One- and two-nucleon transfer in the $^{28}Si+^{68}Zn$ system at energies below the Coulomb barrier

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Excitation functions for one- and two-nucleon transfer in $^{28}Si + ^{68}Zn$ system have been measured at energies below the Coulomb barrier. The experiment was carried out by detecting the forward recoiling targetlike nuclei using the recoil mass separator, HIRA. With a pulsed beam, the time-of-flight of the recoils was measured and used to resolve the M/q ambiguity. This enabled the determination of the two-nucleon transfer yields. The role of one- and two-nucleon transfer in the sub-barrier fusion cross-section enhancement has been investigated. It turns out that the coupling of the positive Q-value two-neutron transfer channel results in a significant contribution to the enhancement. Coupling to both the transfer and the inelastic channels is able to explain the observed enhancement. [S0556-2813(97)00510-4]

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I. INTRODUCTION

Heavy ion fusion cross sections at energies near the Coulomb barrier have been studied experimentally for a large number of systems, and extensive data on the excitation functions are now available in this energy region [1]. Several theoretical models have been suggested [2–7] to understand the most salient features of these data, viz., the enhancement of sub-barrier fusion cross sections and larger values of average angular momenta [8] compared to those expected on the basis of the one-dimensional barrier penetration model (1D-BPM). Of these models, the coupled channels approach [3] has been quite successful in explaining the data. According to this approach, the coupling of the entrance channel to nonelastic channels, like inelastic and transfer, modifies the barrier and results in an enhanced sub-barrier fusion cross section. The merit of such an approach lies in the fact that the explanation of the observed features involves the nuclear structure properties through the relevant form factors [3]. Of these, the inelastic form factors are known from experiments, viz., from the $B(E2\uparrow)$ and $B(E3\uparrow)$ values [9]. Inclusion of the inelastic form factors explains the features of the sub-barrier fusion data to a considerable extent. However, in many cases, it is found that discrepancies remain even after their inclusion [10,11]. These are generally attributed to the coupling of transfer channels. For example, isotopic differences in sub-barrier fusion cross-section enhancements in $^{58}Ni + ^{58,64}Ni$ [10] and $^{32,36}S + ^{58,64}Ni$ [11] systems underline the importance of inclusion of transfer couplings in carrying out the fusion cross-section calculations.

Proper inclusion of transfer channels in the coupled channels approach for fusion has been made in only a few cases. The transfer form factors to be used depend both on the spectroscopic factors for the states involved and on the reaction dynamics [12]. A reasonable theoretical estimate of these can be made for a few nuclei near the closed shells, like in the $^{16}O + ^{208}Pb$ case, where exhaustive quantum mechanical coupled channels calculations have been carried out [13]. However, in the case of the midshell nuclei, such an approach becomes quite cumbersome and unreliable. For such cases, a semiempirical approach may be more reliably adopted where the relevant form factors are extracted from measured transfer reactions data [14,15].

The transfer measurements carried out at energies above the Coulomb barrier utilize the data forward of the grazing angle in order to extract the transfer probability as a function of the shortest distance of approach. However, the transfer probabilities so derived were found to be in disagreement with the theoretically derived values using the semiclassical approach, which gave rise to the so called slope anomaly [16]. This leads to some uncertainty towards using the above barrier data, while extracting the transfer form factors. Several efforts have been made to understand the reasons behind such an anomaly [17] and to extract the transfer form factors from the above barrier data by taking into account such effects [18]. In contrast to the above barrier data, the semiclassical model has been found to describe the sub-barrier measurements quite successfully (see Ref. [19], for example) as contributions to the observed scattering process comes from trajectories with impact parameters corresponding to the Coulomb branch only. Thus the sub-barrier measurements offer a completely unambiguous and reliable way of extracting the transfer form factors. However, experiments aiming for such measurements face certain complications which can be handled only through employment of special instruments and techniques.

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TABLE I. Ground state transfer Q values (Q_{gg}) for the ^{28}Si + ^{68}Zn system.

