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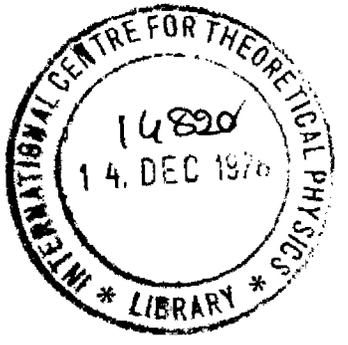

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

A VIEW ON REACTIONS OF COMPLETE FUSION

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A VIEW ON REACTIONS OF COMPLETE FUSION *

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ABSTRACT

Complete fusion reactions are analysed within the framework of a theoretical model. Energy density interaction potentials are made use of and are renormalized for the purpose. A large number of heavy ion reactions are studied and the calculated critical angular momenta are compared with experimental data.

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I. INTRODUCTION

Heavy ion physics has become the most exciting and dynamic branch of nuclear physics. The primary impetus to the study of heavy ion reactions has been given by the possible experimental synthesis of new heavy and superheavy elements. The experimental evidence has revealed a number of interesting phenomena that take place during the collision between two heavy nuclei. At kinetic energies high above the Coulomb barrier, most of the reaction cross-section is due to complete fusion reactions and deep inelastic processes. Experiment suggests the existence of a relation between the two types of processes. Hence, the theoretical explanation and the quantitative description of complete fusion reactions becomes a necessary step towards the understanding of deep inelastic scattering. Most typical of both processes is the considerable transfer of relative kinetic energy into intrinsic degrees of freedom.

The short reduced wavelength of the incident ion allows for a classical trajectory of relative motion [1], i.e. one may attempt a classical description of the reaction process. The phenomenological dynamic models [2-5] consider the energy loss by introducing a dissipative friction force in the classical equations of motion. Usually the former is taken proportional to the velocity. These models do not provide a satisfactory quantitative description of experimental data on complete fusion cross-sections, though there is a wide choice of the strength and the form factors of the friction force, and the ion-ion interaction potential. The failure of the dynamic models to obtain an overall agreement between their numerical predictions and experiments on complete fusion may be hidden in the

rough treatment of the energy relaxation. It would be used that the description of the complete fusion events requires rather unrealistic form factors of the friction force [4]. Form factors of a much shorter range are preferred when the same approach is applied to deep inelastic scattering [6]. A satisfactory set of numerical values about the energy losses and the angular distributions of the products in deep inelastic scattering has been obtained in [7] with a realistic range of the friction force and an in-out asymmetry in the nucleus-nucleus potential. The simultaneous determination of the critical angular momenta (the complete fusion cross-sections) requires, however, a free adjustable parameter.

The most general microscopic analysis of complete fusion and deep inelastic events is performed by the time-dependent Hartree-Fock (TDHF) approach [8]. Unfortunately TDHF calculations are available only to light systems for the present because of the large amount of computation time. Nevertheless, such calculations provide valuable knowledge of the time evolution of the system of two strongly interacting nuclei. Thus, the contour plots that give the density distributions of target and projectile as a function of time allow for the following qualitative conclusions [9]: 1. The distorsions of the density distributions of target and projectile are insignificant at the first stage of mutual overlap, i.e. Coulomb barrier penetration is not accompanied by a noticeable deformation of both nuclei. 2. The energy absorption is very sharp. 3. After clutching, the system starts oscillating around an equilibrium distance between the inertial centres of the two nuclei.

Obviously, such oscillations may possibly lead to fission of the compound system. This stage of the reaction process is quite analogous to spontaneous fission and α-decay phenomena. This probability cannot be accounted for within the framework of the classical dynamic models, where a certain trajectory is either scattered or trapped in the pocket of the interaction potential.

The present paper offers a model which describes approximately the oscillations of the two nuclei with respect to each other by a quasimolecular state in the one-dimensional potential well of the total ion-ion interaction potential.

II. THE MODEL OF COMPLETE FUSION

The competition among the nuclear attraction, the Coulomb repulsion, and the centrifugal force allows the formation of an attractive well in the nucleus-nucleus interaction potential:

$$W_\ell(R) = V_N(R) + V_C(R) + V_\ell^{rot}(R), \qquad (1)$$

R is the distance between the centres of target and projectile, $V_N(R)$ is the nuclear interaction potential, $V_C(R)$ is the Coulomb repulsion, and $V_\ell^{rot}(R) = \frac{\hbar^2 \ell(\ell+1)}{2\mu R^2}$ is the effective centrifugal potential.

