Transfer Cross Sections for $^{58}Ni + ^{58}Ni$ and $^{58}Ni + ^{64}Ni$ in the Vicinity of the Fusion Barrier

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Transfer cross sections have been measured for $^{58}Ni + ^{58,64}Ni$ in the energy range $E_{c.m.} = 100$–107 MeV with use of time of flight in a magnetic spectrograph. The direct reactions are dominated by one-neutron transfer, with other transfer cross sections being smaller by a factor of 3–4 or more. The average kinetic energy loss is ~ 2 MeV. Over the measured energy range the total transfer cross section for $^{58}Ni + ^{58}Ni$ is smaller than that observed for $^{58}Ni + ^{64}Ni$ by a factor of 4.

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Much of the recent interest in heavy-ion reactions at energies near the Coulomb barrier follows from the large subbarrier fusion cross sections[1–9] observed in reactions induced by heavy projectiles ($A > 40$). Particularly striking are the results for the systems $^{58}Ni + ^{58,64}Ni$ (Ref. 3) which revealed a strong isotope dependence in the subbarrier fusion yield. A number of theoretical models have been put forth recently,[10–15] mainly invoking the coupling of quasielastic channels in order to explain the large enhancements of the fusion cross section observed for many systems. While fusion cross sections have now been measured for a variety of heavy systems, only little experimental information is available on the strength of quasielastic reaction channels at energies in the vicinity of the Coulomb barrier.[16–19] It has been argued[11,12] that for $^{58}Ni + ^{64}Ni$ the two-neutron transfer reaction $^{64}Ni(^{58}Ni,^{60}Ni)$ could be responsible for the large enhancement of the subbarrier fusion cross section because of its positive ground state Q value. This paper reports on measurements of the transfer cross sections for the systems $^{58}Ni + ^{58}Ni$ and $^{58}Ni + ^{64}Ni$ at energies in the vicinity of the Coulomb barrier.

Attempts to measure the energy dependence of the total strength of heavy-ion transfer reactions at low incident energies have been mainly performed by detection of characteristic γ rays of the final nuclei.[16,18] This technique allows the measurement of relative yields in an excitation function, but for the extraction of absolute cross sections a detailed knowledge of the decay scheme of the final nuclei is necessary. In addition, transfer to ground states can in principle not be observed and weak channels are difficult to detect because of background problems. Indeed, a recent γ-ray measurement of the reaction $^{64}Ni(^{58}Ni,^{59}Ni)^{63}Ni$ encounters these difficulties. When the strength of these transitions, which are easily observed in the γ-ray spectra, is extrapolated to deduce the total transfer cross section the results are in disagreement with our charged-particle measurements, as discussed below. The direct detection of the outgoing particles requires a detector capable of detecting and identifying low-energy beamlike particles at backward angles. For reactions between nuclei with comparable masses one can detect targetlike fragments at forward angles which correspond to beamlike particles scattered backwards. The problem in this case is the large background of elastically scattered beam particles.

In our experiment we employed an Enge split-pole magnetic spectrograph to directly measure target and projectilelike fragments. Beams of 190–212-MeV ^{58}Ni ions from the Argonne superconducting linac were incident on 150–200-μg/cm^2 Ni targets enriched to 99.9% and 93.6% in ^{58}Ni and ^{64}Ni, respectively. The energy calibration and the measurements of the energy loss in the targets were performed with 93.5-MeV ^{58}Ni beams obtained from the tandem accelerator. The center-of-mass (c.m.) energies corrected for the energy loss in the targets were $E_{c.m.} = 102.0$ and 106.3 MeV for $^{58}Ni + ^{58}Ni$ and $E_{c.m.} = 99.9$ and 106.9 MeV for $^{58}Ni + ^{64}Ni$, respectively.

Beam currents measured in the Faraday cup behind the targets were typically 1–2 nA (particle). The stability of the beam was monitored by two surface-barrier detectors located at small angles on both sides of the beam axis, below the reaction plane. The outgoing particles were momentum analyzed in the Enge split-pole magnetic spectrograph and detected in the focal plane with a 50-cm-long parallel-plate avalanche counter[20] backed by a position-sensitive ionization chamber.[21] Six charge states, representing more than 95% of the total yield, were detected simultaneously in the focal-plane detector. From a measurement of total energy E, position $B\rho$, and time of flight t, an unambiguous determination of mass, Q value, and atomic charge state q was possible. The total time resolution was 500 psec with about equal contributions from the pulsed ^{58}Ni beam and the intrinsic resolution of the parallel-plate timing detector. Because of the low energies and the energy losses in the foils of the detector system, no Z identification for the particles was possible.