Stripping Channels				Pickup Channels			
Channel	Q_{gg} (MeV)	Channel	Q_{gg} (MeV)	Channel	Q_{gg} (MeV)	Channel	Q_{gg} (MeV)
$-1p$	−4.98	$-1p1n$	−10.38	$+1p$	−7.25	$+1p1n$	−5.04
$-2p$	−4.72	$-1p2n$	−12.44	$+2p$	−11.41	$+1p2n$	+0.20
$-1n$	−10.70	$-2p1n$	−8.40	$+1n$	−1.72	$+2p1n$	−7.33
$-2n$	−14.79	$-2p2n$	−4.98	$+2n$	+1.83	$+2p2n$	+1.62

It has been demonstrated that recoil mass separators are powerful tools for studying fusion and transfer reactions at energies around and below the Coulomb barrier [20,21]. For transfer reaction studies, the experiment is usually carried out by detecting the forward recoiling targetlike nuclei using the recoil mass separator [21–23]. With their excellent mass resolution and capability of operation in and around the zero degree direction, it is, in principle, possible to identify both one- and two-nucleon transfer channels. In a recent work, Napoli *et al.* [23] carried out a study in ^{32}S + ^{64}Ni system using the recoil mass separator CAMEL and reported their measurement of the one-nucleon transfer channel. Coupling of this channel was found to account for only a part of the asymptotic barrier shift. The need for coupling of the positive Q-value, two-nucleon transfer channel was conjectured [24] to be responsible for the missing cross section. However, it was not possible to measure the two-nucleon channel in the above experiment. This is due to a limitation of recoil mass separators resulting in the so called M/q ambiguity, wherein different masses with the same M/q are brought to focus to the same position at the focal plane. In most cases this feature hinders the extraction of multinucleon transfer yields, and was apparently responsible for the inability to measure the all important two-nucleon transfer channel in the experiment by Napoli *et al.* [23].

The experimental data for the near and sub-barrier fusion cross sections for the ^{28}Si + ^{68}Zn system [25] were analyzed using the coupled channels code CCMOD [25] where the inelastic channels were coupled. Such calculations gave a partial explanation of the data. The transfer couplings were considered to be responsible for the missing cross section, especially due to the presence of positive Q-value transfer channels. The ground state Q-values of the important transfer channels are listed in Table I. Saha *et al.* [26,27] made attempts to measure the transfer cross sections and angular distributions forward of the grazing angle for energies at and above the barrier. Besides the problems mentioned earlier viz-a-viz data taken at energies above the barrier, the masses could not be separated in their measurement. Consequently neutron transfer strengths could not be obtained and the form factors required for the coupled channels analysis could not be experimentally determined. They showed that the inclusion of the measured $1p$ and $2p$ stripping channels makes only a small contribution to the the observed enhancement and it is clear that a measurement of the neutron transfer yields at energies reasonably below the barrier is indeed required.

Here we report on the results of one- and two-nucleon transfer reaction study on ^{28}Si + ^{68}Zn system using the recoil mass separator HIRA [28] at sub-barrier energies. A technique to resolve the M/q ambiguity is described. This enables determination of the two-nucleon transfer yields as well as allows generation of the Q-value spectra with a high resolution, limited only by target thickness effects. The calculated fusion excitation function, wherein the coupled channels calculations include the inelastic as well as the transfer channels, has been compared with the data.

II. EXPERIMENTAL DETAILS

The experiment was carried out using a pulsed ^{28}Si beam from the 15UD Pelletron at NSC, New Delhi, with a repetition rate of 250 ns and energies ranging from 65 to 83 MeV. The ^{68}Zn (99.3% enriched) target was 109 μg/cm^2 thick, with a 15 μg/cm^2 thick carbon backing. The targetlike reaction products moving in the forward direction were separated out from the beamlike particles by the HIRA and detected at the focal plane by a detector system consisting of a low pressure Multi-Wire Proportional Counter (MWPC) followed by an ionization detector [29]. The HIRA fields were set so that mass 68 of the most probable charge state is brought to focus at the center of the focal plane. Using the buncher RF and the arrival time of the ions at the focal plane, the times-of-flight (TOF) of the recoil ions were recorded. Two monitor detectors were placed on either side of the beam direction at $\pm$ 30° for normalization. Data were recorded for two HIRA angles, 4 and 7 degrees, with respect to the beam direction. The ^{68}Zn target also contained (as per supplier's specifications) 0.25% of ^{66}Zn and 0.11% of ^{67}Zn. Elastically scattered recoils from these isotopes add to the transfer product yields from ^{68}Zn. It is important to have an estimate of such contributions. Hence, data were taken at 65 MeV, an energy well below the nominal Coulomb barrier, where the yield from transfer is expected to be negligible. According to these data, the presence of ^{66}Zn and ^{67}Zn in the target was found to be generally consistent with the specified values. Subsequently, the transfer yields at higher energies were corrected taking into account the elastic scattering contributions from these isotopes.

