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USE OF ^{12}C PROJECTILES AT ENERGIES UP TO 86 MeV/NUCLEON FOR STUDYING THE DISSIPATIVE PHENOMENA IN NUCLEAR COLLISIONS

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I - INTRODUCTION

For ten years, our group has been much involved in the study of reaction mechanisms in heavy ion induced collisions. The experimental work has been carried out at Orsay, using the ALICE facility which delivers 20 beams ranging from Carbone up to Krypton with energies varying from 5 MeV/A up to 15 MeV/A for some of the projectiles.

Our main interest has been focused on the dissipative processes which take place when two nuclei collide On the one hand we have studied the different aspects linked to the formation and deexcitation of a fully equilibrated compound nucleus system issued from the fusion of two heavy nuclei On the other hand, we have extensively investigated the so called "deep inelastic collisions". In the latters, we have shown that the interaction time is large enough for some of the collective degrees of freedom of the system to have reached equilibrium but not sufficient for the compound nucleus stage to be reached The study of these collisions has given us the unique opportunity to follow a nuclear system on its way towards equilibrium

In order to complement all these investigations there is now a great need of much energetic beams. In this respect, the avaibility of a 86 MeV/A ^{12}C beam at the Synchrocyclotron at CERN gives us a good opportunity to initiate some experimental work before GANIL can deliver its first beams. It would be highly desirable to degrade the beam energy all the way down to 20 MeV/A. This would make it possible to trace the evolution of heavy ion reaction mechanisms across what is generally thought to be a transition region with projectile velocities comparable with the Fermi speed.

II - AIMS OF THE EXPERIMENTS

At 10 MeV/A, ^{12}C induced reactions are dominated by two widely open channels : compound nucleus (C N) formation and deep inelastic collisions (D.I C)$^{1)}$

In the first case (C N. formation), the bombarding energy is completely absorbed and shared among all the degrees of freedom The system is thermalized and subsequently cooled down by emission of particles and γ-rays The excitation energy E^{*}_{CN} of the C N. is given by the equation :

$$E^{*}_{CN} = E_{c.m} + Q \qquad (1)$$

$E_{c\,m}$ being the c.m incident energy ($E_{c.m.} = 0{,}9\ E_{lab}(^{12}C)$ for a target mass 108)

Q, expressing the difference in initial and final masses, can be neglected in a first approximation.

This excitation energy results in a nuclear temperature :

$$T = \sqrt{\frac{E^{*}}{a}} \qquad (2) \qquad \text{with } a = \frac{A}{8}$$ A being the C N mass (amu)

The shapes of the evaporated particle spectra are typical of this temperature (particularly the high energy tails of these spectra decreasing as $\exp\left[-\frac{E^{*}}{T}\right]$).

In deep inelastic collisions, the relative motion may be completely damped. The two resulting fragments are then emitted with a c m energy close to the coulomb repulsion[2,3]. Their excitation energies correspond to the same nuclear temperature[4]. The total excitation energy is then (neglecting the rotation energy) :

$$E^{*}_{DIT} = E_{c\,m.} + Q' - E_K \qquad (3)$$

Q' expresses the reaction mass balance and depends on the nuclear reaction (it will be neglected in a first approach).

E_K is the sum of fragment kinetic energies ($E_K \simeq 40$ MeV for ^{12}C + Ag)

The aim of this experiment is to study, by increasing gradually the incident energy, the evolution of these two highly dissipative processes (of their probability and typical features)

II.1. Compound Nucleus Process

The C.N. process is interesting from the double point of view of :

i) the possibility of forming a fusion nucleus with a very high excitation energy (i.e a high nuclear temperature) This question is related to the dynamics of the entrance channel (Is it possible to dissipate very large amounts of kinetic energy, Are there limitations such as critical angular momenta, or critical distances of approach ? [5]), but also to the thermodynamical concept of nuclear matter boiling point

ii) the deexcitation of such highly excited nuclei At incident energies between 10 and 20 MeV/A, one already knows that a non negligible amount of particles are emitted before a thermodynamical equilibrium is reached (preequilibrium emission)[6].