Complete fusion is considered as a two-stage process. The first step is the penetration through the Coulomb barrier. A particle of reduced mass

$$\mu = A_1 A_2 / (A_1 + A_2)\, m_0,$$

with an orbital angular momentum ℓ and incident energy E, penetrates through the interaction barrier with a probability $T_\ell(E)$. The latter is calculated in the quasiclassical WKB approximation. It is assumed that energy losses are negligible during the barrier penetration. The second stage of the process is the formation of a nuclear quasimolecule which should be identified with the lowest possible quasi-stationary state in the potential well of $W_\ell(R)$. The first oscillation of the quasimolecule (the first attempt for tunneling back into the entrance channel) determines the probability that the compound system will remain in its quasi-molecular state. In case that no tunneling occurs, the corresponding partial wave is considered contributing to the complete fusion cross-section. A sudden and strong (large) energy relaxation is assumed during the short time after the barrier penetration and before the formation of the quasimolecule. The present model does not specify and does not treat the rather complicated intermediary stage at which

the effective particle is trapped on the quasibound level. In the time interval after the trapping on the level and before the first collision on the potential barrier ($\tau_{vib} \sim 10^{-22}$ sec), the lowest state in the resultant potential well may be viewed as the ground state of a spontaneously fissioning heavy nucleus. The level width due to diffusion of nucleons is negligible since diffusion is a slower process. The higher lying states in the potential well are strongly coupled to intrinsic and other degrees of freedom, i.e. their level width is much larger and the energy spectrum above the quasimolecular ground state is very close to a continuous one. Hence, trajectories of motion are meaningful only above the quasimolecular ground state. It should be remarked that the forbidden appearance of the effective particle below the first level in the potential well is an essential result of the present model and it is a consequence of the quantum-mechanical treatment of the R-degree of freedom. Classical dynamic models [2-5] do not take this fact into consideration and so they are evidently forced to employ unrealistic friction form factors when trying to describe complete fusion events.

The probability $\omega_\ell(\varepsilon_\ell)$ that the already formed quasistationary state will not decay back into the direct fission channel is determined by the penetration probability $T_\ell(\varepsilon_\ell)$:

$$\omega_\ell(\varepsilon_\ell) = 1 - T_\ell(\varepsilon_\ell),$$

where ε_ℓ is the energy of the lowest possible state in the potential well. ε_ℓ and ω_ℓ are calculated in the WKB approximation. Thus, the partial complete fusion probability T_ℓ^{CF} at a given value of the centre-of-mass kinetic energy E and for angular momentum ℓ is determined by the expression:

$$T_\ell^{CF}(E, \varepsilon_\ell) = T_\ell(E)\,\omega_\ell(\varepsilon_\ell). \qquad (2)$$

The complete fusion cross-section is calculated [illegible] for [illegible]:

$$\sigma_{CF} = \frac{\pi\hbar^2}{2\mu E}\sum (2\ell+1)\,T_\ell^{CF}(E, \varepsilon_\ell). \qquad (3)$$

The infinite summation in (3) is terminated when:

1. The entrance channel kinetic energy becomes lower than the energy of the respective quasimolecular state. Obviously, for a given kinetic energy range the number of ℓ-waves that contribute to the complete fusion cross-section σ_{CF} in (3) will be larger as E increases.

2. In the case of high ℓ-waves, the steeper centrifugal potential makes the corresponding potential wells shallower, while at some maximal value of the angular momentum ℓ the quasistationary state disappears. This maximal ℓ-value is not identical to the critical angular momentum which follows from the sharp cutoff formula:

$$\ell_{cr} \approx \sqrt{\frac{2\mu E}{\pi\hbar^2}\sigma_{CF}}\,. \qquad (4)$$

Numerical calculations within the framework of the present model require a definite choice of the nucleus-nucleus interaction potential. In this paper we have used energy density potentials [10]. The latter make use of the ground state density distributions and are calculated in the sudden collision approximation. Temperature-dependent Hartree-Fock estimates [11] have shown that density distributions of nuclei are generally influenced by the temperature of the system though moderate excitations have no substantial effect on the density distribution parameters. Hence, energy density potentials are realistic enough for not very large excitations of [illegible] projectile. The effective half-value radius and the surface thickness [illegible] density distribution increase at high temperatures. Larger half-[illegible] [illegible] diffuse layers increase the nuclear attraction

around the minimum of $W_\ell(R)$ and lower the value of the interaction barrier [12].