In addition, data were recorded for extracting information on the mass and charge state related efficiencies of the HIRA. For the mass dependent efficiency, the HIRA fields were varied in order to sweep a particular mass across the focal plane and noting the change in the yield, normalized by the monitor detector counts. Similarly, the charge state related efficiency was determined by setting the HIRA fields for the different charge states of the recoils. This also provided the charge state distribution of the recoils. Figure 1

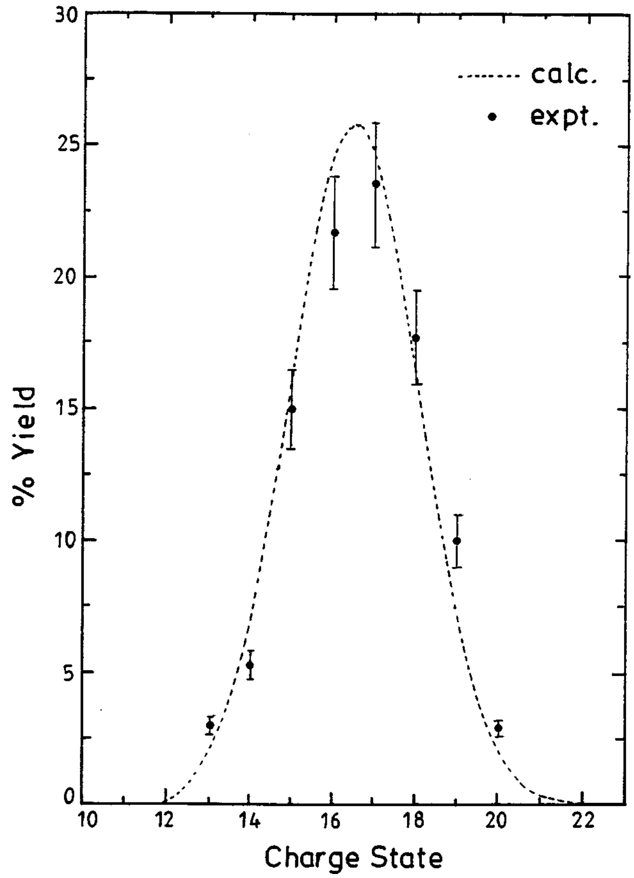

FIG. 1. Plot of a typical charge state distribution obtained from experiment. The data shown are for 65 MeV incident energy with the HIRA at 4°. Results of calculations using the empirical expression of Ref. [31] are shown by the dotted line. The uncertainties shown are from systematic errors only.

shows a typical charge state distribution, measured at 65 MeV incident energy, along with the results of empirical calculations obtained following Ref. [30]. In calculating the transfer probabilities, corrections incorporating the effects of mass and charge state related efficiencies were made as described in Sec. III.

The TOF data served a number of purposes. In spite of the high efficiency of HIRA with respect to beam rejection, a number of beamlike particles reach the focal plane and contaminate the position spectrum. The TOF data were utilized to separate the beamlike particles from the recoils of interest. Although typical times-of-flight for the recoils were of the order of 630 ns and the pulse repetition rate was 250 ns, the recoils were well separated out from the beam like scattered particles as they were confined to a narrow energy and time window which, in this case, does not overlap with the scattered beamlike particles. The TOF was also used to resolve the M/q ambiguity which arises because HIRA focuses mass 66 of charge state 17^+ and mass 70 of charge state 18^+ to almost the same position. Figure 2 is a typical plot of TOF vs position at the focal plane, where it can be seen that the two masses are well separated in TOF. It must be noted here that if the energy spread of the recoils is large, the TOF spread is larger and the ambiguity may not be resolved. However, if the energy of the recoils is known with a reasonable resolution, which in our case is available from the ionization detector following the MWPC at the focal plane, it is still possible to resolve the ambiguity by putting energy gates on the TOF vs position spectra.

