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Various processes occurring in strong interactions between heavy ions: Compound nucleus formation, incomplete fusion, and quasifission

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This paper deals with the problem of various deep processes occurring when two complex nuclei enter in collision. It is suggested that very deep inelastic processes may lead to either a compound nucleus or a composite system which shortly decays into two fission fragments (quasifission process). Particularly for heavy projectiles and targets, the predominant Coulomb potential inhibits the compound nucleus formation *for low l waves.* Then a critical angular momentum can be defined as the limit below which both processes (quasifission and compound nucleus formation) occur. For the heaviest nuclei, nearly all l waves below l_{cr} contribute to the quasifission phenomenon.

[NUCLEAR REACTIONS Ar, Cu, Kr ions; discussed σ complete and incomplete fusion.]

It is now well known that in heavy ion induced reactions the compound nucleus formation cross section is only a fraction of the total reaction cross section. That fraction depends on a critical distance of approach between the two complex nuclei.[1] The concept of a critical l value above which partial waves bring orbital angular momenta which is too high to end up in a compound nucleus into the system has been discussed.[2,3] This critical angular momentum is an interesting parameter which depends on the entrance channel and particularly on the bombarding energy.[3,4] When the partners in the collision have comparable masses and when masses are large enough (probably larger than $A=40$), a few experimental data are now available. They can be interpreted[5-7] as if amongst those l waves which are expected to lead to a compound nucleus, the lowest ones do not succeed in the building up of a spherical shape favorable to an equilibrated compound nucleus, although at least a partial fusion between the two complex nuclei has occurred.

The suggestion is made in this short paper that the *deep process cross section* which could be used in order to define the critical value l_{cr} might be divided into a true complete fusion cross section leading to a well defined compound nucleus and a "deformed" fusion cross section where the composite system is made of a still deformed shape, although the charge to mass ratio and excitation energy have been equilibrated. The last intermediate system is mainly responsible for *quasifission* phenomena which were observed in Kr and Cu induced reactions on heavy targets.[8-10] The main argument for including the quasifission reactions in the category of fusion processes is that, in my opinion, they are originated by low l partial waves which are usually responsible for compound nucleus formation in collisions with lighter projectiles and therefore for lower Coulomb potentials.

I. EXPERIMENTAL RESULTS IN FAVOR OF A TEMPORARY FUSION PROCESS FOR LOW l WAVES

There are three types of experimental results showing that the lowest l waves do not necessarily contribute to the formation of a compound nucleus, although a temporary fusion has probably occurred.

A. Krypton induced reactions on Ge

In the krypton induced reactions on germanium isotopes, where masses of projectile and target are comparable, the complete fusion process has been observed[5] and the subsequently formed compound nucleus decayed through evaporation residues. However, the excitation functions for the reactions (Kr, xn) with $x=4, 5, 6$, were not exactly comparable to the excitation functions for the reactions (Ar, xn) on the same erbium compound nucleus. A consistent explanation of the shift towards higher energies observed for the krypton induced reactions was proposed as follows[6]: Low partial waves do not contribute to a compound nucleus. A lower limit $l_{inf}=45$ was derived from the analysis of the shift in the excitation functions, which would correspond to a cross section $\sigma=\pi\lambda\!\!\!^{-2} l_{inf}^2$ of the order of 280 mb for fusion events which do not result in evaporation residues from a compound nucleus. Our prediction is that this cross section should be searched for "quasifission," i.e., for reaction products in the vicinity of mass 80 (quasi-krypton) and of mass 70 (quasi-germanium) with

TABLE I. Fusion cross sections and critical angular momenta $\lambda\sqrt{\pi} = \left(\frac{8.09\times10^{-13}}{\sqrt{A\bar{E}}}\right)$.

