PRE-EQUILIBRIUM EMISSION AND INCOMPLETE FUSION PROCESSES IN THE INTERACTION OF ^{12}C AND ^{16}O WITH HEAVY NUCLEI BELOW 10 MeV/NUCLEON*

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Even at low energies the study of the reactions occurring in the interaction of two heavy ions reveals a large variety of contributing mechanisms. The complete fusion of the two ions is usually the dominant process, but even at energies only slightly greater than the Coulomb barrier incomplete fusion and deep inelastic processes are far from being negligible. Contrary to a widespread opinion the complete fusion itself may not produce immediately an equilibrated compound nucleus. On the way to the equilibrium the emission of pre-equilibrium ejectiles from the intermediate composite nucleus created in the fusion may be measurable. From its study one may deduce important information on both the two ion mean field interaction and the intranucleon interaction cascade through which the composite nucleus equilibrates. Meaningful information on these phenomena has been obtained by activation studies by measuring the excitation functions for residue formation, residue forward range recoil distributions and mean forward ranges, and residue angular distributions. As an example of such studies I will discuss the results of a study of the interaction of ^{12}C and ^{16}O with heavy nuclei showing how the observations mentioned above may lead to a quite accurate determination of the cross-sections of the contributing mechanisms, and provide information on the fragmentation of the projectile and the emission of fast ejectiles during the composite nucleus thermalization.

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1. Introduction

The study of heavy ion interactions at low relative energies has greatly contributed to our knowledge of nuclear dynamics. Just to mention a few arguments, these studies clarified the role of angular momentum in nuclear interactions and showed that high relative angular momenta lead to a dramatic increase of γ ray emission and fissility and to dynamical instability toward fission [1–5] [1]. They also lead to the recognition of the existence of the *yrast* states and of a large variety of phenomena which range from complete and incomplete fusion processes and deep inelastic collisions to distant interactions [6–11]. Also the existence of angular momentum windows for the occurrence of these processes was clearly recognized [12–17].

The interaction of low energy heavy ions has also greatly increased our knowledge of nuclear structure trough the investigation, by means of the in-beam γ-ray spectroscopy, of giant resonances [18] and nuclear deformation and super-deformation [19–21].

However, in the case of nuclear dynamics, these studies often did not investigate systematically and in detail the phenomena which occur. For example, the fusion cross-section is known with good accuracy, for a large variety of projectile — target combinations [9], but much less is known about the value and the energy dependence of the cross-sections of the reactions which originate from the two ion fusion, even if one knows from light particle reactions that this information is of paramount importance for the study of the thermalization of the compound nucleus (the process which leads to the statistical equilibrium) and of the emission of pre-equilibrium particles. Also the information on non-fusion reactions is often not very systematic.

In this paper I will discuss the results of a systematic study of the reactions induced by low energy ($E_{\rm inc} \leq 10$ MeV/nucleon) ^{12}C and ^{16}O ions on heavy nuclei which was made with the scope of measuring and analysing data related to a large and representative number of reactions in order to investigate if the theory may quantitatively reproduce with a reasonable accuracy these data. These experiments were made using the nuclear activation technique which provides in the simplest and fastest way the comprehensive and at the same time detailed information we are looking for. In the next Section the experiments are briefly described and the results obtained summarized showing the new information which they provided. In the following Section the results of the theoretical analysis are discussed. Last Section is devoted to the conclusions.

[1] No attempt is given to provide an exhaustive reference to the large number of papers devoted to this subject. I quote a few articles which I found useful for understanding the little which I know, but which certainly do not constitute a balanced and fair sample of the work which has been done.

2. Experimental results

In many reactions a single heavy product is produced together with many lighter particles and γ-rays and the measurement of the cross section for its production, of its velocity and of its angular distributions greatly helps one to understand the mechanism(s) by which it was produced. In the case of low energy heavy ion reactions producing heavy residues with very low energy ($E/A \leq 0.1$ MeV/nucleon) time of flight measurements and the use of ΔE·E telescopes do not allow one to identify the residues which are produced. These may be identified by detecting in in-beam experiments the characteristic γ-rays their emit in their prompt decay to the g.s. or by detecting off-beam, in case of radioactive residues, the γ-rays emitted by their decay products, whose intensity decreases exponentially with time with the radioactive residue mean-life [22,23]. While the first technique has been widely used in nuclear structure studies, most of the reaction mechanism studies have used the second technique.

The residue's angle and energy integrated production cross-section is obtained by measuring the activity induced in a target and a catcher, downstream the target, of thickness larger than the residue maximum range. The residue velocity distribution is deduced from their range distribution which is obtained by measuring the activity induced in a set of catchers much thinner than the residue maximum range [24–27]. The residue angular distribution is measured using catchers of suitable shape [28,29].

The enormous improvement in energy resolution and efficiency of γ detectors eliminates, in most cases, the need of the chemical separation of the reaction products before measuring their activity. Present knowledge of the decay schemes and γ-ray abundances [30] allows one to obtain accurate values of the cross-sections from the measured activities. However, one can usually measure the activity of only a fraction of the residues which are produced, and without fast chemical separation many of the measured cross-sections are cumulative. This means that they are a weighted sum of the independent production cross-section of the residue considered and the independent production cross-sections of its precursors [31]. This fact, which, as shown later, may be even useful for certain purposes must be carefully taken into account in the analysis of the data.

