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LETTER TO THE EDITOR

ON THE STUDY OF INCLUSIVE REACTIONS INDUCED BY LIGHT-HEAVY IONS

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Paper devoted to honour the memory of Professor Nikola Cindro

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A major progress in the understanding of nuclear dynamics in light-particle induced reactions was made with the development of the theories of pre-equilibrium phenomena which led to a unified and comprehensive description of the reaction mechanisms. Is this possible also in the case of heavy-ion reactions? This paper addresses this question and shows a few results which have been obtained in a comprehensive study of light-ion induced reactions.

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It is my great pleasure and a great honour to contribute to this commemorative issue in honour of Nikola Cindro. Nikola was one of my closest friends, one of the colleagues I trusted very much and his work often inspired my own work. So, I wish to start my contribution by quoting one of his papers which had a lasting influence on the physical community and on me in particular. This is his paper in collaboration with Wayne Swenson, where, at the beginning of sixties, are shown the spectra of protons emitted in reactions induced by 30.5 MeV α-particles [1]. These spectra, in agreement with the results of other authors [2–5], were found to be incompatible with expectations of the statistical model. They had a high energy continuous component with a forward-peaked angular distribution. The level-density parameter extracted from their reduced plots was much smaller than expected, and the nuclear temperatures had a dependence on the energy of bombarding particle untenable on the basis of the statistical model. Sidorov [6] suggested that the high energy contribution should be ascribed to the processes intermediate between the direct reactions and the compound nucleus reactions and, following this idea, Jim Griffin in 1966 developed his exciton pre-equilibrium model [7]. One of the first applications was the interpretation of the spectra measured by Swenson and Nikola Cindro [8].

Nikola Cindro gave many other important contributions to the development of the pre-equilibrium nuclear reaction theory, not only by original work but also by organizing meetings where the emerging ideas were discussed and inspired further work. I remember in particular the one which he organized at the Plitvice Lakes in 1972 [9] which gave a review of the work done on the subject up to that time and certainly inspired Herman Feshbach's work on the statistical multistep compound and statistical multistep direct processes, which Feshbach exposed one year after at the Munich Conference [10].

The theories of pre-equilibrium nuclear reactions showed that to reach a deeper understanding of the reaction mechanisms one cannot limit considerations to a purely phenomenological description of experimental data. They provided a unification of seemingly different nuclear reaction theories, allowing a comprehensive description of nucleon induced reactions. The importance of these accomplishments cannot be underestimated considering not only the much increased understanding of the reaction mechanisms, which the theories of pre-equilibrium processes afforded, but also the use of nuclear physics in interdisciplinary fields and applications useful to mankind: medical diagnostic and therapy, dosimetry, environmental control, space physics and industrial research. In all these cases what one requires is an accurate prediction of *all* what happens when a nuclear interaction takes place: the reactions which may occur, their cross sections, the yields of particles and γ rays which are produced and their angular and energy distribution, the heavy reaction products and their momentum distributions. All this could not be predicted before the advent of pre-equilibrium reaction theories unless at very low incident energies [11]. The extent to which this information needs to be known is well exemplified by some recent publications [12–14] and the efforts which are actually made for developing codes for the comprehensive nuclear calculations (see, for instance Refs. [15–17]).

At the beginning eighties, we encountered, in heavy ion induced reactions, a situation quite similar to that existing in light-particle induced reactions at the beginning sixties. In that case it was also found that the spectra of nucleons emitted in central collisions had a forward peaked hard component, decreasing with increasing energy much more gently than the evaporative component. A widely used prescription, which was never given a sound justification, and which is still in use, was to reproduce these spectra in terms of isotropic statistical emissions from two (or more) moving sources with different temperatures, some sort of hot spots which were also considered without much success in the case of light-particle induced reactions (see Ref. [11] pp. 435–442). Also in this case Nikola Cindro (together with Korolija and Čaplar) gave an important contribution, showing that a very accurate reproduction of the proton differential spectra in heavy-ion reactions at incident energies of a few tens of MeV/amu may be also obtained by a multisource fit including a non-isotropic (forward peaked) emission from a source moving with the center of mass velocity of the two ions [18].

