PHYSICAL REVIEW C VOLUME 25, NUMBER 3 MARCH 1982

Simultaneous excitations in nucleus-nucleus interaction potential

Bikash Sinha
Nuclear Physics Division, Bhabha Atomic Research Centre, Bombay, 400085, India
(Received 30 July 1981)

The imaginary part of the nucleus-nucleus interaction potential for simultaneous excitations of the target and the projectile has been estimated. For comparatively higher relative energy, the two-body excitation mechanism seems to be the dominant channel. The theoretical predictions agree reasonably well with appropriate experimental form factors.

[NUCLEAR REACTIONS Calculated the imaginary part of the interaction potential for two colliding nuclei for simultaneous excitations.]

For two colliding nuclei, excitations of nuclear states can be initiated either by the single-particle field of the projectile exciting the target states (one-body excitation), or by the two-body nucleon-nucleon interaction potential inducing simultaneous excitations in both the colliding nuclei. Transfer of one or more particles across the neck of the nuclei, in proximate touch, can also lead to excitations; collective degrees of freedom, evidently, can be excited by any one of the above mentioned mechanisms. Typically, for the one-body excitation mechanism, particle-hole states are excited in the target or the projectile, where the single-particle field remains unaltered; for the two-body mechanism, particle-hole states are simultaneously excited in both the nuclei and for transfer, particle in one and hole in the other nucleus is the typical characteristic. For peripheral collision of nuclei, as is the case for elastic and inelastic scattering, it is expected that the excitation spectrum would be primarily dominated by one-body or two-body excitations, the transfer of particles to a large extent is blocked out. At low energy, when the energy per nucleon is relatively small compared to the Fermi energy, the one-body excitation mechanism would be the most important channel; with the increase in energy per nucleon, however, the Pauli blocking gets relaxed and the two-body mechanism tends to become rather more important.

The imaginary part of the interaction potential between two ions is the cumulative signature of all possible excitations. As mentioned, depending on the magnitude of the relative energy, either of two mechanisms would constitute the most likely intermediate states. The traditional format for calculating the imaginary part of the interaction potential is the second-order potential in a Feshbach type of formalism. The pole term corresponding to energy conserving transitions leads to the imaginary potential, whereas the energy nonconserving virtual excitations, corresponding to the principal value of the second-order term, lead to the (real) polarization term.

Recently, there have been several attempts[1–4] to evaluate the imaginary potential. In a previous publication[5] the present author attempted to calculate the second-order term when the driving potential happens to be the single-particle potential of the projectile. In this paper, I propose to compute the second-order potential starting from the two-body effective interaction between the interacting nucleons of the colliding nuclei. It is felt that this procedure is more fundamental—the one-body and the two-body components of the potential can be easily separated; more importantly, the connection between various components of the two-body interaction and the second-order potential can be established with some degree of confidence. It is understood by now that the second-order potential corresponding to the simultaneous excitations of the nuclei can be linked with the two-body dissipation mechanism[6] for the heavy-ion deep inelastic collision—the derivation of a proximity form[7] for such a potential would only be a logical corollary.

The second-order potential in general can be written as

$$U_2=\sum_{\substack{m\neq 0\\ n\neq 0}}\left[\langle\phi_0\psi_0|\sum_{i,j}v_{ij}|\phi_m\psi_n\rangle G_{mn}\langle\phi_m\psi_n|\sum_{i',j'}v_{i',j'}|\phi_0\psi_0\rangle\right], \tag{1}$$

where the propagator G_{mn} is given by

$$G_{mn}=\frac{1}{(2\pi)^3}\int d^3k\frac{e^{i\vec{k}\cdot\vec{s}}}{\hbar^2/2\mu(k_{mn}{}^2-k^2)+i\epsilon}, \tag{2}$$

where plane-wave representation for relative motion has been implicitly assumed, and $(\hbar^2/2\mu)\,k_{mn}{}^2=E-E_m-E_n$, E being the center of mass energy for relative motion, E_m and E_n being the energy of the excited states of the target and the projectile, respectively, ϕ_m and ϕ_n being the corresponding wave functions.