Most of the experiments which I discuss in this paper were made at the Laboratorio Nazionale del Sud in Catania. Only part of the results we have obtained has been published [26,31–35] and many of the results I will discuss have not been previously shown. In these experiments all the methods briefly mentioned above have been used. At first, several tens excitation functions for residue formation in the interaction of ^{12}C with ^{181}Ta and ^{197}Au and ^{16}O with ^{165}Ho and ^{181}Ta have been measured from Coulomb barrier up to about

8.5 MeV/nucleon. Three groups of excitation functions were identified in each case. The first, which includes those for the formation of residues with charge equal to $Z_{\rm CN} = Z_{\rm P} + Z_{\rm T}$ and $Z_{\rm CN} - 1$ ($Z_{\rm P}$ and $Z_{\rm T}$ are, respectively, the projectile and the target nucleus charge), display, as a function of the incident particle energy, an abrupt rise after threshold, a maximum 10 to 20 MeV wide and afterwards a fast decrease (with slope sensibly smaller than that of the initial rise). This shape is characteristic of the decay of nuclei having initially a well defined energy, as occurring in complete fusion processes. The ascent of the excitation function starts as soon as the energy is sufficient for the emission of the particles corresponding to the considered reaction, and the fall as soon as the energy is sufficient for emitting one more particle.

The excitation functions for production of residues with $Z \leq Z_{\rm CN} - 2$ always increase in the considered energy interval. Those of residues with $Z = Z_{\rm CN} - 2$ or $Z = Z_{\rm CN} - 3$ quite fast, those of lower charge residues more gently. The main reason for this behaviour is the contribution to the residue's production of reaction mechanisms which produce in an initial stage excited nuclei with a broad excitation energy distribution, so that their further decay to a particular residue cannot display a sudden decrease with increasing their average excitation energy even in the presence of a dominant evaporation mechanism. The hypothesis that, in the case of ^{12}C and ^{16}O induced reactions, this reaction mechanism could be an incomplete fusion of α-type projectile fragments (α's, ^{8}Be and ^{12}C) [15–17,24–26,28], was confirmed by the measurement of residue forward recoil range distributions (FRRD) using thin targets and stacks of aluminium catchers of thickness as low as 20 μg/cm^2. As explained in the next Section, these experiments showed that the average forward range of $Z \leq Z_{\rm CN} - 2$ residues decreases with decreasing their charge in quantitative agreement with the expected incomplete fusion processes.

In the case of the interaction of ^{16}O with ^{181}Ta, the residue angular distributions were also measured at many incident energies using thin ^{181}Ta targets (50-60 μg/cm^2 thick) and a set of thick catchers made of a central circular catcher and five adjacent annular catchers with increasing outer diameters. With this set of catchers the activity of residues recoiling approximately in the following angular intervals: 0°–12°, 12°–20°, 20°–27°, 27°–34°, 34°–40° and 40°–50° was measured. This experiment showed that the average recoil angle of the residues increases with decreasing the residue charge still in quantitative agreement with the hypothesis that the low charge residues are produced in the incomplete fusion of α type fragments of the projectile. These results are exemplified in Figs 1 and 2 which refer to the interaction of, respectively, ^{12}C and ^{16}O with ^{181}Ta.

Fig. 1 shows the excitation functions and the forward residue recoil range

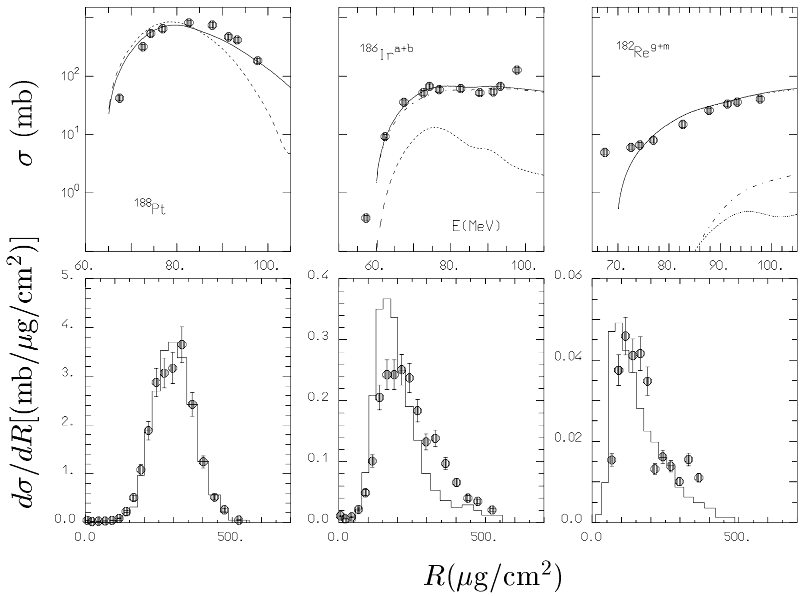

Fig. 1. Excitation functions (EF) and forward recoil range distributions (FRRD) (measured at an incident energy of 77 MeV) of residues produced in the interaction of ^{12}C with ^{181}Ta. In the case of the ^{188}Pt EF, the full line gives the value predicted considering pre-equilibrium emissions, the dashed line considering a pure evaporative decay. In case of the ^{186}Ir^{a+b} EF the dashed line is the contribution of complete fusion (including pre-equilibrium emission), the dot and dash line the contribution of incomplete fusion of ^{8}Be, the full line the sum of the two contributions. In the case of the ^{182}Re^{g+m} EF the dashed and dash and dot lines give, respectively, the contribution of complete fusion and ^{8}Be incomplete fusion. The almost superimposed dotted and full lines give, respectively, the contribution of α incomplete fusion and the sum of all the contributing mechanisms. In the case of FRRD, the black dots and the histograms give, respectively, the measured and calculated values.

