YU ISSN 0015—3206
FZKAAA 17 (4) 481 (1985)

ON THE SUB-BARRIER FUSION ENHANCEMENT IN COUPLED CHANNEL MODEL

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Received 15 May 1985

UDC 539.17

Original scientific paper

Quantum mechanical coupled channels (CC) calculations, including coupling only to the 2^+ first excited state in ^{64}Ni are carried out for fusion of the ^{64}Ni + + ^{64}Ni. Considerable fusion cross section enhancement, down to energies almost below the barrier, are found without restoring to other excited states in ^{64}Ni. Sensitivity of the CC fusion cross section (σ_{fus}) to ambiguities associated with the proper geometry of the absorbing potential are displaced, where as 10 orders of magnitude reduction in σ_{fus} comes out with <20% changes in range of the absorbing potential.

1. Introduction

There is increasing evidence that the fusion cross section (σ_f) of medium/heavy ions systems cannot be reproduced accurately around the coulomb barrier if one describes the fusion process through one-dimensional barrier penetration model for two frozen ions. Going beyond the severe restriction imposed by the concept of frozen ions, Vaz et al.[1] suggested the possibility of taking into account neck formation. Jahnke et al.[2] treated the barrier curvature strength as a free parameter to account for the neck formation numerically. Using the liquid drop model, Royer and Remaud[3] performed a systematic study of symmetrical fusion with a neck degree of freedom and tunnelling effects. Their results shows better agreement to experimental fusion cross section data of ^{58}Ni + ^{58}Ni particularly in comparison with the work of Landowne and Nix[4] in which corrections as dynamical deformations and two-dimensional barrier transparency are considered. The only definite improvement in calculating σ_f along the one-dimensional barrier penetration model is that of Beckerman et al.[5] where specific barrier characteristics have been adjusted for the heavy ion systems ^{58,64}Ni + ^{56,64}Ni and a position-dependent mass has been introduced. Both features considerably enhance the sub-barrier fusion cross section without substantially overpredicting it at energies above the barrier.

The clear need to go beyond the conventional approaches, and to account for the intrinsic structure of the colliding nuclei, has stimulated several attempts to carry out full quantum mechanical coupled channel calculations[5,6,8]. However use of optical potential that differed significantly from the elastic (conventional optical model) potential resulted in a good agreement to data while the use of elastic potential resulted in an overestimate of σ_f. A simple method based on direct reaction theory is proposed by Udagawa and Tamura[9], to describe subbarrier fusion of two heavy ions using convenient elastic scattering potential. Only a part W^F of the whole imaginary part (W) of the elastic potential is considered to be responsible for fusion. However W^F could be parametrized (in sharp cutoff) shape so as fusion cross section taking place in elastic channel can fit experimental data without restoring to the cross section of the direct reaction followed by fusion. In another simplified model that accounts for coupling to inelastic excitation and transfer reaction channels[10] and including all of the collective inelastic modes do not seem to give enough enhancement in σ_f without increasing the coupling strength by 1 MeV to fit data. Also drastic changes in the calculated σ_f resulted from allowing 30% uncertainties in the coupling strength.

Coupled channel formalism with an ingoing-wave boundary condition[11] explained enhancement effects in terms of the coupling interaction at the coulomb barrier, but variation observed at higher energies are not explained in this way where coulomb interaction tends to reduce σ_f at high energies and coupling to states of higher excitation energies tend to increase it. Rhoades-Brown and Braun-Munzinger[12] has made coupled channel calculations for the fusion cross section of ^{58}Ni + ^{58}Ni using short range imaginary potential and ascribe all of the lost flux to fusion. The real potential they used is somewhat different from that of Landowne and Pieper[11] but qualitatively the two calculations give similar results. Although two order of magnitude enchancement in σ_f are reported[12], σ_f overpredicts the data above the barrier and underpredicts it below the barrier. This discrepancy was attributed to the real part of the optical potential as being not sufficiently accurate.

In this note we are looking for quantum mechanical coupled channel calculations (CC) that using realistic nuclear potential geometry generated from double folding of the nuclear densities of the two heavy ions (^{64}Ni + ^{64}Ni) and explore dependence of CC model calculations on the ambiguities associated with geometry of the imaginary nuclear potential.