System	E_{lab} (MeV)	$\bar{E}_{c.m.}$ (MeV)	$l_{grazing}$	$\sigma_{cn}+\sigma_{qf}$ (mb)	$l_{cr}=\frac{(\sigma_{cn}+\sigma_{qf})^{1/2}}{\lambda\sqrt{\pi}}$
$^{32}S + {}^{27}Al$	110	50	34	914	31
$^{40}Ar + {}^{109}Ag$	288	210	130	1300	115
$^{40}Ar + {}^{118}Sn$	200	150	90	~900	70
$^{84}Kr + {}^{74}Ge$	438	200	110	~500 + (280)	100
$^{40}Ar + {}^{165}Ho$	300	242	160	1430	130
$^{40}Ar + {}^{209}Bi$	250	210	114	1110	110
$^{40}Ar + {}^{238}U$	300	257	156	1220	125
$^{40}Ar + {}^{238}U$	416	365	186	1400	126
$^{63}Cu + {}^{186}W$	395	295	157	200 + 250	97
$^{63}Cu + {}^{197}Au$	365	276	110	<30 + 250	75
$^{84}Kr + {}^{165}Ho$	480	325	~160	230 + 200 [a]	115
$^{84}Kr + {}^{186}W$	480	345	~150	150 + 200 [a]	105

[a] σ_{qf} estimated from measured $d\sigma/d\Omega$ and integration similar to the (Cu + Au) case.

kinetic energies much lower than the expected elastic scattering energies and with a maximum in the angular distribution similar to the results obtained in the case of krypton induced quasifissions.

B. Copper induced reactions

In the copper induced reactions on Au and W, as well as in the krypton induced reactions on Ho and W, two categories of fission events were found.[10]

(a) Symmetric fissions were observed corresponding to deexcitation from a compound nucleus. An integrated cross section of such a process could be deduced from the measure of the differential cross section in the reaction ($^{63}Cu + {}^{186}W$) at $E_{c.m.} = 295$ MeV, as well as in the reaction ($^{84}Kr + {}^{165}Ho$) at $E_{c.m.} = 305$ MeV and ($^{84}Kr + {}^{186}W$) at $E_{c.m.} = 346$ MeV. The value was estimated to be around 200 mb in the three cases. It was found much smaller in the case of ($^{63}Cu + {}^{197}Au$) at $E_{c.m.} = 276$ MeV, i.e., at a lower energy (1.1 time the interaction barrier).

(b) Quasifissions were also observed, as they were defined in a first paper[8] on (Kr + Bi) reactions. For the four systems, the cross sections were measured close to 250 mb. The result obtained on the system ($^{63}Cu + {}^{197}Au$) shows very clearly that the first channels to open when the interaction barrier has been overcome are quasifission processes, and the compound nucleus formation occurs only at higher energies when higher l waves are available. This does not really mean that the higher l waves go into complete fusion, but this is a possibility which has also been con-

TABLE II. Determination of V_{cr} with $r_{cr} = 1.00$ fm from experimental values of $\sigma_{fus} = \sigma_{cn} + \sigma_{qf}$.

System	$\bar{E}$ (MeV)	σ_{fus} (mb)	πR_{cr}^2	$\bar{V}_{cr}/\bar{E}$	$\bar{V}_{cr}$	Z_1Z_2	Ref. exp.
$^{32}S + {}^{27}Al$	50	914	1200	0.24	12	208	15
$^{14}N + {}^{103}Rh$	107	1300	1590	0.18	20	315	17
$^{40}Ar + {}^{77}Se$	132	960	1850	0.48	63	612	17
$^{40}Ar + {}^{109}Ag$	210	1300	2113	0.385	80	846	16
$^{40}Ar + {}^{118}Sn$	150	900	2268	0.603	90	918	18
$^{84}Kr + {}^{72}Ge$	200	780	2313	0.663	132	1152	5
$^{40}Ar + {}^{165}Ho$	241	1410	2485	0.570	104	1206	20
$^{40}Ar + {}^{209}Bi$	210	1110	2880	0.015	130	1494	20
$^{40}Ar + {}^{238}U$	257	1220	2902	0.580	150	1656	20
$^{63}Cu + {}^{186}W$	285	450	2940	0.850	250	2146	19
$^{63}Cu + {}^{197}Au$	276	250	3020	0.910	251	2295	19
$^{84}Kr + {}^{165}Ho$	305	400	3057	0.870	265	2412	20
$^{84}Kr + {}^{186}W$	345	350	3197	0.890	307	2664	20

sidered on theoretical grounds by Tsang,[12] and by Bondorf, Sobel, and Sperber. More conclusive evidence would be obtained indeed if quasifission has been observed in the Kr-Ge system, as suggested in Sec. IA.

