RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 27, NUMBER 5 MAY 1983

Rapid Communications

The Rapid Communications section is intended for the accelerated publication of important new results. Manuscripts submitted to this section are given priority in handling in the editorial office and in production. A Rapid Communication may be no longer than 3½ printed pages and must be accompanied by an abstract and a keyword abstract. Page proofs are sent to authors, but, because of the rapid publication schedule, publication is not delayed for receipt of corrections unless requested by the author.

Possible effect of transfer reactions on heavy ion fusion at sub-barrier energies

R. A. Broglia, C. H. Dasso, S. Landowne, and A. Winther
The Niels Bohr Institute and NORDITA, Blegdamsvej 17,
DK-2100 Copenhagen Ø, Denmark
(Received 26 January 1983)

It is proposed that the transfer of two neutrons explains the relative enhancement in the sub-barrier fusion cross section of ^{58}Ni + ^{64}Ni with respect to ^{58}Ni + ^{58}Ni. Similar relative enhancements in other cases of low energy heavy-ion fusion reactions are noted.

[NUCLEAR REACTIONS Fusion, enhancement of sub-Coulomb heavy-ion fusion rates by transfer reactions.]

Systematic measurements of excitation functions for the fusion of various Ni + Ni isotopes have recently been carried out over a range of energies from just above to well below the Coulomb barrier.[1] A striking observation is the fact that the excitation function for ^{58}Ni + ^{64}Ni at energies below the barrier decreases more slowly than those of ^{58}Ni + ^{58}Ni and ^{64}Ni + ^{64}Ni. This behavior cannot be explained in terms of arguments based on a simple scaling of the isotope sizes.

Understanding the absolute magnitudes of these and other heavy-ion fusion reactions at sub-barrier energies is a problem which has attracted considerable interest during the past few years.[2–7] However, none of the various proposals seem to be able to explain the irregular behavior of the ^{58}Ni + ^{64}Ni case, In this Communication we propose that the relative enhancement in the sub-barrier fusion of ^{58}Ni + ^{64}Ni is due to the transfer of two neutrons in connection with the fusion process. The argument is made in a

TABLE I. Values of $Q + \Delta E^C$ in MeV for the reactions indicated. Here Q is the ground state Q value and ΔE^C is the Coulomb barrier E_B of the entrance channel minus that of the exit channel, computed according to Ref. 9, $E_B = Z_1 Z_2 e^2 (1 - 0.63/r_B)/r_B$, where $r_B = 1.07(A_1{}^{1/3} + A_2{}^{1/3}) + 2.72$.

Reaction	Neutrons				Protons			
	Stripping		Pickup		Stripping		Pickup	
Proj. + Targ.	2	1	2	1	2	1	2	1
^{58}Ni + ^{58}Ni	−2.1	−3.2	−2.1	−3.2	−5.2	−4.6	−5.2	−4.6
^{64}Ni + ^{64}Ni	−1.4	−3.6	−1.4	−3.6	−5.9	−5.0	−5.9	−5.0
^{58}Ni + ^{64}Ni	−7.4	−6.1	+3.9	−0.6	+2.6	−0.6	−13.7	−9.0
^{64}Ni + ^{74}Ge	−0.6	−3.2	−1.9	−4.1	−5.0	−5.1	−3.9	−3.9
^{58}Ni + ^{74}Ge	−6.6	−5.7	+3.5	−1.2	+3.6	−0.7	−11.8	−7.9
^{36}S + ^{104}Ru	−2.7	−4.1	−2.6	−4.5	−0.8	−2.3	−6.5	−5.2
^{32}S + ^{104}Ru	−14.0	−9.3	+5.2	−0.1	+7.3	+1.6	−18.2	−11.3
^{36}S + ^{110}Pd	−3.0	−4.3	−2.4	−4.4	−0.8	−2.3	−6.9	−5.5
^{32}S + ^{110}Pd	−14.3	−9.4	+5.4	−0.0	+8.1	+1.9	−18.6	−11.6
^{36}S + ^{100}Mo	−3.6	−4.6	−1.7	−3.9	−0.9	−2.4	−6.4	−5.7
^{32}S + ^{100}Mo	−14.8	−9.8	+6.1	+0.4	+7.9	+1.7	−18.1	−11.8

model independent way, using the experimentally measured cross sections.