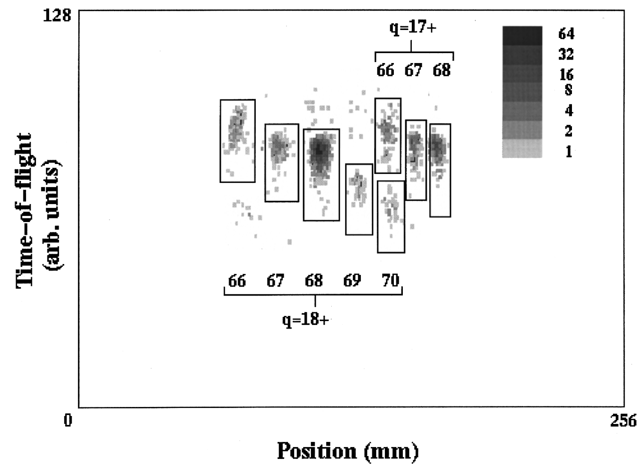

FIG. 2. Time-of-flight versus X position at the focal plane, gated for the recoils, at 79.8 MeV incident energy. It can be seen that the masses are well separated in TOF whereas they come to almost the same position at the focal plane. The excellent mass resolution of the HIRA, providing clean separation between neighboring masses, can also be seen.

Finally, since the mass and flight length through the HIRA [28,31] are known, the TOF information was used to determine the energy of the recoils and hence obtain their Q-value spectra. The spectrum obtained by gating on the elastic channel provided the calibration (zero offset) for the TOF. Using this calibration, the TOF spectra for the other channels were converted to energy and Q-value spectra. Following this procedure, the energy spectrum obtained for the elastic and the $2n$-pickup channel at 79.8 MeV incident energy is shown in Fig. 3. Although the energy resolution obtained from the TOF can be very good ($<$ 0.5%), separation of individual states was not obtained here mainly due to the kinematic broadening ($\sim$ 0.9 MeV) and energy spread in the target (2.2 MeV).

III. RESULTS AND DISCUSSION

Since HIRA focuses the elastically scattered recoils along with the recoiling inelastic and transfer products, the solid angle factor being identical for all channels, the yields of these channels can be directly used for obtaining the transfer probability. Hence, the transfer probability for each channel here is simply taken as the ratio of the yield of the particular channel to the sum of the yields of all the quasielastic and elastic channels obtained at the focal plane. The yields considered here are corrected in order to account for the mass, charge state, and energy related efficiencies, as described below. In addition, as described in Sec. II, the effects of presence of other isotopes in the target were also taken into account.

The mass efficiency was found to be constant to within $\pm$8% for M/q ranging from 3.722 ($67/18^+$) to 3.882 ($66/17^+$) and to fall off for values below 3.7 and above 3.9. As the efficiency for $66/18^+$ is relatively lower and varies considerably with small changes in the field settings, the cor-