Figure 1 shows, as an example, mass and energy spectra obtained for 19^+ charge-state ions from the reaction $^{58}Ni + ^{64}Ni$ at $E_{lab} = 203.8$ MeV and $\theta_{lab} = 30°$. The mass spectrum indicates that the one-nucleon

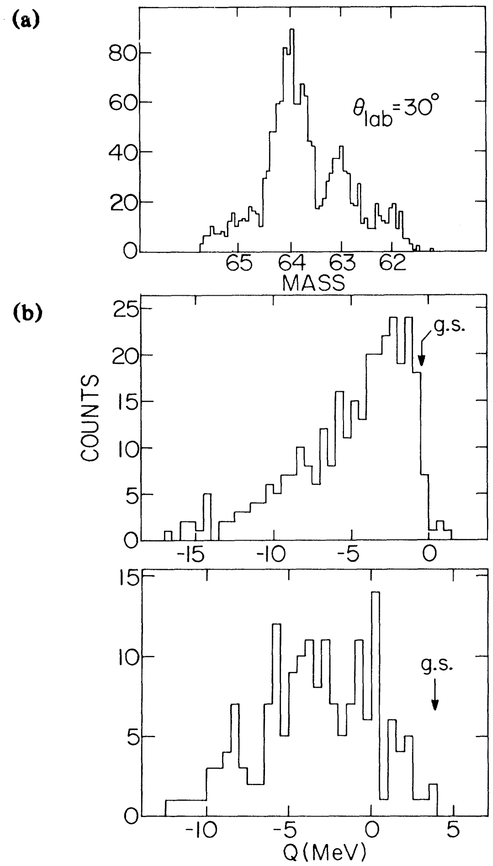

FIG. 1. (a) Mass spectrum of the reaction products observed in the reaction $^{58}Ni + ^{64}Ni$ at $E_{lab} = 203.8$ MeV. (b) Energy spectra for the reactions $^{64}Ni(^{58}Ni,^{59}Ni)^{63}Ni$ and $^{64}Ni(^{58}Ni,^{60}Ni)^{62}Ni$. The spectra are the summed contributions from ions detected in their 18^{+}–21^{+} charge states.

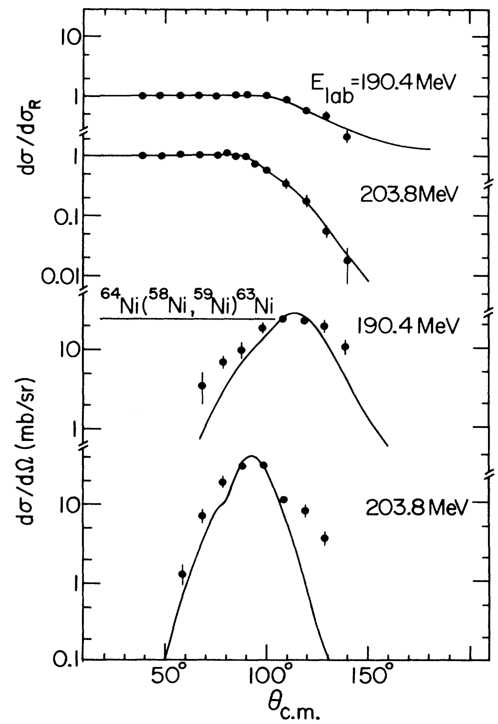

FIG. 2. Angular distributions for elastic scattering (including inelastic excitation to the lowest states in ^{58}Ni and ^{64}Ni) and the one-neutron transfer reaction $^{64}Ni(^{58}Ni,^{59}Ni)^{63}Ni$ measured at $E_{lab} = 203.8$ and 190.4 MeV. The solid lines are coupled-channels (elastic pulse inelastic scattering) and DWBA calculations (transfer) as described in the text.