distributions, measured at an incident energy of 77 MeV, of (a) a complete fusion residue (^{188}Pt), (b) a residue (^{186}Ir^{a+b}) which is mainly produced in the incomplete fusion of a ^{8}Be fragment and (c) a residue (^{182}Re^{g+m}) which is mainly produced in the incomplete fusion of an α-particle. At 77 MeV, the average forward range of ^{188}Pt is about 300 μg/cm^2 in aluminium. That of ^{186}Ir^{a+b} which, at this energy, is expected to be mainly produced in the incomplete fusion of a ^{8}Be is about 200 μg/cm^2. Finally, that of ^{182}Re^{g+m} which is mainly produced in the incomplete fusion of one α particle is about 150 μg/cm^2.

Fig. 2 shows in the upper part the excitation functions for production of

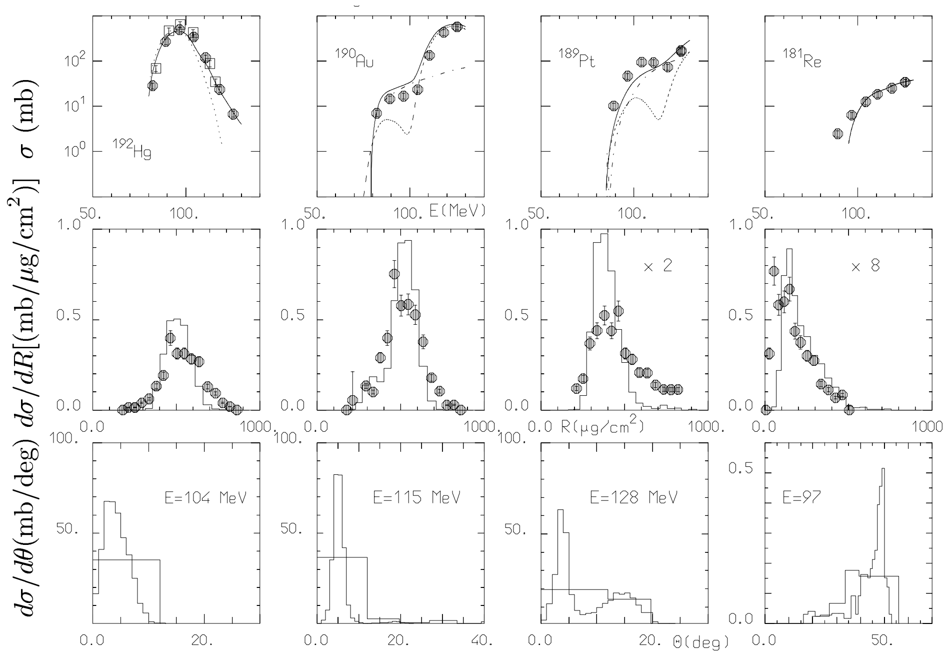

Fig. 2. Excitation functions (EF), forward recoil range distributions (FRRD) (measured at an incident energy of 112 MeV) and angular distributions (AD) (measured at the indicated incident energies) of residues produced in the interaction of ^{16}O with ^{181}Ta. In the case of the ^{192}Hg EF, the black dots are the values measured with a thick target and a thick catcher in contact (thus detecting all residues recoiling in the forward direction), the open squares the values measured using a catcher activated only by residues recoiling within a 12° cone. The full and dashed lines are the calculated values with and without pre-equilibrium emission. In the case of the ^{190}Au and ^{189}Pt EF, the lines give the contribution of complete fusion (dashed line), of incomplete ^{12}C fusion (dash and dot line) and the sum of the two contributions (full line). In case of ^{181}Re, the full line gives the contribution of α particle incomplete fusion (the other mechanisms give a negligible contribution). In the case of FRRD, the black points and the histograms give, respectively, the experimental and the calculated values. In the case of AD, the large bin histograms give the experimental values, the small bin histograms the calculated values.