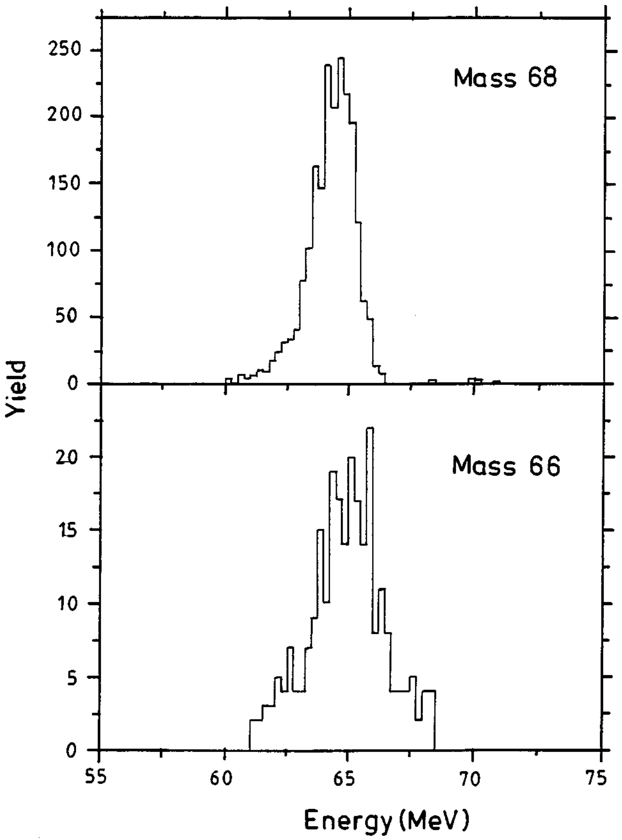

FIG. 3. Energy spectrum for the elastic (mass 68) and the $2n$-pickup (mass 66) channel at 79.8 MeV incident energy. The procedure followed for extraction of the energy from the TOF is described in the text.

responding transfer probability is obtained from the observed yield of $66/17^+$ after correction for the variation in the yield due to the different charge state. This correction is obtained from the charge state distribution information described earlier. As the variation of the charge state distribution from the empirical calculations are found to be less than ± 1.5%, for all the corrections the values obtained from the empirical calculations have been used. The charge state distributions for recoils of different masses and atomic numbers are also different and have been accordingly accounted for. Besides these, in principle, corrections for the energy dependent efficiency must be made. The energy acceptance of HIRA is large, ± 20%, and the efficiencies are known from earlier tests [32]. In this case, as the energy spread of the recoils is low, less than 8%, these effects are limited to less than ± 2.5% and have been neglected.

The transfer probabilities, P_{tr}, for different transfer channels, obtained after appropriate corrections as described above, are plotted against d_0, the reduced distance of closest approach, as shown in Figs. 4(a) and 4(b). The d_0 values were calculated assuming Coulomb trajectories, using the expression

$$d_0=\frac{Z_1Z_2e^2}{2E_{c.m.}}[1+\mathrm{cosec}(\theta_{c.m.}/2)]\frac{1}{(A_1^{1/3}+A_2^{1/3})},$$

where Z_1, Z_2 and A_1, A_2 are the atomic and mass numbers of the projectile and target respectively, $\theta_{c.m}$ is the center-of-mass scattering angle, and $E_{c.m.}$ is the energy in the center-of-mass. Due to the effect of the nuclear force, a slight modification in d_0 can result, i.e., 0.011 for the highest energy run with $d_0=1.55$, which has been neglected.