C. Krypton induced reactions on ^{209}Bi and ^{238}U

In krypton induced reactions on ^{209}Bi and ^{238}U, a very large fraction of the total cross section corresponds to quasifission, at least for the energy range which has been explored at the present time[9,11] (between E_B and 1.8 E_B, where E_B is the interaction barrier). Some other inelastic scattering processes, like the transfer reaction of several nucleons, and also fission reactions following quasielastic transfer, have also a substantial cross section and correspond to angular momenta approaching the grazing wave value. Then, quasifission processes should be attributed to partial waves with l values much lower than l grazing. Since the cross section is large and the angular distribution is peaked around a particular angle, there is a strong focusing effect indicating that many l waves correspond to a narrow width of angular distribution in the exit channels. Therefore the smallest impact parameters should induce a rather long orbiting trajectory and the large impact parameters correspond to short orbiting.

II. CRITICAL DISTANCE FOR FUSION BETWEEN TWO HEAVY IONS

Let us now make the hypothesis that the sum of the quasifission cross section σ_{qf} and the compound nucleus cross section σ_{cn} are used in order to determine a limiting angular momentum. Let us call it "deep" or "fusion" cross section. Then we can write:

$$\sigma_{deep} = \pi \lambda\!\!\!^{-2}(R_{cr}+1)^2 = \sigma_{cn} + \sigma_{qf} \qquad (1)$$

and a critical distance might be deduced[7-13] in the approximative relationship:

$$\sigma_{deep} = \pi R_{cr}^2 \left(1 - \frac{V_{cr}}{E}\right), \qquad (2)$$

where V_{cr} is the potential at the critical distance R_{cr} for a s wave ($V_{nuclear} + V_{Coulomb}$).

Using the new definition of deep process or fusion cross section, the results obtained on l_{cr} with krypton ions are now consistent with the results obtained with argon or other projectiles. In Table I, such data are presented and $l_{cr}\hbar$ varies normally as a function of the energy, as one should expect, and there are no abnormal values for krypton ions. In Table II, the data are presented in terms of expression (2), where $R_{cr} = r_{cr}(A_1^{1/3} + A_2^{1/3})$ has been calculated with the assumption that r_{cr} is a constant parameter equal to 1.00 fm, as it was sug-