(a) ^{192}Hg in a complete fusion reaction, (b) ^{190}Au and ^{189}Pt which may be produced both in a complete fusion and in a partial fusion of a ^{12}C fragment from ^{16}O break-up, and (c) ^{181}Re which is produced only in the incomplete fusion of one α particle from ^{16}O break-up. In fact such a low charge residue cannot be produced in a significant amount by charged particle decay of higher charge excited nuclei produced in the primary projectile-target interaction. In the considered reaction the observed Re isotopes are predominantly produced through neutron decay of higher mass Re isotopes produced in the primary interaction. The middle part of the figure shows the residue FRRD measured at an incident energy of 112 MeV. The ^{192}Hg distribution has a maximum at a range (in aluminium) of about 500 μg/cm^2, as expected for a complete fusion process where the projectile linear momentum is completely transferred to the compound nucleus. At 112 MeV, as it is shown in the figure, the theory suggest that ^{190}Au is predominantly produced in a complete fusion reaction while ^{189}Pt is predominantly produced in an incomplete ^{12}C fusion. In fact their FRRD peak, respectively, at 500 and about 400 μg/cm^2. The FRRD of ^{181}Re peaks at about 100 μg/cm^2 in agreement with the expected low linear momentum transferred in an incomplete α particle fusion. The lowest part of the figure shows for each considered residue

$$\frac{d\sigma}{d\Theta} = \frac{1}{d\Theta}\int \frac{d\sigma}{d\Omega}F(\Theta)2\pi\sin\Theta d\Theta \tag{1}$$

as a function of Θ at the ^{16}O incident energies indicated ($F(\Theta)$ is the catcher response function). ^{192}Hg and ^{190}Au have an average emission angle of 5°. The angular distribution of ^{189}Pt, which at 128 MeV is expected to be produced with comparable cross-sections both in the complete fusion reaction and in the incomplete fusion of a ^{12}C, splits into two contributions emitted at average angles of, respectively, ≈5 and 15°. The angular distribution of ^{181}Re, which at 97 MeV is produced only through the incomplete fusion of one α particle, peaks at the substantially larger angle of 40°–50°.

This discussion suggests that in a carefully planned experiment one may quite easily identify the residues that are produced in, respectively, complete and incomplete fusion reactions (or transfer processes). In all the experiments which we made we have been able to deduce the cross-section for fusion without fission $\sigma_{\rm CF}(1-P_{\rm F})$ ($P_{\rm F}$ is the fission probability) by summing the measured cross-sections for the production of the complete fusion residues. This was possible, even if only a fraction of the residues which were produced has been observed, by exploiting the fact that several residues were produced cumulatively and thus their cross-section gave us the rate of independent production of all their isobars also if most of them were not directly observed. This procedure is discussed in [31]. The cross-section $\sigma_{\rm CF}(1-P_{\rm F})$ is given for the four considered reactions in Fig. 3 which shows the extreme detail of the information obtained with these experiments in comparison with that obtained with other experimental methods. As shown in Fig. 4, the values we find for the fusion cross-section by summing to $\sigma_{\rm CF}(1-P_{\rm F})$ the fission cross-section [36–39] are in excellent agreement with those predicted by the systematics based essentially on the results of counter experiments [9].

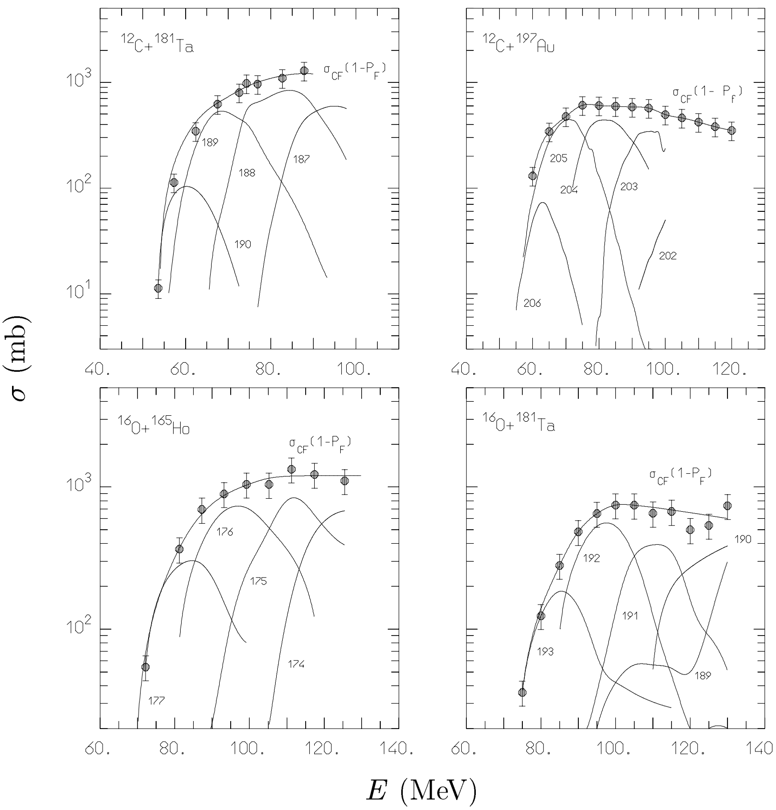

Fig. 3. The black dots give the experimental values of $\sigma_{\mathrm{CF}}(1-P_{\mathrm{F}})$, the cross section for complete fusion without fission, for the heavy ion interactions indicated. The full line passing through these points averages over local fluctuations due to the experimental uncertainty. The other lines give the contribution of the cross sections for production of the isobars with the mass number shown.