A contribution of this type is predicted by microscopic calculations of the spectra of the nucleons emitted during the thermalization of the composite nucleus created in the fusion of the two ions made with the Boltzmann master equation theory. A typical result [19] is shown in Fig. 1 for the spectra of neutrons emitted in the central collision of ^{40}Ar ions with $^{\rm nat}$Ni, ^{92}Mo and ^{122}Sn [20]. The higher-energy neutrons are emitted in a short time interval after the overlap of the two ions (less than $\approx 5{\cdot}10^{-22}$ s), much earlier than the statistical equilibrium could be reached.

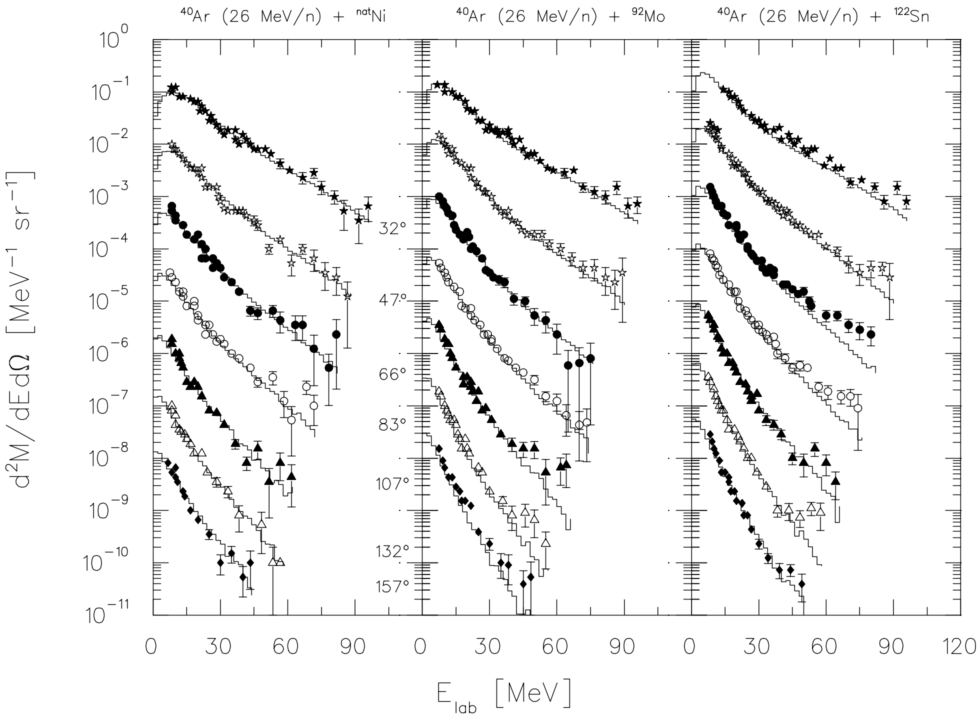

Fig. 1. Spectra of neutrons emitted in the interaction of ^{40}Ar *with* $^{\rm nat}$Ni, ^{92}Mo *and* ^{122}Sn *at an incident energy of 26* MeV/amu *in coincidence with residues emitted at an angle of 8.1°±1.6° with about CM velocity. The symbols give the experimental values [20], the histograms the result of the calculation [19]. Starting from top, the spectra are progressively scaled down by a factor ten.*

As in the case of the calculations made with pre-equilibrium models for nucleon induced reactions, these calculations allow a comprehensive description of all processes which may occur in the fusion of the two ions, and, because they are based on the same basic hypotheses, provide a unification of light-particle and fusion heavy-ion reactions.