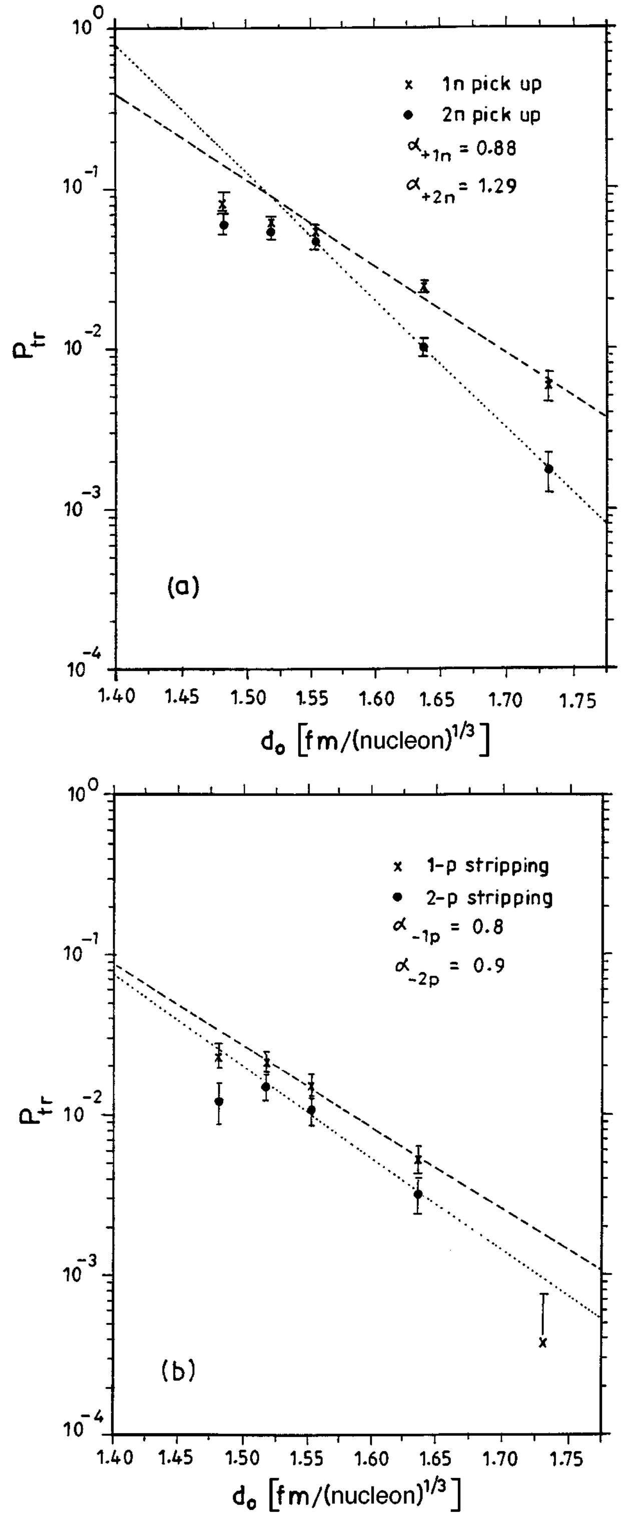

FIG. 4. Transfer probability, Ptr vs d_0 for (a) one and two neutron pickup and (b) one and two proton stripping. The channels are identified as proton or neutron channels from Q-value arguments. The slopes are extracted by a least squares fit to the data points with d_0 above 1.55 fm/(nucleon)$^{1/3}$.

The necessary corrections for energy loss in the target

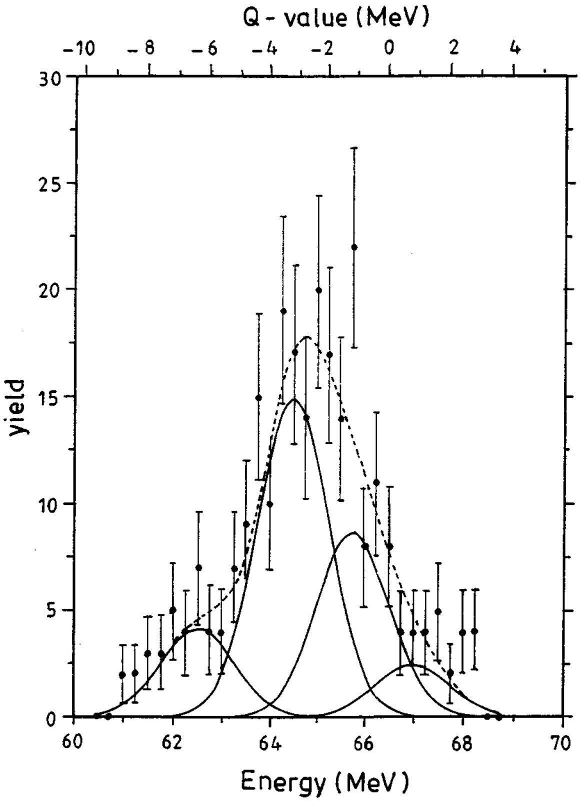

FIG. 5. Energy/Q-value spectrum for the two-neutron channel, shown along with Gaussians of 1.95 MeV width at the expected energies, using which the strengths to the individual states are extracted.

were incorporated. The slopes were obtained by a least squares fit to the data points with d_0 values above 1.55 fm/(nucleon)$^{1/3}$, where diffractive effects are not expected to play any role [19]. The stripping channels were primarily proton channels, whereas the pickup channels were primarily neutron channels as deduced from the Q-value spectra. As expected, the slope parameters obtained are more or less consistent with the semiclassical picture except for the $2p$ stripping channel. The calculated values are: α_{+1n}=0.69, α_{+2n}=1.26, α_{-1p}=0.78, and α_{-2p}=1.52 fm^{-1}. For experimentally obtained values, see Figs. 4(a) and 4(b).