The cross-section for several incomplete fusion reactions could be also measured quite accurately in all the considered heavy ion interactions and from these values it was possible to deduce the total cross-section of incomplete fusion processes. Their values are compared in Fig. 5, in the case of the interaction of ^{12}C and ^{16}O with ^{181}Ta with those predicted by the systematics [9]. The activation experiments allowed us to obtain also the contribution of the different incomplete fusion reactions which we suggest to be the incomplete fusion of a ^{8}Be and one α particle in the case of the ^{12}C interaction and the incomplete fusion of ^{12}C, ^{8}Be, ^{6}Li and α fragments in the case of the ^{12}O interaction.

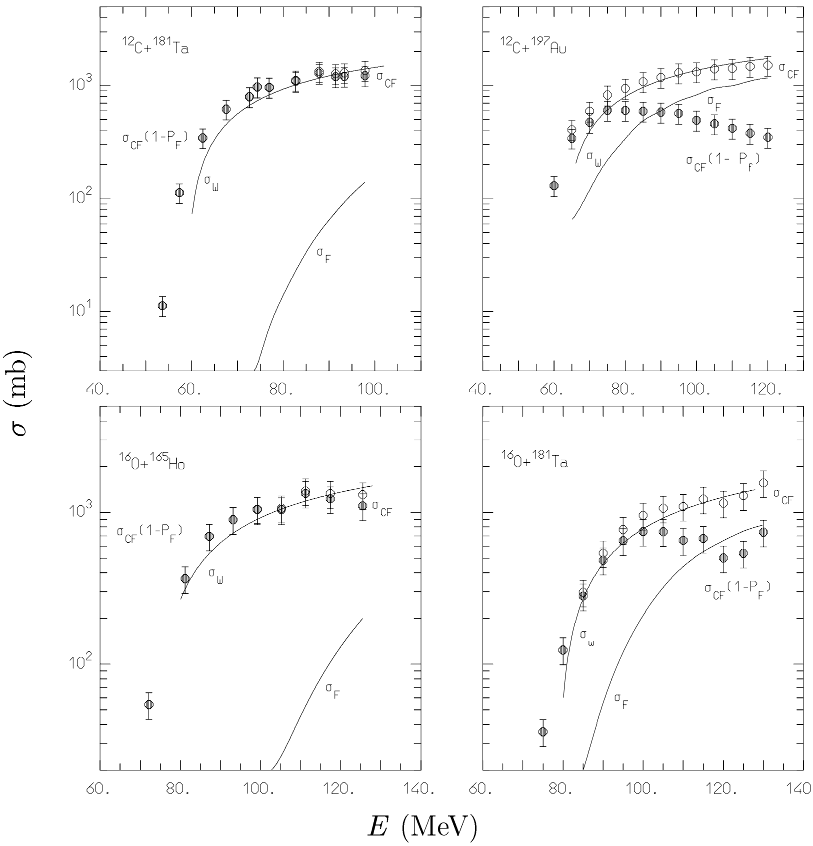

Fig. 4. The black points give $\sigma_{\rm CF}(1-P_{\rm F})$, the open dots the total complete fusion $\sigma_{\rm CF}$ obtained by adding to the previous cross-section the fission cross section $\sigma_{\rm F}$. The line with the label $\sigma_{\rm W}$ gives the value of the complete fusion cross section predicted by Wilcke *et al.* [9].

3. Theory

3.1. Complete fusion processes

As shown in previous Section, the excitation functions of complete fusion reactions have approximately an asymmetric bell shape. In one of the first studies of these reactions, Alexander and Simonoff, measuring the excitation functions of several (^{12}C,xn) and (^{16}O,xn) reactions on rare earth nuclei [4,5] at incident energies below 10 MeV/nucleon, noted that these excitation functions have widths considerably larger than those of the excitation functions of reactions induced by light particles creating composite