Let us consider the case when the incident energy in the entrance channel is close to both the interaction barrier and the bottom of the potential well. That happens for the high partial ℓ waves which contribute to the complete fusion cross-section σ_{CF}. The allowed energy loss is evidently small and "frozen" potentials can be used. Note that these high ℓ-waves have the largest partial weight in the summation of the complete fusion formula (3). A deeper interaction potential well due to internal excitations of the nuclei at lower intermediary ℓ-values will not affect too much the direct fission probability of the quasimolecule. One might be obliged to follow the energy dissipation along a trajectory of motion for the lowest ℓ-waves since a large amount of energy transfer is possible in that case. Furthermore, a consistent treatment of the excitation energy effect on the ion-ion potential may be necessary. It is possible that for low values of the impact parameter some of the trajectories might get scattered by the repulsive core of the resultant potential without the formation of a quasimolecule. This possibility is not accounted for in our model. Nevertheless, the scattered low ℓ-waves will not influence too much the value of the computed complete fusion cross-section since their partial weights in formula (3) are rather small.

III. THE ION-ION INTERACTION POTENTIAL

The present work is based upon heavy ion interaction potentials calculated in the sudden collision approximation within the energy density formalism [10,13]

$$V(R)=\int \mathcal{E}(\rho_1+\rho_2)\,d\tau-\int \mathcal{E}(\rho_1)\,d\tau-\int \mathcal{E}(\rho_2)\,d\tau. \qquad (5)$$

$\mathcal{E}(\rho)$ is the energy density. Details about the specific choice of $\mathcal{E}(\rho)$ for the case of the Fermi density distribution used herein can be found in [14]. The study of the complete fusion cross-sections on the basis of these potentials shows disagreement between theory and experiment. Correct values of the complete fusion

cross-section can be obtained after a modification of the surface term:

$$V_S(R)=\eta_o\int\left\{\left[\nabla(\rho_1+\rho_2)\right]^2-(\nabla\rho_1)^2-(\nabla\rho_2)^2\right\}d\tau,$$

of the energy density potential. Such a modification can be carried out if one replaces the η_o parameter by an effective local variable $\eta(R)$ of the following type:

$$\eta(R)=\begin{cases}\eta_o & S\geq 1.16\\ BS+C & 1.16\geq S\geq 1.06\\ 1.06B+C & 1.06>S\end{cases}, \qquad (6)$$

where $S=\dfrac{R}{(1-k\alpha^2)(A_1^{1/3}+A_2^{1/3})}$, $\alpha=\dfrac{N-Z}{N+Z}$, $k=2.15$, $\eta_o=15.2$.

While in reactions, where one of the two nuclei has a mass number $A\leq 20$, the parameters in (6) take values $B=-280$, $C=340$, and when the mass numbers of target and projectile are greater than 20, $B=-469$, and $C=560$. This difference in the parameter choice is due to the universal symmetrized Fermi density distribution used in all calculations. It is well established, however, that density distributions of light nuclei are much closer to a Gaussian than to a Fermi distribution. The different surface gradient of the density distribution affects mostly the surface part of the nuclear ion-ion interaction. Hence, two separate sets of parameter values are used in (6) when the target or the projectile mass number is higher or lower than 20. The corrected potential exhibits a weaker attraction in the peripheral overlap region. Various arguments support this modification of the interaction potential. It should be noted, in fact, that the surface (gradient) term is the least justified quantity in the energy density formalism. Furthermore, it was shown [15] that a more

general definition of the surface energy term does not change the binding energy value of a separate nucleus but brings about noticeable additional attraction in the surface part of the nuclear interaction potential. The conclusions drawn in [15] are in qualitative agreement with the present approximation about the surface interaction energy. This renormalization can account also for the dynamic deformation of target and projectile.

IV. RESULTS AND DISCUSSION

The model described in Sec.II has been applied to the study of complete fusion reactions between complex nuclei. The numerical results obtained are reported in the table. There is satisfactory agreement between the calculated and the experimental values of the critical angular momenta for all pairs of nuclei given in the table. The simultaneous description of the $^{40}Ar + ^{121}Sb$ and the $^{84}Kr + ^{209}Bi$ reactions should be noted, since all other approaches [2-5] have failed at this point. The calculations are only qualitatively in agreement with the experimentally found channeleffect [16] when different combinations of target and projectile are fused, and form one and the same compound nucleus ($^{11}B + ^{159}Tb$, $^{12}C + ^{158}Gd$, $^{16}O + ^{154}Sm$, and $^{20}Ne + ^{150}Nd$). The cross-section dependence on the relative kinetic energy is of great importance for the study of the complete fusion mechanism. It is seen from the table that the present numerical calculations reproduce fairly well the experimental energy dependence of the critical angular momenta. That becomes evident in the case of the $^{40}Ar + ^{121}Sb$ reaction where the calculations are set against the values of the critical angular momenta experimentally deduced at six different values of the centre-of-mass kinetic energy ($E \in [120, 266]$ MeV). Saturation of ℓ_{cr} in reactions between light nuclei starts at lower values of E as compared with the experiment. At present the determination of ℓ_{cr} at very high kinetic energies remains an open problem. Reactions at high kinetic energies are characterized by the large amount of excitation energy which possibly leads to a different mechanism of com-

plete fusion. The present treatment neglects a number of possible competitive processes such as the transfer of mass and angular momentum.