2. *Method of calculation*

The usual coupled differential equation for the radial wave functions of relative motion may be written as

$$\left[\frac{\mathrm{d}^2}{\mathrm{d}r^2} + K_\alpha^2(r)\right] U_\alpha(r) \quad \sum_\beta \frac{2\mu}{\hbar^2} V_{\alpha\beta}(r)\, U_\beta(r). \tag{1}$$

The transition potential V_α^{eff} incorporating the intrinsic degrees of freedom was constructed from ground state or excited states eigenfunctions appropriate to the nuclei of interest. $K_\alpha(r)$ is the local wave number in the sub-channel α, that is

$$K_\alpha(r) = \left[\frac{2\mu}{\hbar^2}(E_\alpha - V_\alpha^{eff}(r))\right]^{1/2} \tag{2}$$

where E_α and V_α^{eff} are the relative energy and effective potential (coulomb + nuclear + + centrifugal) for the sub-channel and μ is the reduced mass. The equations (1) are solved using the coupled channels version of Ptolemy[13]. All coupled channel calculations are performed with a standard first order derivative model for the transition potential.

Our model calculation for fusion is based on the assumption that any loss of flux from the model space (inelastic as well as elastic channels) we can call fusion, that is

$$\sigma_f = \sigma_{fus} = \sigma_A(\mathrm{CC}) - \sigma_{inel} \tag{3}$$

where σ_A (CC) is the reaction absorption coupled channel cross section:

$$\sigma_A = \sum_l (2l+1)(1 - |S_{\alpha l,\alpha l}|^2)$$

and

$$\sigma_{inel} = \sum_l \sum_{\beta l'} (2l+1)\,|S_{\beta l',\alpha l}|^2$$

where $S_{\alpha l,\alpha l}$ and $S_{\beta l',\alpha l}$ are the elastic and inelastic S matrix elements calculated using equation (1). Fusion cross section could be written as

$$\sigma_{fus} = \sum_l (2l+1)\,T_l$$

where

$$T_l = 1 - \sum_{\beta l'} |S_{\beta l',\alpha l}|^2. \tag{4}$$

As there is no information for the proper optical model elastic scattering potential of ^{64}Ni + ^{64}Ni (the system we have in the present study), we used for the real part of the nuclear potential, a potential generated from folding an effective nucleon-nucleon interaction (V_{eff}) into the density distribution of ^{64}Ni and ^{64}Ni. Two parameters Fermi shapes were used for the densities. V_{eff} was taken as a sum of Yukawa terms ($M3Y$) based upon G matrix calculations. The generated potential was then exactly simulated to a WS shape in the surface region (Fig. 1) and then used in our CC calculations. This potential has depth, radius parameter and diffuseness 63 MeV, 1.187 fm and 0.61 fm, respectively. Phenomenological imaginary potential of WS geometry as the real one, except with shallow depth = 5 MeV, was used (set II of Table 1). Also, the short ranged WS squared imaginary potential, that applied in previous CC calculations[12], was used (set I of Table 1).

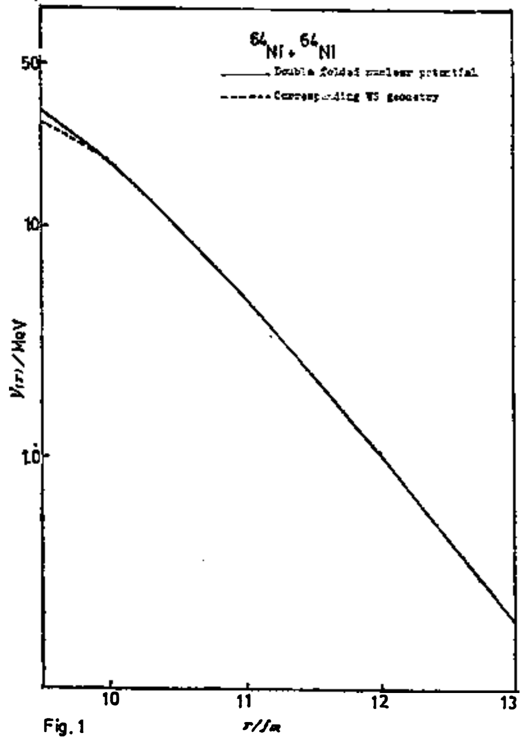

Fig. 1

Fig. 1. Real nuclear potential $V(r)$ versus r. It is generated from double folding calculations (— solid line) and simulated to WS geometry (- - - dashed line).