For collisions of two nuclei with moderate relative energy, the center of mass energy is usually much larger than the excitation energies, as has been argued out.[2,5] The assumptions in our calculation are, therefore, (i) $E>>E_m+E_n$ and (ii) the energy of excitation E_m or E_n can be approximated by an average constant value $\langle\Delta E\rangle$,[2,5] the magnitude of which would depend on the characteristics of the entrance phase. With these two assumptions, one can now perform the integration over the kinetic energy of the two nuclei in the intermediate states, yielding

$$\bar{G}\equiv G_{mn}\simeq(\mu/2\pi\hbar^2)(e^{iKs}/s)\bar{k}/K, \tag{3}$$

where

$$K^2=(2\mu/\hbar^2)(E-\langle\Delta E\rangle-U_R),$$
$$\bar{k}^2=(2\mu/\hbar^2)(E-\langle\Delta E\rangle), \tag{4}$$

U_R being the real part of the interaction potential. The second-order potential now becomes

$$U_2(R,s)=\bar{G}(s)\sum_{\substack{m\neq 0\\ n\neq 0}}\left[\langle\phi_0\psi_0|\sum_{ij}v_{ij}|\phi_m\psi_n\rangle\times\langle\phi_m\psi_n|\sum_{i'j'}v_{i'j'}|\phi_0\psi_0\rangle\right] \tag{5}$$

In order to evaluate Eq. (4), we shall now add and subtract the ground states of the target and projectile, i.e., $\phi_m\psi_n\equiv\phi_0\psi_0$, a procedure which allows one to apply "closure" for the intermediate states $|mn\rangle$, exhausting a complete set. Thus[2,5]

$$U_2(R,s)=\bar{G}(s)\left[\langle\phi_0\psi_0|\sum_{ij}v_{ij}\sum_{i'j'}v_{i'j'}|\phi_0\psi_0\rangle-|\langle\phi_0\psi_0|\sum_{ij}v_{ij}|\phi_0\psi_0\rangle|^2\right]. \tag{6}$$

There can be four types of leading terms, arising from the first matrix corresponding to (1) $i=i'$; $j=j'$, (2) $i\neq i'$, $j\neq j'$, (3) $i=i'$, $j\neq j'$, and (4) $i\neq i$, $j=j'$. Inequality either in (i,i') or (j,j') leads to a two-body correlation function,[2,5] further, it turns out that from conditions (3) and (4) one gets back the second-order potential when the driving potential is the single-particle field of the target and/or projectile, as has already been calculated.[5] This leaves one with the first two conditions which correspond to the two-body interaction v_{ij} exciting projectile and target states simultaneously, the subject of the present investigation. In configuration space, for the latter type of excitation, one gets

$$U_2(R,s)=\bar{G}(s)\left[\int\rho_1(r_1)\rho_2(r_2)v(|\vec{r}_1-\vec{r}_2+\vec{R}+\tfrac{1}{2}\vec{s}|)v(|\vec{r}_1-\vec{r}_2+\vec{R}-\tfrac{1}{2}\vec{s}|)d^3r_1\,d^3r_2-\tfrac{1}{16}\int\rho_1{}^2(R_1s_1)\rho_2{}^2(R_2,s_2)v(|\vec{R}_1-\vec{R}_2+\vec{R}+\tfrac{1}{2}\vec{s}-\tfrac{1}{2}\vec{s}_0|)\times v(|\vec{R}_1-\vec{R}_2+\vec{R}-\tfrac{1}{2}\vec{s}+\tfrac{1}{2}\vec{s}_0|)d^3R_1d^3R_2\,d^3s_1\,d^3s_2\right] \tag{7}$$

with $\vec{s}_0=(|\vec{s}_1-\vec{s}_2|)$.

As is well known,[8] both the central and the tensor components of the two-body interactions would contribute to Eq. (6). A suitable choice of the two-body interaction is conditioned by the following motivations: the interacting nuclei, although in different nuclei are, however, embedded in the nuclear medium of their own nucleus, the "effective"