However, the fusion of two ions is only one of the possible reaction mechanisms, and we can ask ourselves if it is possible to predict also the cross sections of inclusive reactions when all the possible interaction mechanisms of two ions contribute. At the moment, this seems to be impossible in general, not only because of the lack of a complete formal theory of heavy ion reactions, but also because of the absence of detailed experimental information. However, some recent investigations seem to suggest that this might be possible in the case of the reactions induced by light-ion projectiles, such as ^{12}C and ^{16}O, where only a relatively small number of reaction mechanisms need to be considered. Comprehensive analyses of large sets of data, including ejectile's spectra (light particles and intermediate mass fragments), angle and energy integrated cross sections for production of a large number of residues, residue's velocity and forward recoil range distributions, have been made for the interaction of these ions with $A \approx 60$ and $A \approx 100$ nuclei at incident energies up to 45 MeV/amu for ^{12}C and 25 MeV/amu for ^{16}O [21–27]. These analyses show that it is possible to reproduce all these data with a reasonable accuracy, comparable to that obtained in the analysis of light particle reactions [11]. However, the interaction mechanisms appear considerably more complex than those occurring in the interaction of a nucleon or a light particle with a nucleus. The incident ion may either fuse with the target nucleus or break-up, and before doing this, it may loose a non-negligible fraction of its energy [25,26]. These interactions lead to a large variety of phenomena, the most frequent of which seems to be the fusion of one of the projectile's fragments with the target nucleus [22–24]. The incomplete fusions induce a series of processes which include the re-emission of the absorbed fragment if it is very stable, as in the case of α-particles [24], and the emission of fast ejectiles (among which intermediate mass fragments) during the thermalization of the excited composite nuclei which are produced [24,27]. Eventually, a thermalized system is created which further evaporates particles and γ rays. I will not discuss how these different reaction mechanisms have been taken into account in these works, but for saying that there is ample space for refinement and improvement of the rather crude methods which have been used. However, it may be of some interest to briefly mention some results and some of the conclusion which have been reached. The first of these is that there are no *simple processes* which may be studied without considering the full complexity of the two-ion interaction. For instance, one might expect that heavy-projectile fragments are produced by projectile break-up and thus their analysis should not require to take into account most of the mechanisms which have been mentioned before. However, the experimental findings show that this is not the case. All spectra of heavy fragments which have been measured show two distinct contributions: one dominant at the most forward angle, which is certainly due to the projectile's break-up, the other which becomes progressively dominant at the larger emission angles with a maximum yield at the Coulomb-barrier energy. The total cross section of this contribution is surprisingly high, some tens of mb in all cases which have been considered, and certainly cannot be explained as due to the evaporation from thermalized systems. It is suggested that it is due to the coalescence of nucleons during the de-excitation intranucleon interaction cascade by means of which the excited composite nuclei (which are produced both in complete fusion of the projectile with the target and in the fusions of part of the projectile with the target) thermalize [27–29]. A typical result is shown in Fig. 2. Nucleon coalescence is statistical in nature and competes with a large number of other de-excitation modes the probabilities of which need to be also evaluated.