The experimental full width at half maximum (FWHM) for the kinetic energy distribution of the elastically scattered recoils is found to be 1.95 MeV corresponding to the beam energy of 79.8 MeV. Since individual states are not resolvable, a fit to the energy (Q-value) spectrum for two-neutron transfer is made by considering Gaussians of width 1.95 MeV centered at the expected energies (Fig. 5), from which the strengths are extracted. The transfer form factors are then extracted following the procedure of Ref. [15,26]. Coupled channels calculations have been performed using the CCNSC code [33], which is based on the code CCMOD [25] and treats the finite range effects more extensively. The parameters used for the calculations are given in Tables II and III. A plot of the cross section vs the energy is shown in Fig. 6. The experimental fusion cross sections are taken from [25]. Considering the fact that the resolution does not allow the strengths to individual states to be determined with sufficient accuracy, there may be an error in the determination of the form factor for the positive Q-value ground state. The

TABLE II. Deformation parameters β_2 and β_3 for excitation of the lowest 2^+ and 3^- states for the ^{28}Si and ^{68}Zn nuclei, along with the energies of the excited states [9].

Nucleus	Transition λ	β_λ	E (MeV)
^{28}Si	2^+	0.407	−1.78
	3^-	0.400	−6.87
^{68}Zn	2^+	0.205	−1.08
	3^-	0.238	−2.75

effect of the coupling of this state can be seen by switching off the strength to the ground state and putting the strength into the 2^+ state. Hence, the form factor for the ground state is changed from 0.36 to 0.0 MeV and for the 2^+ state from 0.56 to 0.62 MeV. The results in this case underpredict the data significantly (see Fig. 7). The asymptotic shift for the former is 2.4 MeV, whereas the shift for the latter is 1.7 MeV. Note that the latter is close to the asymptotic shift of 1.4 MeV when only the inelastic channel is coupled. The results clearly show the importance of the two-neutron pickup channel, specially the importance of the transfer strength to the positive Q-value ground state in that channel, in bringing the calculated cross sections close to the measured ones in the sub-barrier energy region.

IV. CONCLUSION

In conclusion, measurements of one- and two-nucleon transfer in the ^{28}Si+^{68}Zn system have been performed using the recoil mass separator HIRA. Using a pulsed beam, the TOF and energy of the recoils were recorded. With this information, beam rejection was improved, the M/q ambiguity was resolved, and the Q-value spectra for the recoils were obtained. With the help of this technique we were able to study two-nucleon transfer at energies below the barrier. To the best of our knowledge, this is the first time this has been possible for a beam-target combination in this mass region.

TABLE III. Form factors and slope parameters extracted from the data for the different transfer channels which were used in the coupled channels calculations. For the two-neutron pickup channel, Q values of the individual excited states for which transfer form factors have been estimated are also listed. For the other channels, average Q values were used as listed along with.

Channel	Q value (MeV)	F (MeV)	α (fm^{-1})
$+2n$	+1.8	0.36	1.3
	0.0	0.56	1.3
	−3.5	0.83	1.3
	−6.0	0.83	1.3
$+1n$	−2.2	0.26	0.88
	−4.2	0.50	0.88
$-1p$	−4.7	0.44	0.8
$-2p$	−5.0	0.58	0.9