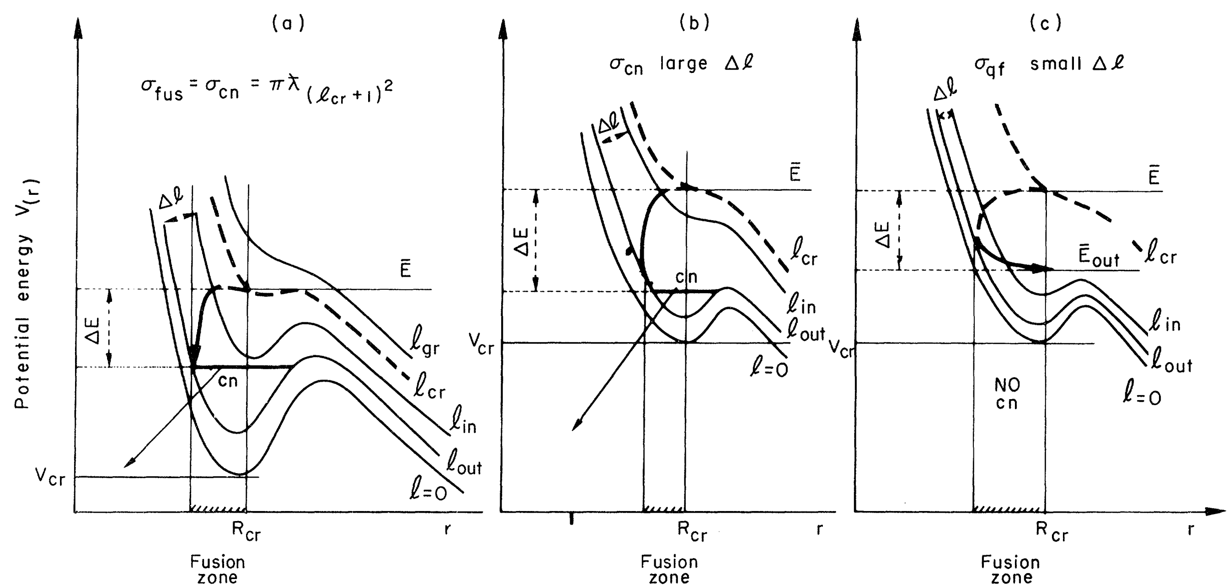

FIG. 1. Schematic diagram representing potential energy curves for the interaction between two heavy ions at different orbital angular momenta. The grazing and the critical angular momenta are indicated, respectively, by l_{gr} and l_{cr}. (a) Small Coulomb potentials. A compound nucleus is formed. ΔE and Δl are large enough. (b) High Coulomb potentials. Large Δl and ΔE. A barrier appears on the l_{out} wave. A compound nucleus is formed. (c) High Coulomb potentials. Small Δl. There is no barrier for the outgoing wave: Quasifission.

gested in a recent analysis of the distance of approach concept.[1-7] Then, from the experimental determination of σ_{deep} and from the value $R_{cr} = r_{cr}(A_1^{1/3} + A_2^{1/3})$, the critical potential V_{cr} was deduced. The resulting data are very close to the potentials calculated by the Bruckner's matter density potential using the sudden approximation.[1] It is obvious that the calculated values of V_{cr} should not be considered as very precise data, since there are large experimental uncertainties on σ_{fus} and furthermore the choice of $r_{cr} = 1.00$ fm is perhaps not the best.[14] However, the systematics of V_{cr} values shows a tendency for V_{cr} to increase at the same rate as the product Z_1Z_2 as expected, particularly when the Coulomb potential is the dominant factor.

III. CONCLUSIONS

Let us summarize the main points with the help of the usual diagram representing the potential energy as a function of the distance between two approaching centers (Fig. 1). We distinguish three cases:

(a) With light projectiles, the Coulomb contribution is not very large and the potential curve exhibits a deep well, even for l waves close to the grazing wave. Then, as long as the incident energy is high enough to overcome the barrier, the transition between a virtual level and a bound state in the potential pocket occurs. A two body composite system is made which develops shortly into a single compound nucleus. The critical angular momentum $l_{cr}\hbar$ appears when the turning point corresponding to the intersect of the potential curve for that particular l and the kinetic energy line of the incoming nucleus occurs at a distance equal to R_{cr}. In that case, as illustrated by Fig. 1(a), $\sigma_{deep} = \sigma_{cn}$.

(b) With heavy projectiles and medium mass targets, the Coulomb potential is predominant and the pocket in the potential curve is shallow, but still exists for $l = 0$ and for a number of low l values. Let us consider a bombarding energy higher than the barrier of interaction. For large l waves, the turning points are found at distances larger than R_{cr} and all the partial waves between l_{cr} and the grazing trajectory l value l_{gr} cannot contribute to a fusion process because of the large centrifugal potential exerted on the peripheral region of both nuclei.

For $l < l_{cr}$, but still with rather large l values, the dissipative process occurs from virtual levels to bound levels down in the pocket through large Δl changes corresponding to tangential friction effects. Then a number of l waves contribute to the formation of a system which has a life-time long enough for many level crossings and which ends up into a compound nucleus [Fig. 1(b)]. For small $l\hbar$, Δl cannot be large even if $l_{out} = 0$. Therefore in the range of distances smaller than R_{cr} where deep processes occur, the energy loss is not large enough and the two partners escape after a short time, since there is no barrier for the energy level above the transitory potential well [Fig. 1(c)], and quasifission occurs.

(c) With heavy projectiles and very heavy target nuclei, all pockets have vanished, even for s waves, and the dissipation of energy at distances shorter than R_{cr} cannot lead to bound states of an intermediate molecular type system. Therefore, even when there is a sticking process which lasts some time, the final result is a quasifission type.

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