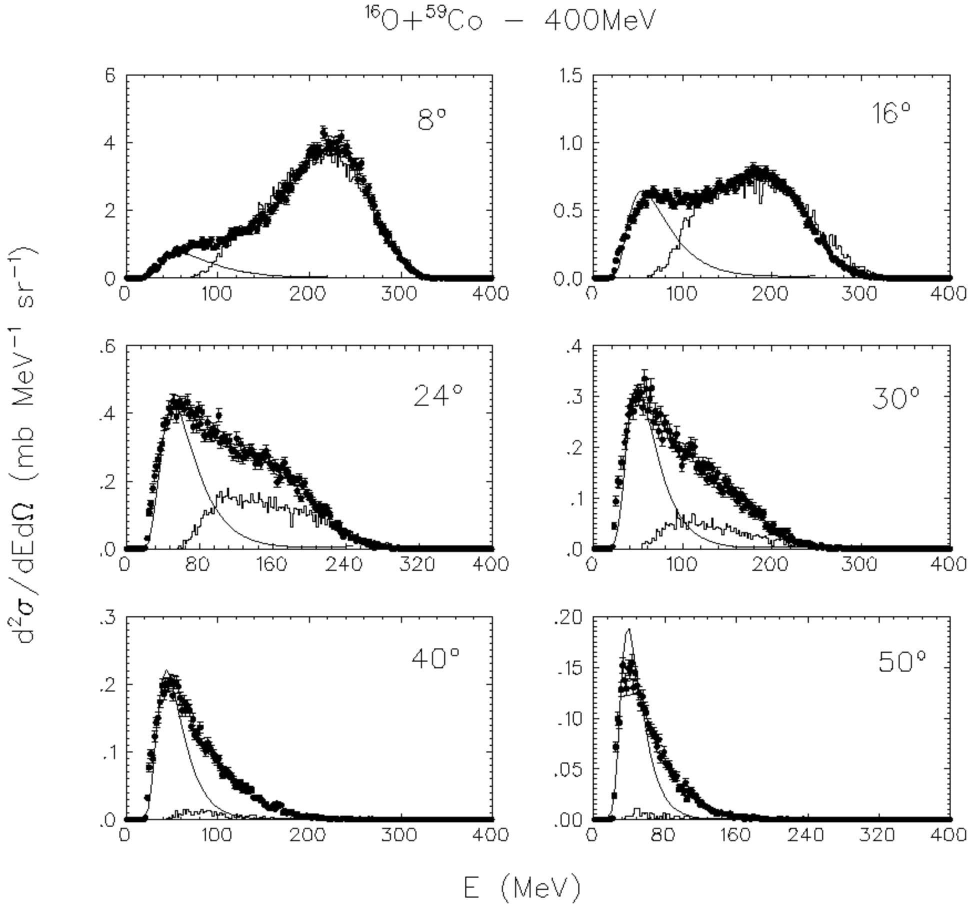

Fig. 2. Spectra of boron fragments emitted in the interaction of ^{16}O *with* ^{59}Co *at an incident energy of 400* MeV. *The experimental spectra are given by the black points, the theoretical ones by the full lines for the coalescence contributions and the histograms for the break-up contributions [29].*

Perhaps the best example of a comprehensive comparison of experimental data and theoretical predictions is the analysis of the formation cross section of residues with many different masses which may be produced with cross sections varying from one tenth of mb to about one hundred mb. A comparison of this type is shown in part (a) of Fig. 3 which shows the measured (black symbols) and calculated cross sections (open symbols) for the production of residues with mass varying from $A = 39$ to $A = 65$ in the interaction of 45 MeV/amu ^{12}C ions with natural copper [30]. In part (b) of the figure are given the ratios of the experimental to theoretical cross sections and one may see that the calculations reproduce the experimental cross sections with a very reasonable accuracy, independently of their absolute values. The calculations which will be described in detail elsewhere [31] include the complete fusion of ^{12}C with copper and many incomplete fusions following the break-up of ^{12}C in the target field, the transfer of single nucleons from ^{12}C to the target and ^{12}C inelastic scattering. Figure 4 shows the predicted residue's mass distribution. Many residues contribute to this distribution, however, their formation cross section has not been measured, but only predicted by theoretical calculations. We see that the residues which should be produced with the highest yield are those with mass near to that of the target nucleus. This was anticipated by our previous