The coulomb potential was calculated for a uniformly charged sphere of radius $R_c = 1.2\,(64^{1/3} + 64^{1/3})$. Conventional vibrational model is used for the nuclear form factor with a deformation parameter of $\beta = 0.19$[14] for the $2^+ - (1.34$ MeV) transition to the ground state.

3. *Results and discussion*

Coupled channels calculations that includes only coupling to the 2^+ first excited state in ^{64}Ni (1.34 MeV) are shown in Fig. 2. The dotted line is CC calculations using real and imaginary nuclear potentials defined as set I of Table 1. It is clear that strong fusion cross section enhancement is needed. Instead of going further towards including all other collective inelastic modes of ^{64}Ni, where considerable enhancement could be definitely acheived[12], we find it convenient to tray applying another set of nuclear potential parameters, set II of Table 1, where the imaginary potential is different. We find as shown in Fig. 2 (— · — · — line) that CC calculations, again including only coupling to the 2^+ state, are sufficiently describing experimental fusion cross section over a wide range of energy from E_{cm} = 107 MeV down to E_{cm} = 93 MeV, much below the barrier. This is directly suggesting nec-

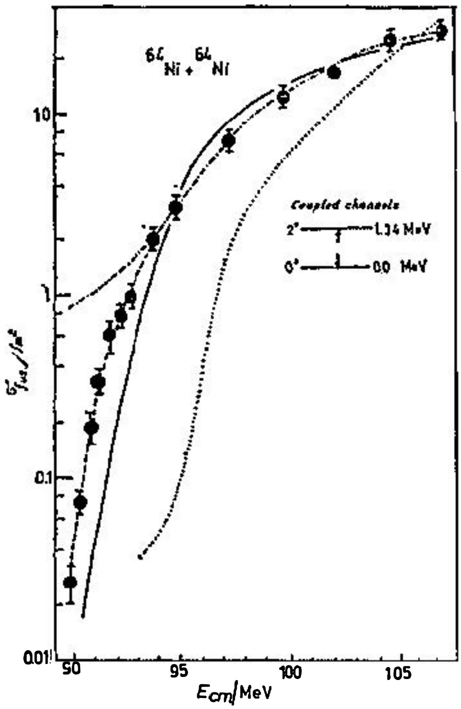

Fig. 2. Comparison of experimental and theoretical excitation function for complete fusion of $^{64}Ni + {}^{64}Ni$. Filled circles represents the experimental data[5].

·········· CC calculations using set I of Table 1

— · — · — CC calculations using set II of Table 1

– – – – – CC calculations using set II of Table 1 and allowing gradual decrease in r_{oi}.

————— WKB calculations[5].

cessity of studying the crucial role of the involved nuclear potential, particularly its imaginary part as seen in comparing sets I and II (Table 1).

TABLE 1.

	V/MeV	r_0/fm	a_0/fm	W/MeV	r_{0i}/fm	a_{0i}/fm
Set I	63.0	1.187	0.61	10.0	1.0	0.4
Set II	63.0	1.187	0.61	5.0	1.187	0.61
Set III	50.0	1.20	0.61	35.0	1.0	0.61

Nuclear potential parameters used in the CC calculations.

A 17% change (reduction) in the range of the absorbing potential produces 10 orders of magnitude reduction in the predicted CC fusion cross section (Fig. 3a). Less drastic effects are associated with changes in the absorbing potential depth

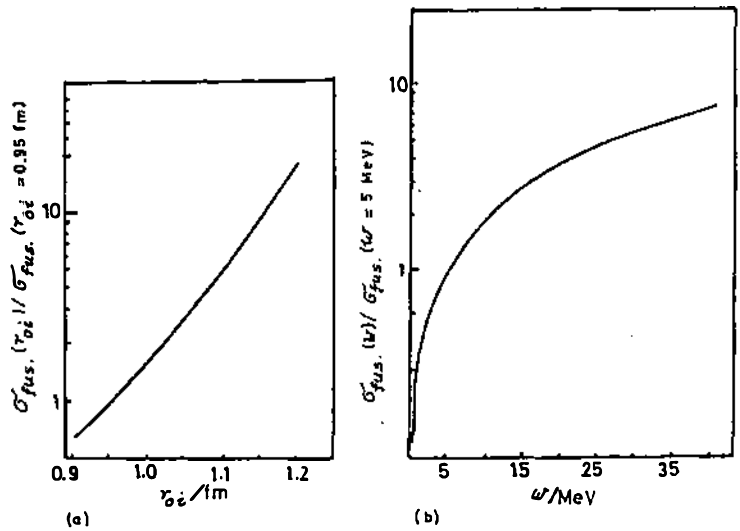

Fig. 3. Ratio of CC fusion cross section calculations at $E_{cm} = 90.1$ MeV using set II of Table 1; (a) versus r_{0i} (b) versus W.