transfer is the dominant transfer channel. From the energy spectra [Fig. 1(b)] and from Q-value considerations we conclude that the one-nucleon transfer is due to the reaction $^{64}Ni(^{58}Ni,^{59}Ni)^{63}Ni$. Other reactions producing mass-59 and mass-63 nuclei have either large negative Q values [e.g., $^{64}Ni(^{58}Ni,^{59}Cu)^{63}Co$] or are more complicated multistep processes [e.g. $^{64}Ni(^{58}Ni,^{59}Co)^{63}Cu$]. Similar arguments apply for the mass-62 and mass-65 channels. We also observe from Fig. 1(a) that cross sections for the two-neutron transfer reaction $^{64}Ni(^{58}Ni,^{60}Ni)^{62}Ni$ and for the stripping reaction $^{64}Ni(^{58}Ni,^{57}Co)^{65}Cu$ are smaller than the one-neutron transfer reaction mentioned above by factors of about 2 and 4, respectively. Because of the use of relatively thick targets and the strong kinematic shifts in these reactions, transitions to individual levels could not be resolved. The resolution of ~ 1.5 MeV, however, is sufficient to establish that, for both the one- and two-neutron transfer reactions, states are populated with excitation energies corresponding to an average Q value of about -3 MeV and -1 MeV, respectively. This is expected from optimum Q-value considerations for neutron transfer. We find in particular that the ground state in the two-neutron transfer reaction $^{64}Ni(^{58}Ni,^{60}Ni)^{62}Ni$ is weakly populated and mainly transitions to states at higher excitation energies ($E^* \sim 4$ MeV) are observed in this reaction. This is similar to the behavior found for other two-neutron transfer reactions.[22,23]

Angular distributions for the sum of elastic and inelastic scattering to low-lying states in the Ni isotopes and for the one-neutron transfer reactions ($^{58}Ni,^{59}Ni$) are shown in Fig. 2. The solid lines for elastic plus inelastic scattering are results from coupled-channels calculations with the code PTOLEMY[24] including excitation of the first 2^{+} and 3^{-} states in ^{58}Ni and ^{64}Ni,[25] with the following optical-model potential parameters: $V_0 = 100$ MeV, $W = 40$ MeV, $r_0 = 1.25$ fm, $a = 0.50$ fm. The potential from Doubre *et al.*,[26] obtained from a fit to elastic Ca+Ca scattering ($V = 35$ MeV, $W = 12.13$ MeV, $r_0 = 1.35$ fm, $a = 0.43$ fm), gave practically the same result, while the potential from Christensen *et al.*[27] obtained from global systematics predicts a quarter-point angle which is smaller than the experimental value by about 8° at $E_{c.m.} = 106.9$ MeV. For the system $^{58}Ni + ^{58}Ni$ no separate optical potential could be extracted from our data because the symmetry of the angular distribution around 90° masks the large-angle behavior. In the following the 100-MeV-deep potential was used for the distorted-wave Born-approximation (DWBA) calculations in both systems.

The solid lines in Fig. 2 for the transfer reactions $^{64}Ni(^{58}Ni,^{59}Ni)^{63}Ni$ are the result of DWBA calculations with PTOLEMY including the $\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-, \frac{7}{2}^-$, and $\frac{9}{2}^+$ single-particle states in ^{59}Ni and ^{63}Ni, respectively. As spectroscopic factors the average values obtained from (d,p), (p,d), and (d,t) reactions were used (see Andersson *et al.* and Auble *et al.*[28]). The bound-state parameters in the calculations were $r_0 = 1.2$ fm and $a = 0.65$ fm. Details about the calculations will be published in a forthcoming paper. The maximum of the angular distributions is described quite well, both in position and in absolute magnitude, whereas the width is underpredicted at both energies. Thus the integrated cross sections obtained from the calculations are smaller than the experimental values by about 10%.

The experimental angular distributions were integrated over all angles and the cross sections are plotted in Fig. 3 together with the fusion cross sections measured in the same energy range.[3] The value for the one-nucleon transfer cross section at $E_{c.m.} = 99.9$ MeV measured in the present work is 114 mb which is about a factor of 2 larger than the extrapolated result obtained in the γ-ray studies of Ref. 18. We should point out that the partial strength from the selected transitions observed in the γ-ray measurements agrees reasonably well with the corresponding fraction measured in our experiment and also with DWBA predictions using light-ion spectroscopic factors. A noticeable disagreement with our measured transition strength occurs, however, in estimating contributions from those transitions not observed in the γ-ray work. Furthermore, two-neutron transfer reactions, which according to several theoretical calculations should strongly influence the subbarrier fusion cross sections, could not be measured with the γ-ray technique.

