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THE CROSS SECTIONS FOR DIFFERENT CHANNELS
IN HEAVY ION NUCLEAR REACTIONS

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Résumé. — La valeur critique \( l_c \) du moment angulaire au-delà duquel un noyau composé de fusion ne peut plus être formé, a été estimée. Les résultats ont été obtenus selon une nouvelle méthode qui consiste à mesurer la section efficace de tous les processus ne faisant pas intervenir le noyau composé (diffusion inélastique, réactions de transfert, émission de particules alpha vers l'avant). L'étude a été effectuée au moyen d'ions \(^{12}\text{C}\) de 86 MeV et d'ions \(^{14}\text{N}\) de 78 et 113 MeV bombardant des cibles d'argent. On a trouvé \( l_c \) compris entre 38 et 45 \( \hbar \) quelque soit l'ion incident et l'énergie. On discute ensuite brièvement pour quelle région de moments angulaires les réactions de transfert ont lieu. On montre que les cas de transferts quasi élastiques sont possibles seulement pour des \( l \) élevés, en valeur moyenne \( l_T \) dépendant de l'énergie incidente. \( l_T \) devient très supérieur à \( l_c \) lorsque l'énergie croît et un mécanisme d'échange de nucléons très inélastique intervient dans la région comprise entre \( l_c \) et \( l_T \). Un modèle est proposé qui consiste en une fusion de durée très brève des deux noyaux sous la forme d'une configuration très déformée.

Abstract. — Estimates have been made for the critical value \( l_c \) of the orbital angular momentum above which a complete fusion nucleus cannot be formed. The results have been obtained by measurements of cross sections for noncompound inelastic processes (inelastic scattering, transfer reactions, \( \alpha \) particle emission) when Ag targets were bombarded by 86 MeV \(^{12}\text{C}\) ions and by 78 and 113 MeV \(^{14}\text{N}\) ions. The average value of \( l_c \) was found between 38 and 45 \( \hbar \). A short discussion is given on the range of angular momenta at which transfer reactions occur. It is shown that quasi elastic single and multi-nucleon transfer reactions are possible only for large values of \( l \) called \( l_T \). When the bombarding energy is high enough, theses values \( l_T \) are larger than \( l_c \) and there is a region of \( l \) between \( l_c \) and \( l_T \) where a very inelastic mechanism takes place. A model called « fusion prompt scission » process is proposed. It is suggested that a deformed shape for the two fissioning nuclei is temporarily formed and breaks off very shortly after.

It is well known that when bombarding medium targets by heavy projectiles like C, N, O, many inelastics processes may occur. Inelastic scattering and compound nucleus formation are the two open channels. Nevertheless, when the bombarding energy is far above the Coulomb barrier, other channels, like single and multinucleon transfer reactions, also show a large width.

Attempts have been made to measure \([1, 2]\) or to calculate the total reaction cross section, \( \sigma_R \), as described by Thomas \([3]\). There is e. g. a fairly good agreement between the experimental measurements and the results of diffuse-well optical-model calculations for 114 MeV \(^{12}\text{C}\) ions and 150 MeV \(^{18}\text{O}\) ions on various targets \([1]\).

Attempts to ascertain the compound-nucleus formation probability, have been based on several experimental data, as the angular distribution of charged particles \([4]\), the angular correlation \([5]\) between fission fragments produced in the irradiation of uranium nuclei with \(^{16}\text{O}\), and measurements of the momentum deposited in the product nuclei. The ratio of the cross section for complete fusion \( \sigma_{\text{CF}} \) to the calculated reaction cross section has been estimated for heavy targets (Ba to U) as 0.7 ± 0.1 for \(^{12}\text{C}\) projectiles and 0.6 ± 0.1 for \(^{22}\text{Ne}\) over a wide range of energies \([5]\). It depends very much on the energy for light targets (Al 1) and decreases from values close to 1 at 80 MeV down to 0.2 for 200 MeV \([6]\). Recently, Natowitz \([7]\) has given a large set of ratios for intermediate energies.

We have investigated the reactions induced in silver targets by 86 MeV \(^{12}\text{C}\) ions and 78 and 113 MeV \(^{14}\text{N}\) ions and we have measured all the non-compound nucleus cross sections, \( \sigma_{\text{ICN}} \). It was therefore interesting to see if one arrives at the same conclusions on the ratio of complete fusion to total cross section as when this ratio was obtained by the compound nucleus cross section measurement.

In the sharp cut-off approximation, a critical value of the orbital angular momentum \( l_c \) has been defined as the value above which a complete fusion cannot occur. A simple approximation was used by Kalinkin \([8]\):

\[
\sigma_{\text{CF}} = \pi \hbar^2 \frac{l_c^2}{(2 \mu \epsilon)^2},
\]

where \( \epsilon \) is the bombarding energy in the center of...
By measuring $\sigma_{\text{ICN}}$, the cross section of all the processes which do not proceed through complete fusion, data were obtained corresponding to $l$ values larger than $l_c$, lying between $l$ and $l_{\text{max}}$ where $l_{\text{max}}$ may be given, in the sharp cut-off approximation by $\sigma_R = \pi \hbar^2 l_{\text{max}}^2 / 2 \mu \bar{\sigma}_R$, being the total reaction cross section. All the charged particles produced at different angles (from helium up to fluorine) were detected by $\Delta E/dX$ and $E$ measurements [9]. By integrating the differential cross sections, the total cross section was obtained for each particular product. For $^4\text{He}$ there is a well known contribution of the decay from the compound nucleus, which has been studied in detail previously [4] and we have subtracted that part in order to obtain only the cross section for $\alpha$-particles emitted in the forward direction through a non-compound mechanism. There is also an emission in the forward direction of protons and deuterons, but the contribution is small and most of these particles may belong to events already counted in the form of their heavy partners detected after a stripping process.