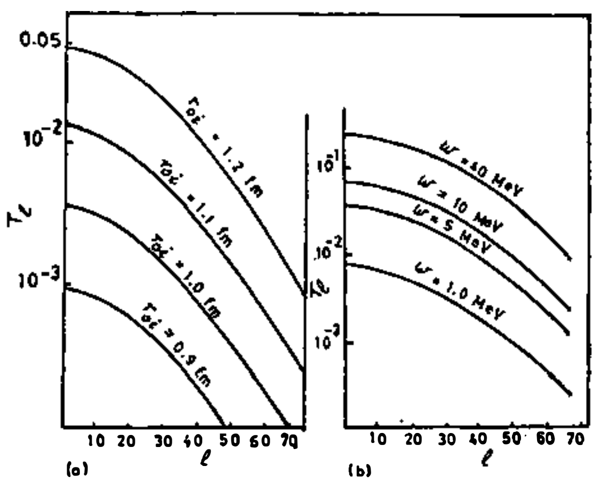

Fig. 4. Transmission coefficients T_l calculated according to equation (4) for $^{64}Ni + ^{64}Ni$ fusion at $E_{cm} = 90.1$ MeV: (a) different r_{0i} values (1.2 fm $\leq r_{0i} \leq$ 0.9 fm), (b) different W values (40 MeV $\leq W \leq$ 10 MeV).

W (Fig. 3b), however, decreasing W from 10 MeV to 5 MeV reduces CC fusion cross section by a factor of 2.

A phenomenological theoretical interpretation could be drawn from the character of the CC transmission coefficients T_l calculated according to equation (4). They are shown in Fig. 4, and clearly displaying the drastic changes in T_l due to changes in geometry of the absorbing potential, particularly at low partial waves that almost have the largest contribution to the fusion cross section. Implications of these changes on the CC fusion cross section as compared to experimental data could be viewed if one allow (just as an example) for r_{0I} to vary slightly with going down in energy below 93 MeV. We get an exact fit to the data as shown by the dashed (— — — —) line in Fig. 2. This may be compared with the WKB calculations of Beckerman et al.[5] (solid line in Fig. 2), that assuming radially dependent effective mass $M(r)$ instead of M (the usual reduced mass)[6] in the effective potential.

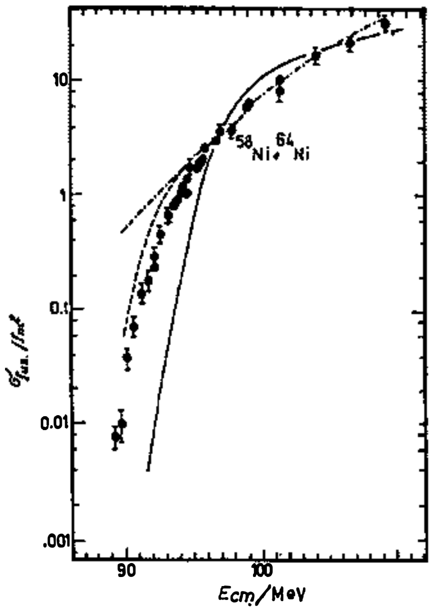

Fig. 5. Comparison of experimental and theoretical excitation function for complete fusion of ^{58}Ni + ^{64}Ni. Filled circles represent the experimental data[5].
··················· CC calculations using set III of Table 1
– – – – – – CC Calculations using set III of Table 1 and allowing gradual decrease in r_{0I}.
————— WKB calculations[5].