influence of nucleons, surrounding the interacting nucleons has to be taken into account; a simple form of v_{ij} such as a Gaussian reduce the integration to a manageable form. Guided by these two motivations our Gaussian interaction was matched with that of Bertsch *et al.*[9] with the constraints that the mean square radius and the volume integral should be the same in both cases. As an optimum choice the two-body interaction inclusive of the tensor component was taken to be $-v(r)=10.25\ e^{-0.26r^2}$. It should be noted that owing to the nonlocality of the potential, the tensor component gives rise to terms such as $S_{12}(r)S_{12}(r')$, which was estimated as per the prescriptions of Brown *et al.*[8]. For the purpose of estimating the second-order potential for colliding nuclei the triplet component of the central part of the two-body interaction is slightly overestimated by Bertsch *et al.*,[9] since the tensor component is already included in the central force in the style of Kuo and Brown[8]; the nominal renormalization was incorporated in our prescription. Considering the present state of the art, it is felt that a stringent test of the two-body interaction is not the primary purpose, but rather to investigate the efficiency of the basic physical assumptions in our model. With a Gaussian two-body interaction, the first integral reduces to $[v(r)=v_0e^{-\alpha r^2}]$,

$$U_2(R)=4\pi {v_0}^2 \int e^{-1/2\alpha s^2}\bar{G}(s)j_0(Ks)s^2\,ds \times \int \rho_1(r_1)\rho_2(r_2)e^{-2\alpha(r_1-r_2+R)^2} \times d^3r_1\,d^3r_2\ . \quad (8)$$

The second integral, evaluated using the Negele-Vautherin-Campi[10] approximation for the density matrix, was found to be less than 5% of the first integral, expressed in Eq. (7). In transforming the nonlocal potential Eq. (6) to an equivalent local potential Eq. (7), the Perey-Saxon method was employed as reported earlier.[2,5] For the evaluation of $\bar{G}(s)$, $\langle \Delta E \rangle \equiv E_m + E_n$ was considered to be ~ 20.0 MeV. It turns out that for the kind of relative energy range (see later text) we are interested in, the results are not that sensitive to the value chosen for $\langle \Delta E \rangle$. For the real part of the interaction potential we utilized the results of Sinha and Moszkowski.[11]

In Fig. 1, the theoretically computed results for the (^{16}O,^{16}O) system have been compared with the energy dependent shallow potential form-factors of Siemssen[14]; also shown in the diagram is the comparison for the recently calculated potential of Izumoto *et al.*[13] for the system (^{16}O,^{40}Ca), who derived the potential using the many-body Brueckner-Hartree-Fock method. The equivalent Woods-Saxon potentials, fitted to the theoretical form factors are presented in Fig. 1. Izumoto *et al.*[13] found the quality of the fits quite excellent. The polarization term, not shown in the diagram, was found negligible. The following observations are worth noting: With the increase in relative energy the theoretical prediction of the potential suggests an increase in depth, in agreement with experimental results. The results tend to agree quite closely with the shallow energy dependent phenomenological predictions of Siemssen[14] for the ^{16}O + ^{16}O system, in effect, substantiating the author's earlier claim[12] that simultaneous excitation mechanism gives rise to a shallow but larger range potential. Although it differs from that of Izumoto *et al.*,[13] the form factor for the ^{16}O + ^{40}Ca system inside the nucleus agrees reasonably well at the all important strong absorption radius R_s. Comparing the present results with the one-body mechanism,[5] it appears that at low energy the two-body excitation strength is comparatively weak; the physical situation is emphatically a one-body excitation, whereas for higher energy, the two-body mechanism dominates, since the one-body potential drops off rather sharply with the increase in energy.[5] This of course is what is anticipated.

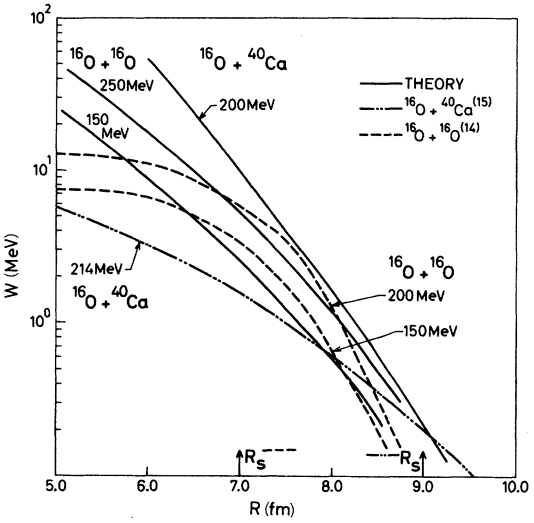

FIG. 1. The imaginary part of the interaction potential for simultaneous excitations in target and projectile ^{16}O + ^{16}O (Ref. 14); ^{16}O + ^{40}Ca (Ref. 15).

