however, depend sensitively on target mass, showing a strong decrease with decreasing target mass. To demonstrate this correlation we replot the cross-section data in Fig. 2(b) as transfer probability (P_t) versus distance of closest approach (d) for a zero-impact-parameter Coulomb trajectory. The quantities P_t and d are defined as

$$P_t(180°,d)=\sigma(180°,E_{\text{c.m.}})/\sigma_{\text{Ruth}}(180°,E_{\text{c.m.}}), \quad (1)$$

which is the quantity measured directly in this experiment, and

$$d=Z_1Z_2e^2/E_{\text{c.m.}}. \quad (2)$$

This plot shows that the differences between the measured cross sections do not result from "trivial" effects such as differing laboratory to center-of-mass frame conversion factors, or differences in the radii of the colliding systems—the shift in d between the curves for adjacent isotopes is approximately 0.25 fm, whereas the corresponding difference in radius is less than 0.04 fm.

At the highest energies the measured transfer probabilities are of order 10% which are to be compared with the corresponding calculated quantities for Coulomb excitation of the low-lying collective 2^+ and 3^- states in the target which total approximately 15%. The calculated Coulomb excitation cross sections, based on measured $B(E2)$ and $B(E3)$ values, do not, however, show any strong isotopic dependence, falling only by 30% from ^{124}Sn to ^{116}Sn at 220 MeV, whereas the $1N$ transfer at the same energy falls by a factor of 3.

The trend observed in the subbarrier $\theta_{\text{c.m.}}=180°$ cross sections is similar to that observed in total cross sections for the same reaction channels at energies above the Coulomb barrier[3] and in subbarrier fusion[6] for these systems. An estimate of the total cross sections in the subbarrier region can be obtained from the present results if simplifying assumptions are made concerning the structure of the transfer amplitude[7] which lead to the following expectation regarding the dependence of P_t on scattering angle and d:

$$P_t(\theta_{\text{c.m.}},d)=\sin(\theta_{\text{c.m.}}/2)f(d), \quad (3)$$

where

$$P_t(\theta_{\text{c.m.}},d)=\sigma(\theta_{\text{c.m.}},E_{\text{c.m.}})/\sigma_{\text{Ruth}}(\theta_{\text{c.m.}},E_{\text{c.m.}}). \quad (4)$$

The function $f(d)$ can be obtained from the $\theta_{\text{c.m.}}=180°$ data, and therefore, for systems for which data were taken over a wide range of energies, we can generate angular distributions which can be integrated to give total cross sections. For the ^{124,122,120}Sn targets, these derived total cross sections are shown in Fig. 2(c). The cross sections are large, equaling 60, 45, and 28 mb for ^{124,122,120}Sn, respectively, at 220-MeV bombarding energy. These values are 2 orders of magnitude greater than the measured[6] evaporation-residue cross sections at this energy, but show the same isotopic dependence.

A series of distorted-wave Born-approximation (DWBA) calculations have been carried out to see if the present results can be accounted for within the simplifying assumptions of this model. Calculations were performed with the code PTOLEMY[8] for all transfers between the low-lying states of the target and projectile

TABLE I. Cross sections $(d\sigma/d\Omega)(\theta_{\text{c.m.}}=180°)$ (mb/sr) for $1N$ pickup of ^{58}Ni+Sn. The values of Q_{gg} for one-neutron pickup are also listed.

E_{lab} (MeV) \ A_t, $Q_{gg}(1n)$ (MeV)	116 −0.56	118 −0.33	120 −0.11	122 0.18	124 0.51
183.4	···	···	0.7 ± 0.2	···	0.7 ± 0.3
190.7	···	···	0.9 ± 0.1	1.4 ± 0.2	2.4 ± 0.2
196.2	···	···	1.7 ± 0.2	2.2 ± 0.2	3.7 ± 0.3
201.7	···	···	2.5 ± 0.3	3.3 ± 0.3	···
208.0	2.2 ± 0.3	3.9 ± 0.4	4.3 ± 0.3	7.4 ± 0.6	9.0 ± 0.5
208.0[a]	1.2	2.6	3.3	5.8	9.2
214.0	···	···	6.8 ± 0.6	10.4 ± 1.4	14.1 ± 1.5
220.0	6.0 ± 0.8	···	8.9 ± 0.8	15.9 ± 1.6	21.7 ± 1.6

[a]DWBA.

with use of experimental spectroscopic information where available or model predictions.[9,10] The scattering potentials were taken from the work of Lesko *et al.*[11] and the bound-state parameters were $r_0=1.20$ fm and $a=0.6$ fm. The results of the calculations were insensitive to changes in the scattering potentials. Changes in the bound-state parameters produced changes in the predicted absolute magnitudes but not the energy dependence. As expected on the basis of simple considerations, the neutron transfer reactions were predicted to dominate by orders of magnitude over the corresponding proton transfer, which leads us to conclude that we are observing neutron rather than proton transfer. The results of the calculations for the ^{124}Sn target are shown as a dashed line in Fig. 2(a). The calculated isotopic dependence is given for one energy in Table I. The calculated energy dependence showed excellent agreement with the observed slope of the 180° data and is close to that expected from the simplest models of the transfer process, namely, that the transfer probability should fall off as $\exp(-2Kd)$, where K is the wave number of the bound neutron in the target. The binding energies change only slowly from isotope to isotope, resulting in the observed near equality of the experimental slopes. The calculations further predict that the observed transfer strength is concentrated in a few strong transitions to low-spin single-quasiparticle states in both targetlike and projectilelike final nuclei. In the case of Sn, as a consequence of strong pairing correlations, these excitations lie at more or less constant excitation energy in each isotope. Their Q values therefore reflect the respective ground-state Q values (Q_{gg}), and thus give rise to the observed correlation between cross section and Q_{gg}. This result is a direct consequence of the structure of the interacting nuclei and it can therefore be imagined that there will be cases in which the Q_{gg} systematics are not followed, especially near closed shells. These expectations will be tested in a future experiment in which both cross sections and details of the final-state populations are measured with the RMS, with use of coincident gamma rays to identify specific states in the final nuclei.

The exact manner in which the transfer channels influence the fusion is not clear, or indeed whether it is necessarily the strongest observed channels which most affect the fusion process. It is true nevertheless, that for systems such as Ni+Sn, the transfer process is at least as important as inelastic scattering in the subbarrier region, and in any coupled-channels treatment of the overall division of the reaction cross section, must therefore be included. This is particularly so in the present case as it is the transfer cross sections which show the strong isotopic variation correlated with the behavior of the evaporation-residue cross sections—the calculated dependence of the low-impact-parameter inelastic scattering varying relatively much more slowly from isotope to isotope. It is likely therefore than any nonpathological coupling between the quasielastic and fusion channels will give rise to the observed isotopic behavior of the fusion cross sections. It will be of some interest to see if calculations are able to account for the large body of data now available at both sub- and above-barrier energies for these systems.

In summary, we have used a recoil mass separator in a novel manner to measure cross sections for transfer reactions at energies well below the classical barrier for ^{58}Ni+^{116,118,120,122,124}Sn. These results provide a unique set of data in this energy region. The observed isotopic dependence of the subbarrier fusion cross sections is seen to be closely related to the quasielastic cross sections and, as suggested by the results of DWBA analysis, to the variation of Q value with mass for a few strong transitions.

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