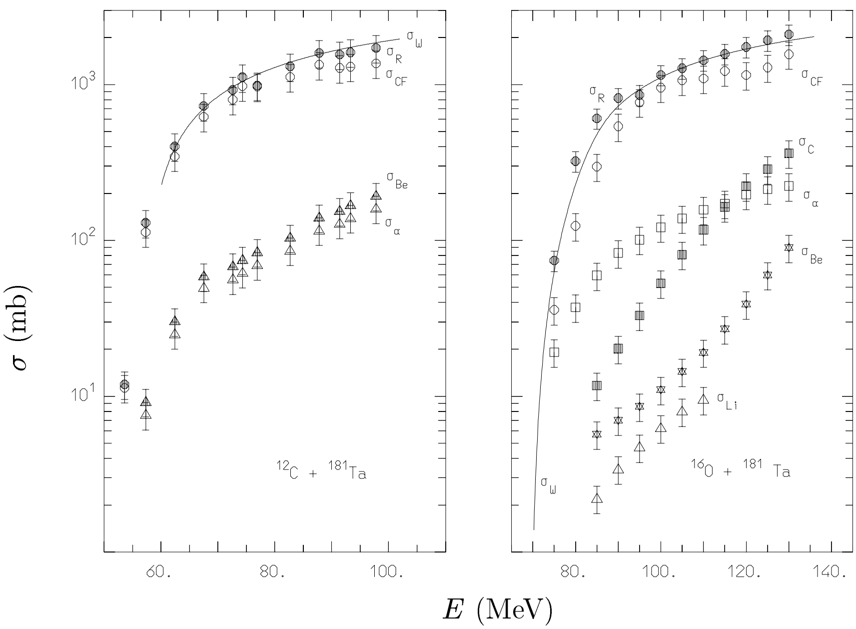

Fig. 5. Left part: Complete fusion cross section (open dots), and ^{8}Be (black triangles) and α (open triangles) incomplete fusion cross sections for the interaction of ^{12}C with ^{181}Ta. The black dots give the total reaction cross section (σ_R) and the line the values predicted by Wilcke *et al.* ($\sigma_{\rm W}$) [9]. Right part: Complete fusion cross section (open dots) and ^{12}C (black squares), ^{8}Be (superimposed up and down triangles), ^{6}Li (open triangles) and α (open squares) incomplete fusion cross sections for the interaction of ^{16}O with ^{181}Ta. The black dots give the total reaction cross section and the line the values predicted for this quantity by Wilcke *et al.* [9].

nuclei of comparable mass, charge and excitation energy. Assuming that these reactions proceed through the formation of a compound nucleus in a state of statistical equilibrium this broadening may be a consequence of the high angular momentum of the nuclei which are created in the two heavy ion interaction. As shown by Mollenauer [1] and Grover [6] this causes a considerable increase of γ-ray emission at the end of the evaporation cascade where particle emission is suppressed by the lack of high angular momentum states of low excitation energy. This led to the discovery of the existence of the yrast states, the states of minimum energy for a given angular momentum which revealed itself so fruitful both in nuclear dynamics and nuclear structure studies. In fact it has been assumed for a long time that angular momentum effects alone might explain the observed features of heavy ion complete fusion reactions at incident energies below 10 MeV/nucleon. However, the accumulation of the data showed that to reproduce accurately the observed broadening of the excitation functions one has to assume that the γ emission is enhanced much more than expected considering the constraints to particle decay due to the presence of the yrast states. The situation is best summarized by the results of a study made by Gilat, Jones and Alexander [40] who found that, in order to approximately reproduce the observed broadening of the excitation functions measured by Alexander ad Simonoff [4,5] in the interaction of 70–155 MeV ^{16}O ions with ^{140}Ce, the γ decay rates of compound nucleus states with energy about 10 MeV greater than that of the corresponding yrast states should be enhanced by a factor of about 100 with respect to the γ decay rates of the neutron resonances. This increase greatly reduces the probability of emission of particles at the end of the evaporation chain and thus automatically increases the width of the excitation functions. However, the calculation still underestimated by about 10 MeV the broadening of some excitation functions and, in addition, the thresholds of the calculated excitation functions was too high in comparison with the experimental ones. A better reproduction of these excitation functions was obtained assuming that the γ decay rates increase linearly with $(2J+1)$, where J is the compound nucleus angular momentum, as suggested by Sperber [41]. In this case the thresholds were correctly reproduced, but at energies exceeding that of the maximum of the excitation function the calculated values still underestimated the experimental ones. According to the same authors the γ ray enhancement is not necessary, and does not change or even makes worse the agreement between the calculation and the experiment in case of reactions induced by α particles with energy up to about 120 MeV on ^{154}Gd and up to about 60 MeV on ^{181}Ta [40].

As an alternatively explanation, one may assume that the emission of pre-equilibrium particles may contribute to the observed broadening of the excitation functions. In fact these particles have considerably higher energy than the evaporated particles and, thus, their emission reduces the total number of particles which may be subsequently evaporated. This leads to an increase of the width of the excitation functions because the cross-section for emission of a given number of particles may be still sizeable at energies where a pure evaporative process greatly favours the emission of a higher number of ejectiles.

The analysis of heavy ion interactions producing heavy compound nuclei ($A \geq 200$) is of prominent interest since, due to the competition with fission, only compound nucleus states of relatively small angular momentum may decay by particle emission and this minimizes the influence of angular momentum effects on the excitation functions for production of spallation residues. This is the case of the interaction of ^{12}C with ^{197}Au, because the maximum angular momentum of the compound nucleus for particle decay is estimated to be about $28 \pm 2\hbar$ [31,32]. The analysis of the corresponding reactions suggests the presence of pre-equilibrium emissions already at energies of the order of the two-ion Coulomb barrier.

The theory we use for the analysis of the data is discussed in a series of papers [42–45] and the application to the reactions considered here is discussed in [31]. One assumes that the approaching and the probability of fusion of the two interacting ions are ruled by their mean field interaction. At the low energies we consider here, the two ions are greatly slowed down by their Coulomb repulsion. Thus, when they eventually come in contact, their translational velocity is much smaller than the internal velocity of their nucleons. The two ions start to exchange nucleons as soon as they are in contact, but have not yet merged in a common potential well. The cascade of interactions between the projectile's and target's nucleons, which we simulate by means of a set of Boltzmann Master Equations (BME), brings to the composite nucleus thermalization when still a sizeable part of the total excitation energy (of the order of the two-ion Coulomb barrier at contact) is frozen as collective deformation energy. It takes a much longer time to transform this energy into thermal excitation energy of the compound nucleus. The initial energy distribution of the nucleons of the intermediate composite nucleus is evaluated by coupling the translational and the internal momenta of the projectile's and target's nucleons. The shell model internal momentum distributions of the nucleons are approximated by Gaussian and Saxon–Wood distributions [44]. Solving the BME one evaluates, as function of time, the angle integrated pre-equilibrium particle spectra [42–44] which further are used in a Monte Carlo calculation for evaluating the probability of emitting a given number of particles (including those emitted in the subsequent chain of evaporations) and thus for predicting the cross-sections of the reactions which may occur [45]. Using a set of input parameters weakly dependent on A and Z, which are given in [31], one obtains a satisfactory reproduction of the excitation functions of all the complete fusion reactions in the four heavy ion interactions which we are considering. An example of the results which one obtains is shown in Fig. 6 which shows the comparison between the calculated and the experimental values for four representative excitation functions.