The results, obtained in the present work, show that the proposed theoretical procedure correctly accounts for the main features of the complete fusion process; the formation of a nuclear quasimolecular system, the maximal energy dissipation and the Coulomb barrier tunneling, which is mostly responsible for the channel and energy dependence of the complete fusion cross-section.

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TABLE

Experimental and theoretical values of the critical angular momenta for different centre-of-mass kinetic energies.

	Centre-of-mass kinetic energy (in MeV)	Present results on the critical angular momenta	Experimental values of the critical angular momenta	Reference
$^{12}C + ^{27}Al$	31	20	19 ± 2	17
	44	24	24 ± 2	
	56	25	28 ± 3	
	59	25	28 ± 3	
	67	25	28 ± 3	
	69	29	29	
	125	25	35 ± 3	
$^{12}C + ^{48}Ti$	65	32	29 ± 3	17
	78	38	32 ± 3	
	144	52	49 ± 4	
$^{12}C + ^{58}Ni$	37	21	24	17
	53	30	27 ± 3	
	67	34	34 ± 3	
	80	35	35 ± 3	
	81	35	38 ± 3	
	149	35	50 ± 4	

TABLE (cont.)

	Centre-of-mass kinetic energy (in MeV)	Present results on the critical angular momenta	Experimental values of the critical angular momenta	Reference
$^{12}C + ^{63}Cu$	37	21	21 ± 3	17
	54	31	29 ± 3	
	66	35	29 ± 3	
	81	35	35 ± 3	
	82	35	39 ± 4	
	106	35	45	
	150	35	50 ± 3	
$^{12}C + ^{108}Ag$	113	40	40 ± 4	18
$^{12}C + ^{158}Gd$	117	47	46 ± 4	
$^{12}C + ^{197}Au$	119	53	53 ± 8	18
$^{11}B + ^{159}Tb$	107	43	40 ± 3	16
$^{16}O + ^{27}Al$	66	35	34 ± 3	21
	101	37	27 ± 3	
$^{16}O + ^{59}Co$	128	43	41 ± 3	22
$^{16}O + ^{63}Cu$	134	45	44 ± 5	18
$^{16}O + ^{107}Ag$	146	57	46 ± 5	18
$^{16}O + ^{154}Sm$	124	53	58 ± 4	19

TABLE (cont.)

	Centre-of-mass kinetic energy in (MeV)	Present results on the critical angular momenta	Experimental values of the critical angular momenta	Reference
$^{16}O + ^{197}Au$	135	70	76 ± 12	18
$^{20}Ne + ^{27}Al$	115	41	35	21
$^{20}Ne + ^{63}Cu$	159	83	43 ± 5	18
$^{20}Ne + ^{107}Ag$	177	60	54 ± 6	18
	146	80	56 ± 6	
$^{20}Ne + ^{209}Bi$	192	77	89 ± 14	18
$^{20}Ne + ^{235}U$	161	71	78 ± 8	19
	192	75	86 ± 6	
	232	75	93 ± 5	
$^{14}N + ^{103}Rh$	71	37	40 ± 5	20
	107	40	52 ± 5	
$^{20}Ne + ^{150}Nd$	127	62	70 ± 6	16
$^{40}Ar + ^{77}Se$	96	48	50 ± 5	20
	132	64	70 ± 8	
	138	70	70 ± 10	
$^{40}Ar + ^{107}Ag$	134	59	57 ± 5	21
	144	64	70 ± 5	
	210	114	113 ± 7	

TABLE (cont.)

	Centre-of-mass kinetic energy in (MeV)	Present results on the critical angular momenta	Experimental values of the critical angular momenta	Reference
$^{40}Ar + ^{121}Sb$	120	28	29 ± 3	23
	135	56	57 ± 5	
	148	73	80 ± 8	
	168	88	91 ± 9	
	195	106	114 ± 12	
	226	123	132 ± 13	
$^{40}Ar + ^{165}Ho$	190	88	86 ± 5	24
	254	120	129 ± 7	
$^{40}Ar + ^{238}U$	214	81	92 ± 6	24
	257	102	127 ± 7	
$^{84}Kr + ^{209}Bi$	357	40–50	35	24
$^{84}Kr + ^{238}U$	370	0–20	18	24

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