For low bombarding energies, the fusion rate in a transfer channel will be different from that in the entrance channel both because of the Q value of the reaction and because of the difference of the Coulomb barrier. Fusion will be favored in a transfer channel if $Q+\Delta E^C$ is positive, where ΔE^C is the difference between the heights of the barriers in the two channels. The values of $Q+\Delta E^C$ for the stripping and pickup of one and two nucleons in Ni + Ni reactions are listed in Table I. It is seen that for the ^{58}Ni + ^{58}Ni and ^{64}Ni + ^{64}Ni cases there are no transfer channels which favor the fusion process. On the other hand, for the ^{58}Ni + ^{64}Ni reaction, the two-neutron pickup and the two-proton stripping enhance fusion rates.

It may also be noted that the doubly closed shell nucleus ^{56}Ni is the ground state of well-developed pairing vibrational bands whose members are the ground states of the different Ni isotopes and $N=28$ isotones (cf. Ref. 8 and references therein). One can thus expect large matrix elements for two-particle transfer reactions connecting these states.

At low bombarding energies the form factor for two-neutron transfer is considerably larger than that for two-proton transfer. Also, since $Q+\Delta E^C$ is larger for the two-neutron pickup in the ^{58}Ni + ^{64}Ni case, we may conclude that the main contribution to the observed enhanced fusion cross sections is due to the ^{64}Ni(^{58}Ni, ^{60}Ni)^{62}Ni reaction. This allows us to make a simple analysis of the data as follows: We assume that the measured fusion cross section σ_m for ^{58}Ni + ^{64}Ni at the center of mass energy E is given by

$$\sigma_m(E)=[1-P(E)]\sigma_0(E)+P(E)\sigma_1(E+Q+\Delta E^C)\ , \tag{1}$$

where σ_0 is the fusion cross section in the ^{58}Ni + ^{64}Ni entrance channel, σ_1 is the fusion cross section for the ^{60}Ni + ^{62}Ni transfer channel, and P is an effective probability for two-neutron transfer followed by fusion. To construct σ_0 and σ_1 we take the measured cross section for ^{58}Ni + ^{58}Ni and shift it to account for the mass differences. The result for $\sigma_0(E)$ is shown by the dashed curve in Fig. 1. It turns out that $\sigma_1(E)$ is essentially the same as $\sigma_0(E)$, thus one only has to read the dashed curve at $E+Q+\Delta E^C$ to determine the desired σ_1. Using the measured data points, one can extract $P(E)$ from Eq. (1). We find that an acceptable fit to σ_m is rather insensitive to the energy dependence of P. We show by the solid curve in Fig. 1 the result of taking a constant $P(E)=0.06$ in Eq. (1).

The measurements of Ref. 1(c) also show that the sub-barrier fusion cross section for ^{58}Ni + ^{74}Ge is enhanced relative to ^{64}Ni + ^{74}Ge. This is to be expected since the corresponding values of $Q+\Delta E^C$ show the same pattern as those for the Ni + Ni case (cf. Table I). Proceeding as above, we extract a transfer probability $P(E)=0.10$ (cf. Fig. 1). However, since the value of $Q+\Delta E^C$ for the two-proton stripping in this case is close to that of the two-neutron pickup, the extracted probability may reflect the combined effect of both reactions.