The complete fusion residues recoil in the forward direction with an average emission angle of about 5° and have an average linear momentum almost equal to that of the projectile (the reduction due to the emission of the pre-equilibrium nucleons is quite small at the low incident energies considered here). As it is shown in Fig. 1 and 2, both these experimental findings are well reproduced by the calculations. The linear momentum of the nuclei of the de-excitation chain changes at each particle emission. The angular

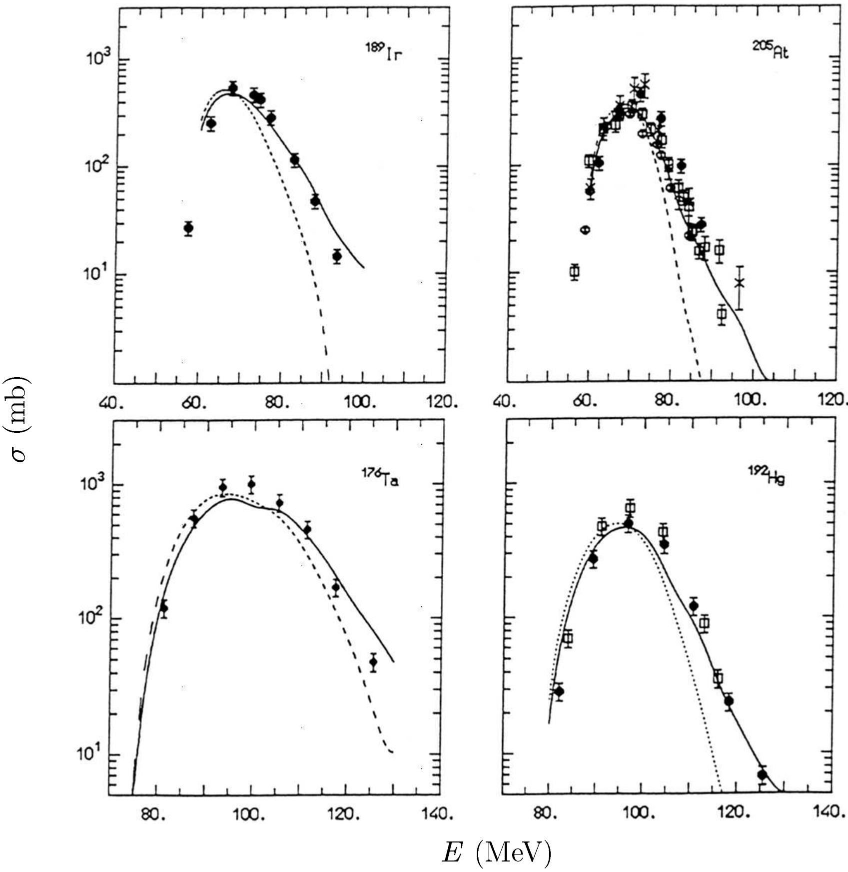

Fig. 6. Typical excitation functions of complete fusion reactions occurring in the four heavy ion interactions considered. ^{189}Ir is produced in the interaction of ^{12}C with ^{181}Ta, ^{205}At in the interaction of ^{12}C with ^{197}Au, ^{176}Ta in the interaction of ^{16}O with ^{165}Ho and ^{192}Hg in the interaction of ^{16}O with ^{181}Ta. In all the cases the full line gives the predicted cross sections considering pre-equilibrium emissions, the dashed lines the values obtained considering a pure evaporative decay of the compound nuclei created in the complete fusion reactions.

distribution of the pre-equilibrium particles is approximately given by

$$\frac{d^2\sigma}{dE d\Omega} \propto \exp(-\theta/\Delta\theta)\,, \tag{2}$$

where θ is the emission angle with respect to the recoil direction of the decaying nucleus, $\Delta\theta = 2\pi/kR_{\rm CN}$, k is the emitted particle wave number and

$R_{\rm CN} \approx 1.3 A_{\rm CN}^{1/3}$ is the radius of the decaying nucleus [46,47]. The evaporated particles are assumed to be emitted with either an isotropic or a $1/\sin\theta$ distribution, according to the angular momentum $\boldsymbol{J}$ of the decaying nucleus [32]. If $\boldsymbol{J}$ is much greater than the emitted particle orbital angular momentum, the particles are assumed to be emitted in the plane perpendicular to $\boldsymbol{J}$. For smaller angular momenta the particles are assumed to have an isotropic distribution with respect to the direction of $\boldsymbol{J}$. The calculations reproduce also satisfactorily the width of the measured residue FRRD, as shown in Figs 1 and 2.