We propose to investigate these two points by studying the evolution, versus incident energy, of the energy spectra and angular distributions of charged particles (H,He) in coincidence with the evaporation residues from a C.N. Using several charged particle detectors, the charged-particle (c.p.) mean multiplicity $\overline{M}$, and the second (and eventually third) moment of the multiplicity distribution can also be measured The whole set of data : energy, angular distribution and multiplicity of light particles, mass, kinetic energy and angular distribution of the evaporation residues will be used as a signature for the C.N. process (see the expected numbers in table 1 given in annex) We thus hope to be able to collect elements for answering the following questions:

Is there an incident energy above which the fusion process is no more possible ? Is there a nuclear temperature that the excited nucleus cannot hold ? Is there any saturation around T = 8 MeV as suggested by experimental data obtained with 1 or 2 GeV/A projectiles[7] ? Is there an incident (or excitation) energy such that the preequilibrium emission becomes the dominant deexcitation process.

II.2. Deep Inelastic Collisions

Very little is known about the evolution of D.I.C. with increasing incident energy One may think, however, that the completely damped collisions will occur with a decreasing probability, while the partially damped events will have an increasing probability. Moreover, these last reactions may exhibit an evolution towards reactions of the type described by the fireball model[8].

Difficulties in distinguishing completely damped collisions from C N

Some of the data from ref [9] suggest that strongly damped events may still be observed at 75-100 MeV/A. If one assumes a complete damping of the kinetic energy one can calculate the resulting excitation energies of the heavy and light fragments. Typical numbers are given in table 2 (anne)

By comparing the numbers in tables 1 and 2, one can see that, when the incident energy is increased, the characteristics of heavy fragments from D I C become very similar to those of an evaporation residue At the lowest energies, the angular distribution can be used to distinguish between the two processes, but this is no more possible at high energy, since the maximum lab emission angle of the D I.C. heavy fragment (before evaporation) becomes very low (less than 12° for ^{12}C + ^{108}Ag at 86 MeV/A)

If one assumes that this heavy fragment is preferentially emitted backwards in the c m s , its energy can be calculated (this gives a lower limit) This leads to energies which can be significantly lower than those of evaporation residues But the evaporation process following the first reaction step may wash out the difference Therefore, one may think that, for high incident energies, the D I C and C N reactions will not be easy to separate and will have to be considered together This will not reduce much the interest of the study, as both processes are highly dissipative phenomena

Use of the multiplicity data for identifying partially damped (or fireball-type) collisions

The partially damped events are associated with kinetic energies of the fragments higher than the coulomb repulsion This leads to the excitation energies of the system lower than for completely dissipative processes, and the number of evaporated particles will be reduced Therefore, the data concerning the particle multiplicity will be useful to separate these events from the completely damped (+CN) events : the mean c p multiplicity $\overline{M}$ should be reduced by one unit when the kinetic energy E_K is increased by about 20 MeV This effect will be enhanced by placing the light particle detectors in the backward hemisphere, in order to avoid as much as possible the detection of the particles emitted by the light fragment (assumed to be emitted forward).

The processes of the type described by the fireball model[8)] may also, in principle, lead to residues of masses equivalent to those of E.R But, in such processes, a significant part of the incident energy is used to heat up only a fraction of the nucleons moving at an intermediate velocity, and in the lab system the observed particle spectra should exhibit very high energy tails Moreover, the c p multiplicity should be much lower than for completely dissipative phenomena

Finally, the second (and third) moment of the M-distribution, related to its width (and squewness), will be useful in order to detect the possible presence of two reaction mechanisms (such as C N + partially damped events, for example)

It is clear, however, that the use of several incident energies will be of the greatest interest to help clarify the high energy observations

III - THE EXPERIMENTAL SET UP

III 1 Detectors

The experimental set-up is shown in fig. 1 The light particles will be identified using 6 solid state detector (SSD) telescopes Each telescope consists in three detectors of respective thicknesses 60 µm, 500 µm and 5000 µm, and of active area equal to 3 cm^2. The telescopes will be preferentially placed in the backward hemisphere in order to avoid direct light particle emission which must be significant forward and negligible elsewhere[9] (with exceptions for angular distribution measurements for which it will be desirable to get information at forward angles) The particles H and He can thus be identified unambiguously in the energy ranges of 2 5-200 MeV and 10-300 MeV respectively)

The evaporation residues will be detected by 4 SSD (500 µm and 4.5 cm^2), placed forward as indicated in fig 1a Monte-Carlo simulations have shown that, due to the large number of evaporated particles, the heavy residue angular distribution is quite broad. Therefore, by placing the detectors at angles between 5° and 30°, one should observe them with a significant probability, and avoid the main flux of direct fragments (the calculated grazing angle being about 2° for A = 100 targets and 86 MeV/A ^{12}C).