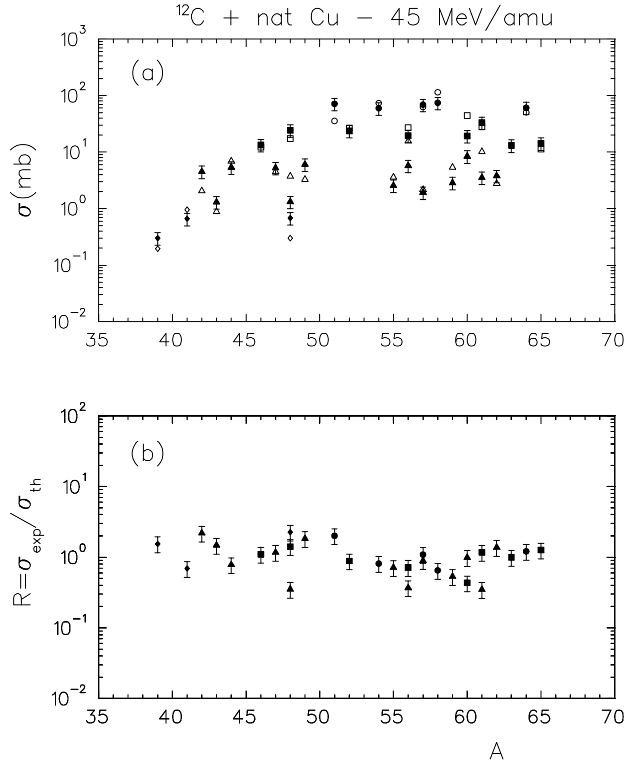

Fig. 3. Part (a): Comparison, as a function of the residue's mass, of the experimental [30] (black symbols) and the calculated [31] (open symbols) cross section for residue's production in the interaction of 45 MeV/amu ^{12}C *with natural copper. Part (b): ratios of the experimental to theoretical cross sections.*

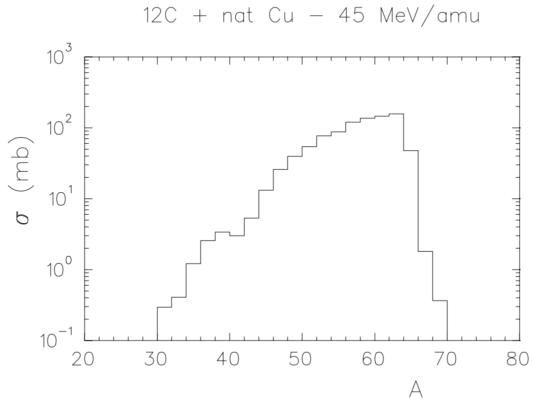

Fig. 4. Calculated isobaric yield distribution of the residues produced in the interaction of 45 MeV/amu ^{12}C *ions with natural copper [31].*

calculations concerning the interaction of 33 MeV/amu ^{12}C with ^{103}Rh [23] and it is now confirmed by the more refined calculations. Figure 5 shows the measured (black symbols) [30] and predicted [31] (open symbols) residue's average forward ranges. In this case, too, the calculations reproduce quite well the experimental trend.

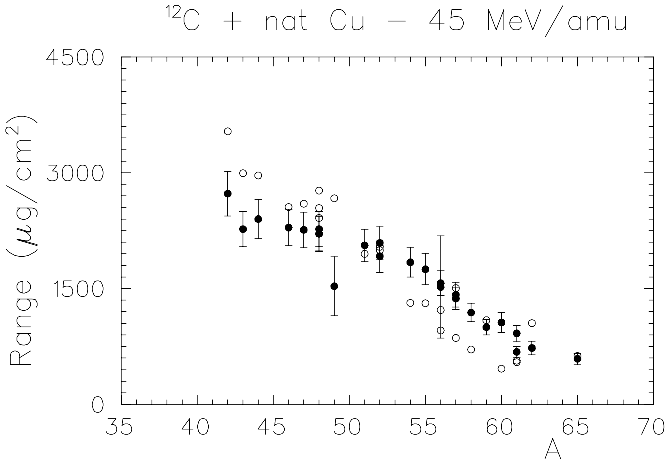

Fig. 5. Average forward ranges of residues produced in the interaction of 45 MeV/amu ^{12}C *ions with natural copper. The experimental values are given by the black circles [30], the theoretical predictions by the open circles [31].*