It was found experimentally[5] that σ_f (^{58}Ni + ^{64}Ni) decreases much faster than did σ_f (^{64}Ni + ^{64}Ni) when the energy was lowered. So we did coupled channel calculations that includes coupling only to the first excited state in ^{58}Ni (2^+ — — 1.45 MeV, $\beta = 0.2$[15]) and ^{64}Ni (2^+ — 1.34 MeV, $\beta = 0.19$[14]). The optical model potential used (set III) is basically different from sets I and II in its deep imaginary strength (35 MeV). As shown in Fig. 5, CC fusion cross section calculations are in close agreement with the corresponding experimental data over wide energy range (95 MeV $< E <$ 110 MeV), but overpredicting data at lower energies. This may further justify the question that whether one has realy sub-barrier fusion cross section »enhancement« at least, in view of the present coupled channel model calculations.

In conclusion the usual ambiguity encountered in the proper choice of optical model potential, strongly affecting CC fusion cross section calculations, leading to indefinitness (almost misleading conclusion) in studying the role of coupling to higher excited states in explaining fusion cross section enhancement. At least the present results address the difficulty of isolating effects which specific (other) couplings may have on the sub-barrier fusion cross section.

Acknowledgments

The authors are highly appreciating the fruitful discussions with Prof. G. R. Satchler and the kind hospitality of Oak Ridge National Laboratory during their visit to the Lab. where this work was almost completed.

References

1) L. C. Vaz, J. M. Alexander and G. R. Satchler, Phys. Rep. **69** (1981) 373;
2) U. Jahnke, H. H. Rosner, D. Hilscher and E. Holub, Phys. Rev. Lett. **48** (1982) 17;
3) G. Royer and B. Remaud, J. Phys. G. **9** (1983) 1103;
4) S. Landowne and J. R. Nix, Nucl. Phys. A **368** (1981) 352;
5) M. Beckerman, M. Salomaa, A. Sperduto, H. Enge, J. Ball, A. DiRienzo, S. Gazes, Y. Chen, J. Molitoris and M. Nai-Feng, Phys. Rev. Lett. **45** (1980) 1472;
M. Beckerman, J. Ball, H. Enge, M. Salomaa, A. Sperduto, S. Gazes, A. DiRienzo and J. Molitoris, Phys. Rev. **C23** (1981) 1581;
M. Beckerman, M. Salomaa, A. Sperduto, J. Molitoris and A. DiRienzo, Phys. Rev. **C25** (1982) 837;
6) R. G. Stochkstad and E. E. Gross, Phys. Rev. **C23** (1981) 281;
7) G. M. Berkowitz, P. Braun-Munzinger, J. S. Karp, R. H. Freifelder, T. R. Renner and M. W. Wilschut, Phys. Rev. **C28** (1983) 667;
8) W. S. Freeman, H. Ernst, D. F. Geesaman, W. Henning, T. J. Humanic, W. Kuhn, G. Rosner, J. P. Schiffer, B. Zeidman and F. W. Prosser, Phys. Rev. Lett. **50** (1983) 1563;
9) T. Udagawa and T. Tamura, Department of Phys., University of Texas, Austin, Preprint (1983);
10) R. A. Broglia, C. H. Dasso, S. Landowne and G. Pollarolo, Phys. Lett. **133B** (1983) 34;
11) S. Landowne and S. C. Pieper, Argone National Laboratory, Argone, Illinois 60439, preprint, (1983);
12) M. J. Rohades and P. Braun-Munzinger, Phys. Dept. State University of New York at Stony Brook, preprint (1983);
13) M. Rhoades-Brown, M. H. Mcfarlone and Steven C. Pieper, Phys. Rev. **C21** (1980) 2417; ibid, **C21** (1980) 2436;
14) G. Bruge, J. C. Faivre, H. Farragi and A. Bussiere, Nucl. Phys. **A146** (1970) 597;
15) A. Bernstein, Adv. Nucl. Phys. **3** (1969) 325.

O POJAČANJU SUBBARIJERNE FUZIJE U MODELU VEZANIH KANALA

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UDK 539.17

Originalni znanstveni rad

Za fuziju ^{64}Ni + ^{64}Ni napravljeni su računi u modelu vezanih kanala, s uključivanjem vezanja samo na prvo pobuđeno stanje 2^+ u ^{64}Ni. Dobiveno je znatno povećanje fuzijskog udarnog presjeka, sve do energija gotovo ispod barijere. Pokazana je osjetljivost računatog fuzijskog udarnog presjeka (σ_{fus}) na neodređenosti povezane s geometrijom apsorbirajućeg potencijala. Dobivena je redukcija σ_{fus} za oko 10 redova veličina za promjenu 20% u dosegu apsorbirajućeg potencijala.