Because of the thickness of the $\Delta E$ counter, some energy spectra were cut down on the low-energy side and a few events might have been lost mainly for the heaviest products like $^{16}\text{O}$ or $^{18}\text{F}$, but their contribution is small. Also there was some defect at small angles since we have not been able to make measurements at smaller angles than $6^\circ$ for $113$ MeV $^{14}\text{N}$, $10^\circ$ for $78$ MeV $^{14}\text{N}$ and $8^\circ$ for $^{12}\text{C}$. As the differential cross section seems to be very large at these small angles, the extrapolation to zero degree is difficult and the integrated values should be considered as lower limits. The last criticism to the results is relative to the inelastic scattering measurement at small angles where the elastic scattering contribution was very high and produced a secondary scattering effect on the collimator in front of the detectors. A correction had to be made for it. In order to calculate $l_c$ $\sigma_R$ was taken from Kalinkin [11] and Thomas [12]. Both calculations give very similar results although they differ in principle, and an average value has been used.

In table I, cross sections are given for inelastic scattering, quasi-elastic transfer reactions, very inelastic exchanges of nucleons, and $\alpha$-particle emission in the forward direction. Also are given the total reaction cross section after Thomas and Kalinkin, the total non-compound cross section $\sigma_{\text{NC}}$ and the derived critical angular momentum $l_c$. The values are similar to the results of Natowitz [7], although our method is very different, and $l_c$ between 38 and 45 can be taken as a reasonable value for energies largely above the Coulomb barrier. In the case of $^{12}\text{C}$ projectiles, the cross section for $\alpha$-particle emission is very high, because there is a particular situation. If $^{12}\text{C}$ is split into three $\alpha$-particles, the cross section for the process yielding $\alpha$-particles should be $1/3$ of the $\alpha$-particle cross section. If $^8\text{Be}$ is the result of stripping of the projectile, and subsequently decays into two $\alpha$-particles, then the cross section should be $1/2$ of the $\alpha$-particle cross section. There might be at last a process similar to what is observed with $^{14}\text{N}$, and each $\alpha$-particle might correspond to a single event. In order to estimate that part of the non-fusion cross section we have assumed that as an average the most frequent case is the second one and therefore the assumed cross section was $1/2$ of the $\alpha$-particle cross section.

A concluding remark may be made on the range of angular momenta at which transfer reactions occur. The quasi-elastic treatment [9] of single and multinucleon transfer reactions shows that only the very edge of both the projectile and the target participate to the nuclear interaction. From angular distributions peaking at a preferential angle it can be deduced that the distance between the centres of the nuclei corresponds to a value of $r_0$ of the order of $1.5$ fm [9]. If the measured cross section is expressed in terms of:

$$\pi \hbar^2 \sum_{l=\text{min}}^{l_{\text{max}}} (2l + 1) T_l$$

where $l_{\text{max}}$ is calculated with $r_0 = 1.5$ fm, the number of partial waves involved depends on $T_l$. In the sharp cut-off approximation, only two or three values of $l$ are sufficient to account for the experimental value. It is certainly not correct to use $T_l = 1$ for values as large as 50 or 60 $h$. Nevertheless one might define an average $l$ corresponding to the elastic transfer process, $< l_T >$. It is of the order of 38, i.e. very close to $l_c$ for $78$ MeV $^{14}\text{N}$, of 55 for $113$ MeV $^{14}\text{N}$ and of 48 for $86$ MeV $^{12}\text{C}$.

For $l$ values between $l_c$ and $< l_T >$, collisions occur at distances where the density of nuclear matter is not yet the density of the core, or in other words, for $r_0$
values between 1.1 and 1.4 fm. It is precisely in this region that very inelastic processes [13] might occur which do not end in a classical excited compound nucleus but which are followed by the reemission in the very forward direction of a complex particle similar to the projectile, but considerably less energetic [10, 13].

It is believed that during a very small time \(2 \times 10^{-22}\) s, a very deformed fusioning nucleus is formed, somewhat similar to a fissioning nucleus at the saddle point. Then, the neck between the two humps is broken again by centrifugal and Coulomb effects, and a scission occurs. The angular momentum effect integrated over all directions located in the plane perpendicular to the beam leads to a forward peaked emission. The duration of existence for the fusion state is too short for a complete rotation. Such a process, that we call «fusion-prompt scission», (FPS), occurring for \(l\) values between 40 and 50 could explain the cross sections for the phenomena observed in the forward direction of very inelastic transfer reactions, inelastic scattering and \(\alpha\)-particle emission.

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