From Fig. 3 we observe that for the system $^{58}Ni + ^{58}Ni$ at the lowest energy measured ($E_{c.m.} = 102$ MeV), the fusion process is the dominant reaction channel. At this energy the cross-section ratio $R = \sigma_{transfer}/\sigma_{fusion} = 0.48 \pm 0.25$. For the system $^{58}Ni + ^{64}Ni$, in contrast, transfer reactions are the dominant reaction channels in this energy range with the cross-section ratio $R = 2.23 \pm 0.50$ at $E_{c.m.} = 99.9$ MeV. The dominant contribution comes from the one-nucleon transfer while the two-neutron transfer is smaller by a factor of ~ 3. The one-neutron transfer channel alone is stronger than the fusion channel at energies below about $E_{c.m.} = 102$ MeV; DWBA predic-

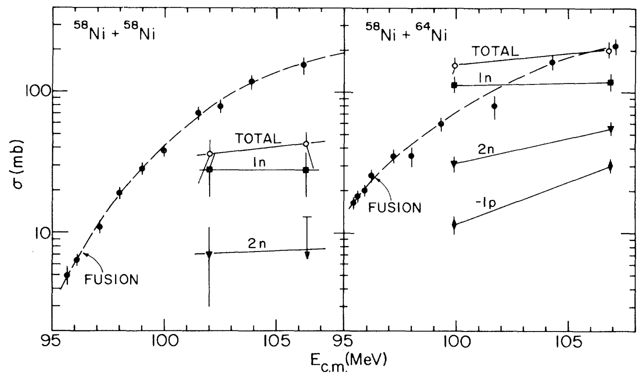

FIG. 3. Energy dependence of the dominant quasielastic transfer cross sections as measured for the systems $^{58}Ni + ^{64}Ni$ and $^{58}Ni + ^{58}Ni$. The data for the fusion cross sections are from Ref. 3. The lines serve to guide the eye.

tions indicate that about 70% of the one-neutron transfer strength is concentrated in transitions to a few final states. This clearly suggests that in this energy range coupled-channels effects need to be included, since fusion is no longer the dominant reaction channel. It is tempting to connect the strong transfer channels with the large subbarrier fusion cross sections which were observed in the system $^{58}Ni + ^{64}Ni$. Calculations along these lines have been done by several authors.[11–15] In these coupled-channels calculations most of the enhancement of the subbarrier fusion cross sections relies on the existence of transfer reactions with *positive* Q values.[11,12] Our data indicate, however, that most of the quasielastic neutron-transfer strength is associated with slightly negative Q values, quite similar to the behavior observed in other measurements of transfer reactions induced by heavy projectiles.[22] It is clear that the models for subbarrier fusion, based on an excitation-energy independent coupling strength, and thus favoring positive Q values, should not neglect the strong transfer channels with slightly negative Q values. The data for the transfer reactions presented in this paper should allow a relative normalization of the transfer strength observed for different channels in further investigations of direct reactions as possible doorway states towards complete fusion.

To summarize, we have measured transfer cross sections for the systems $^{58}Ni + ^{58}Ni$ and $^{58}Ni + ^{64}Ni$ at energies in the vicinity of the Coulomb barrier. In both reactions the one-neutron transfer shows the largest cross sections with the two-nucleon transfer reactions being smaller by about a factor of 3. For $^{58}Ni + ^{64}Ni$ the integrated cross section for the one-neutron transfer reaction $(^{58}Ni,^{59}Ni)$ is even stronger than the fusion cross section for energies below ~ 102 MeV. Despite the availability of final states with positive ground-state Q value for the system $^{58}Ni + ^{64}Ni$ ($Q_{gg} = 3.89$ MeV), our data indicate that the transition to the ground state in the reaction $^{64}Ni(^{58}Ni, ^{60}Ni)^{62}Ni$ is very weak. The average Q value is -2 MeV. Most importantly, a large difference in the total transfer cross sections has been observed, with $^{58}Ni + ^{58}Ni$ showing smaller transfer cross sections by about a factor of 4 if compared to $^{58}Ni + ^{64}Ni$ at similar energies. These results imply that there is a direct correlation between the total transfer strength and the enhancement of the low-energy fusion behavior. The detailed connections between these different processes, however, are not yet fully understood.

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