Different experimental data confirm the presence of pre-equilibrium emissions in low energy heavy ion interactions. As an example, in Fig. 7 the experimental [48] double differential spectra of the neutrons emitted in the

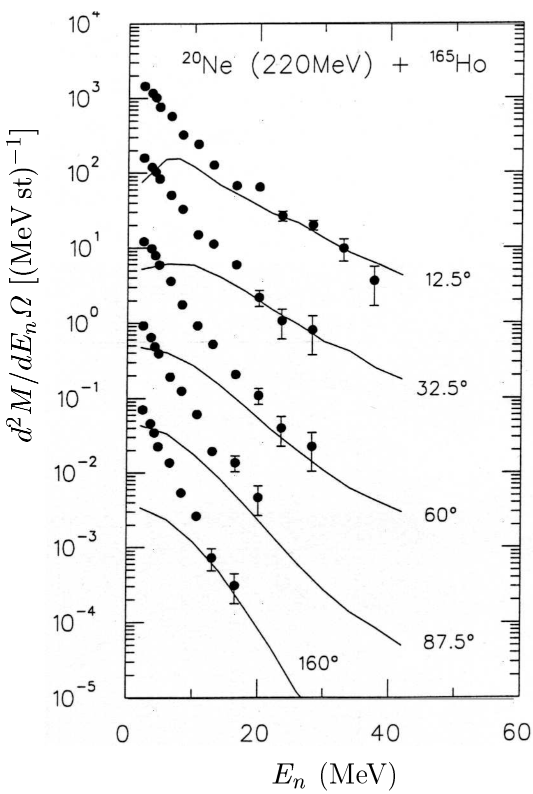

Fig. 7. The black points give the double differential spectra of the neutrons emitted in the interaction of 220 MeV ^{20}Ne ions with ^{165}Ho [48]. The full lines show the spectra of the pre-equilibrium neutrons emitted before attaining the statistical equilibrium state.

interaction of 220 MeV ^{20}Ne ions with ^{165}Ho are compared to the predicted pre-equilibrium spectra [49]. This comparison confirms that the highest energy neutrons are emitted in the course of the nuclear thermalization before reaching the statistical equilibrium.

As a conclusion, I feel that these studies provide convincing evidence of the presence of pre-equilibrium processes even in quite low energy heavy ion interactions.

3.2. Incomplete fusion reactions

Fig. 5 shows that a non-negligible fraction of the reaction cross-section is accounted for by non complete fusion reactions. As mentioned before, the study of the excitation functions, of the forward recoil ranges and the angular distributions of the corresponding residues is consistent with the hypothesis that these processes might be the incomplete fusions of fragments from projectile break-up. In a first approximation, the double differential spectra of the spectator fragments (those which do not interact with the target nucleus and fly away almost undisturbed) are calculated, with the Serber approximation [26,32,50,51]. At such low energies one must also take into account the bending, due to the Coulomb field, of the projectile trajectory before the break-up. Once one knows the emission probability of the spectator fragment both as a function of the energy and the angle, the excitation energy and the linear momentum of the intermediate composite nucleus formed in the incomplete fusion reaction is evaluated by imposing the energy and linear momentum conservation. Further particle emissions change only weakly the direction of the decaying nuclei. Figs 1 and 2 show that these calculations reproduce reasonably well both the residue's average forward ranges and the widths of the recoil distributions. Particularly intriguing is the large recoil angle ($40°$–$50°$) of the residues created in the incomplete fusion of α particles, which is very satisfactorily reproduced by the calculation. However, while at higher incident energies the absolute value of the cross sections for the incomplete fusion of ^{12}C and ^{16}O fragments seem to be reasonably well described by the critical angular momentum model [15,52], I am not aware of a satisfactory theory of these processes for such low energies, even if the measured excitation functions, the forward recoil range and the angular distributions are those we expect on the basis of a break-up-fusion mechanism.

4. Summary and conclusion

I have shown how the study of heavy ion interactions at low incident energy may still provide useful information on the reaction mechanisms. I have mainly discussed the results of activation studies showing that they provide an extremely detailed information and I have shown that the measurement of the residue's recoil ranges and angular distributions may greatly help to disentangle the processes which occur in a heavy ion reaction. For instance, it is likely that low cross section spallation reactions of fissile composite nuclei produced in the complete fusion reactions may be studied in presence of a dominant fission background using small forward catchers where most of the residues produced in such processes recoil. These studies might reveal of great interest for a better understanding of the fission — spallation competition and of the angular momentum dependence of fission widths.

More sophisticated experiments using 4π particle and γ-ray detectors are now possible and may provide important insight on the reaction mechanism. In fact, even if a great progress has been made in the interpretation of low energy heavy ion reactions, further work is necessary to understand several important details for which an accurate quantitative understanding is still lacking.

In this paper I have discussed the results of a series of experiments in which many of my colleagues and students have been involved. I wish in particular to acknowledge the invaluable contribution of M. Cavinato, E. Fabrici, E. Gadioli Erba, M. Galmarini, P. Vergani and of my former students F. Vettore, E. Vaciago, C. Passagrilli, S. Filice and M. Crippa.

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