These results seem to indicate that the cross sections of the reactions which occur in these inclusive heavy-ion interactions can be quite accurately reproduced by a comprehensive theoretical calculation, and this induces to consider with a level of confidence some predictions which cannot be directly compared with the experimental information. One of these is the average energy $\overline{E}$ of the equilibrated nuclear matter at the end of the fast stage of the interaction after the emission of the fast projectile's fragments and the pre-equilibrium particles. This quantity is predicted to be quite small as it is shown in Fig. 6 which gives the predicted excitation energy distribution of the equilibrated nuclei. The double-humped shape of this distribution at the lowest energies reflects the complexity of the interaction, to which many reaction mechanisms contribute. Most of these nuclei are produced with a quite small energy. The average energy per nucleon is ≈ 1 MeV/amu, less than one fifth of the energy per nucleon which would be carried in by the projectile in a fusion reaction. This seems to imply that light-ion interactions are very inefficient in producing hot equilibrated nuclear matter. The average temperature $\overline{T}$ of the equilibrated nuclear matter is less than 3 MeV. The analysis [31] of the same kind of data at a ^{12}C bombarding energy of 35 MeV/amu [32] gives values of $\overline{E}$ and $\overline{T}$ almost equal to those given above, suggesting that the values of these quantities do not increase with bombarding energy above 35 MeV/amu.

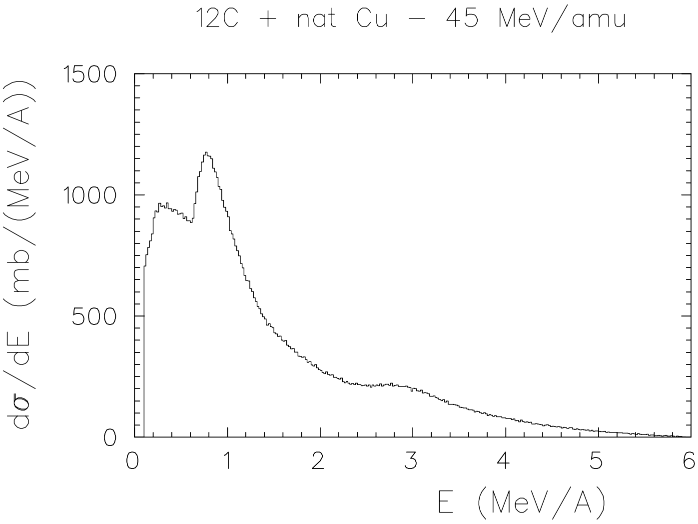

Fig. 6. Predicted excitation energy distribution of the equilibrated nuclei produced at the end of the fast stage of the interaction of 45 MeV/amu ^{12}C *ions with natural copper after the emission of fast-projectile fragments and pre-equilibrium particles [31].*

The last time I saw Nikola was on the occasion of the 1999 Rab Conference on "Clustering Aspects of Nuclear Structure and Dynamics" which was dedicated to him. On that occasion, I gave a talk [33] in which I presented preliminary results of the calculations which I have discussed in this paper. Nikola was already very ill, however participated actively in the Conference and showed a keen interest for these results making some enlightening comments. This greatly encouraged me to pursue this line of research and it is a further reason to dedicate to him this paper.

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PROUČAVANJE UKLJUČIVIH REAKCIJA IZAZVANIH LAKO-TEŠKIM IONIMA

Razvoj teorija predravnotežnih pojava doveo je do velikog napretka u razumijevanju nuklearne dinamike u reakcijama izazvanim lakim ionima, te do ujedinjenog i cjelovitog opisa reakcijskih mehanizama. Da li je to moguće i u slučaju reakcija s teškim ionima? U ovom se radu razmatra to pitanje i prikazuju mogući ishodi koji su postignuti u cjelovitom proučavanju reakcija izazvanih lakim ionima.