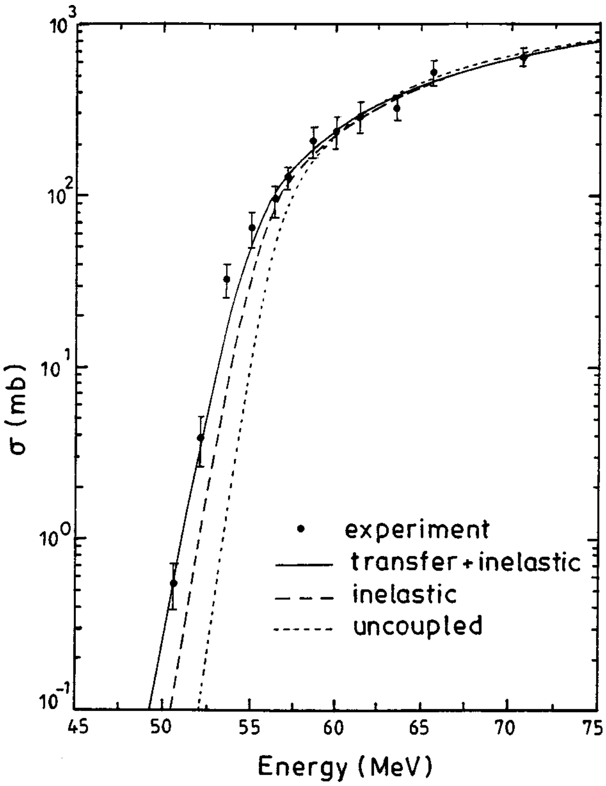

FIG. 6. A plot of the fusion cross section vs energy. The experimental data are taken from Ref. [25]. Results of fusion calculations using the CCNSC code are shown as indicated.

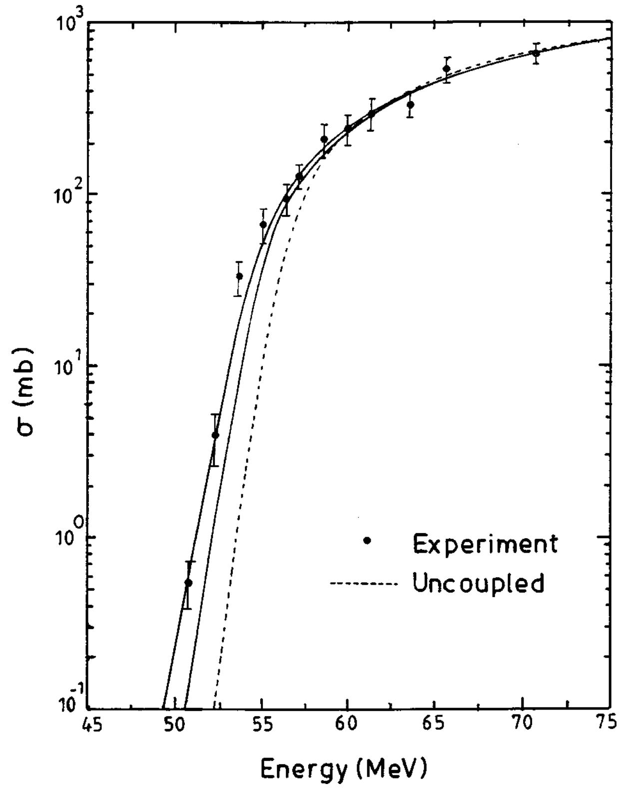

FIG. 7. Plot of the fusion cross section vs energy showing the importance of the transfer strength to the positive Q-value 1.8 MeV ground state. The thick solid line is the result of calculations for the parameters given in Tables II and III. Zero strength for the ground state and 0.62 MeV for the 2^+ state give the thin solid line. For details, see text.

An earlier attempt [23] for the $^{32}S + ^{64}Ni$ system failed due to the nonresolution of the M/q ambiguity. Transfer probabilities and form factors were extracted for all the channels. The observed slopes, extracted from the fits to experimental points with d_0 values greater than 1.55 fm/(nucleon)$^{1/3}$, are consistent with the predictions of the semiclassical model. With the completion of this study, the relevant inputs for all the different channels viz-a-viz the coupled channels formalism have been experimentally determined. Simplified coupled channel calculations have been performed using the CCNSC code. These calculations are able to reproduce the experimental data reasonably well.

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