The not so unimpressive agreement with experimental analysis leads to the following suggestion:

for the imaginary component of Eq. (7),

$$U_2(R)=v_0^2(\mu/2\hbar^2)\sqrt{2\pi/\alpha}(\bar{k}/K^2)[1-e^{-2k^2/\alpha}] \times \int \rho_1(r_1)\rho_2(r_2)e^{-2\alpha(r_1-r_2+R)^2}d^3r_1\,d^3r_2\ . \tag{9}$$

The double folding type of integral[15] in Eq. (9) has two advantages: (a) An unambiguous analysis of scattering data is now plausible (utilizing the abundant experimental data now available), where both the real (using, say, a double folding model[16]) and the imaginary potential are evaluated microscopically. A systematic study for the depth, range, and other properties of the two-body interaction especially relevant for heavy ion collision is, therefore, plausible. (b) For the intranuclear distance $R \gtrsim R_1 + R_2$, it is straightforward to show[16] that a proximity type of potential can be written out, yielding approximately: ($\tilde{s}=R-R_1-R_2 : T\approx 0.5$),

$$U_2=2\pi v_0^2(\mu/\hbar^2)\sqrt{2\pi/\alpha}(\bar{k}/K^2\bar{R})[1-e^{-2K^2/\alpha}] \times \left[e_0(\tilde{s})+\tfrac{1}{2}\bar{R}e_1(\tilde{s})\right], \tag{10}$$

$$e_n(\tilde{s})=\int_{\tilde{s}}^{\infty} y^{n+1}/(e^{y/T}-1) : \bar{R}=(R_1+R_2)/R_1R_2\ .$$

The form of Eq. (10), although approximate, has the tremendous advantage of being algebraically transparent, thus enabling a global study to be somewhat meaningful. Further, utilizing the established relationship between the imaginary potential and dissipation within the proximity approximation,[17] a comprehensive microscopic understanding of the two-body dissipation mechanism is no longer unrealistic.

In conclusion, therefore, I would like to suggest that a simultaneous excitation of two nuclei is the dominant channel for the imaginary part of the interaction potential when the relative energy is ~ 15 MeV per nucleon or higher. A global analysis using microscopic form factors for both the real and the imaginary potential should be carried out. And finally, the connection between dissipation and the imaginary potential can be utilized within the proximity approximation for a detailed understanding of both the phenomena.

I would like to thank most warmly Nicole Vinh Mau, David Brink, and S. C. Phatak for their critical and illuminating remarks.

[1]B. Sinha, Phys. Rev. C 11, 1546 (1975).
[2]N. Vinh Mau, Phys. Lett. 71B, 5 (1977).
[3]W. G. Love, T. Terasawa, and G. R. Stachler, Nucl. Phys. A291, 183 (1977).
[4]A. J. Boltz *et al.*, Phys. Rev. Lett. 40, 20 (1978).
[5]B. Sinha, Phys. Rev. Lett. 42, 690 (1979).
[6]J. Randrup, Ann. Phys. (N.Y.) 112, 356 (1978).
[7]J. Blocki *et al.*, Ann. Phys. (N.Y.) 113, 330 (1978).
[8]G. E. Brown, in *Unified Theory of Nuclear Models,* 2nd ed. (North-Holland, Amsterdam, 1967).
[9]G. Bertsch *et al.*, Nucl. Phys. A284, 399 (1977).
[10]X-Campi and A. Bouyssy, Phys. Lett. 73B, 263 (1978).
[11]B. Sinha and S. A. Moszkowski, Phys. Lett. 81B, 289 (1979).
[12]B. Sinha, Phys. Rev. Lett. 44, 1207 (1980).
[13]T. Izumoto *et al.*, Phys. Lett. 95B, 16 (1980).
[14]R. H. Siemssen, in *Nuclear Spectroscopy and Reactions,* edited by J. Cerny (Academic, New York, 1974), p. 233.
[15]D. M. Brink and N. Rowley, Nucl. Phys. A219, 979 (1974).
[16]G. R. Satchler and W. G. Love, Phys. Rep. 55, 183 (1979).
[17]B. Sinha, Phys. Lett. 71B, 243 (1977) and Ref. 7.