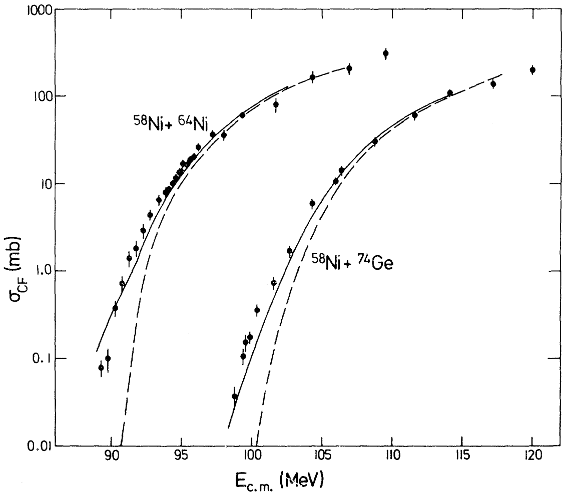

FIG. 1. Fusion cross sections for ^{58}Ni + ^{64}Ni and ^{58}Ni + ^{74}Ge. The data are from Beckerman *et al.* [Ref. 1(c)]. The dashed curves are predictions obtained by extrapolating the measured cross sections (Ref. 1) for ^{58}Ni + ^{58}Ni and ^{64}Ni + ^{74}Ge. The solid curves include the contribution to fusion which occurs after the transfer reaction (^{58}Ni, ^{60}Ni) according to Eq. (1), assuming a transfer probability of 6% and 10% for the ^{64}Ni and ^{74}Ge targets, respectively.

Additional evidence that supports the present argument has been found in sub-barrier fusion reactions using ^{32}S and ^{36}S projectiles on various targets.[7] It is found that the fusion cross sections for ^{32}S are enhanced with respect to those of ^{36}S in several cases where the values of $Q+\Delta E^C$ for transfer channels are positive. The relative enhancements are of the same order as those for the cases discussed above.[7] Some examples are also listed in Table I. It is seen that in these cases proton transfer is expected to play an important role.

The empirical data thus seem to indicate that the transfer of particles is capable of driving the fusion process between heavy nuclei at energies well below the Coulomb barrier.

We would like to thank H. Esbensen, E. Maglione, and G. Pollarolo for discussions on sub-barrier fusion and transfer reactions. One of us (S.L.) acknowledges the support of the Sektion Physik, Universität München and the Bundesministerium für Forschung und Technologie, Federal Republic of Germany, during part of this work.

---

[1](a) M. Beckerman, M. Salomaa, A. Sperduto, H. Enge, J. Ball, A. DiRienzo, S. Gazes, Yan Chen, J. D. Molitoris, and Mao Nai-feng, Phys. Rev. Lett. 45, 1472 (1980); (b) M. Beckerman, J. Ball, H. Enge, A. Sperduto, S. Gazes, A. DiRienzo, and J. D. Molitoris, Phys. Rev. C 23, 1581 (1981); (c) M. Beckerman, M. Salomaa, A. Sperduto, J. D. Molitoris, and A. DiRienzo, *ibid.* 25, 837 (1982).

[2] L. C. Vaz, J. M. Alexander, and G. R. Satchler, Phys. Rep. 69, 373 (1981).

[3] H. Esbensen, Nucl. Phys. A352, 147 (1981).

[4] S. Landowne and J. R. Nix, Nucl. Phys. A368, 352 (1981).

[5] U. Jahnke, H. H. Rossner, D. Hilscher, and E. Holub, Phys. Rev. Lett. 48, 17 (1982).

[6] W. Reisdorf, F. P. Hessberger, K. D. Hildenbrand, S. Hofmann, G. Münzenberg, K.-H. Schmidt, J. H. R. Schneider, W. F. W. Schneider, K. Sümmerer, G. Wirth, J. V. Kratz, and K. Schlitt, Phys. Rev. Lett. 49, 1811 (1982).

[7] R. Pengo, D. Evers, K. E. G. Löbner, U. Quade, K. Rudolph, S. J. Skorka, and I. Weidl, in Symposium on Detectors in Heavy Ion Reactions, Berlin, 1982 (unpublished); and (to be published); R. Pengo (private communication).

[8] D. R. Bes, R. A. Broglia, O. Hansen, and O. Nathan, Phys. Rep. 34, 1 (1977).

[9] R. A. Broglia and A. Winther, *Heavy Ion Reactions* (Benjamin, Reading, Mass., 1981), Vol. 1, p. 116.