A time of flight between any telescope and any heavy residue SSD will allow us to determine the mass of the residues A time resolution of about .2 ns can be achieved between two SSD. Considering a flight path of 40 cm for the heavy residue, the mass resolution can be

$\frac{\Delta m}{m} = \frac{\Delta E}{E} + \frac{2\Delta t}{t} \simeq 1\text{-}2\ 10^{-2}$ depending on the E-resolution (The energy calibration can be performed using elastic scattering with the ALICE accelerator)

The configuration of fig. 1b will be adopted for measuring the angular distribution of heavy residues in coincidence with at least one charged particle

III.2. Targets

Taking into account the low velocity of the heavy residues, thin targets ($\simeq$ 1 mg/cm^2) should be used We intend to use Ag (or Rh) targets to study the influence of incident energy from 20 to 86 MeV/A on the dissipative phenomena On the other hand, the study of the influence of the nuclear temperature effects would be performed, with the 86 MeV/A beam by using targets of different masses (^{58}Ni, ^{107}Ag, ^{165}Ho) : see table 1

Although we had rather initiate the study by the lowest incident energies, it would be possible, if these low energies are not available at the beginning, to start by the high energy experiments.

IV - BEAM-TIME REQUIREMENT AND TECHNICAL SUPPORT

IV 1 Expected counting rates

Assuming a cross section of 100 mb for the studied process, a target thickness of 1 mg/cm^2, and a beam flux of 10^{10} ions/s, the counting rates corresponding to the detection of 1 charged particle or two-fold coincidences, three-fold coincidences are given in the following table (The numbers and equations used in this calculation are given in the annex)
The first column corresponds to the case for which there is no requirement for a coincidence with a residual nucleus. In the second column, this coincidence is required.

q = number of light c p detected in coincidence	Cq = number of q-fold coincidences/hr	CRq = number of coincidences q-particles + 1 residue per hour
1	$1\ 5\ 10^6$ (singles)	$5\ 6\ 10^3$
2	$4.6\ 10^4$	166
3	700	2 6

IV 2 Beam-time requirements

We hope to be able to get a preliminary run on the ALICE accelerator, in which the detection system would be tunedup and calibrated, and in which data corresponding to an incident energy of ∿ 15 MeV/A would be collected Taking this into account, the realisation of the whole experimental program (one target at 4 incident energies, and 3 targets at full energy = 6 systems) would require 4 runs of about 20 eight-hour shifts each, on a period of about two years This time would be used as follows : For each of the 6 systems studied : the tuning-up, timing and calibration would take about 2 shifts. A complete angular distribution for light particles requires 3 measurements, the heavy residue counters being fixed, the telescope angles varied between 10 and 170° Taking as a basis the counting rate for two-fold coincidences (CRq = 166/h for q = 2), each measurement should last 2 shifts, i e. 6 shifts for the c p angular distributions Similarly, the heavy residue angular distribution would require 6 shifts (3 measurements of 2 shifts), the telescopes being fixed as indicated in fig 1b and the heavy fragment detector angles varied from 5 to 60 by 5° steps

The multiplicity measurements would be performed simultaneously with the angular distributions.

This leads to a mean time of 14 shifts per system, i e. a beam time requirement of 84 shifts for the whole study.

If the experiment is accepted, we think that the experimental set-up could be ready in Spring 1980.

IV 3 Technical support from CERN

The relatively small diameter of the reaction chamber (∿ 1 m) would allow us to realise the experiment in an experimental area of 4 x 5 m^2.

Although we hope to be able to bring the whole experimental set-up including the electronics, we would be grateful if CERN could provide us with :

- a magnetic tape recorder system, interfaced with CAMAC,
- primary and secondary pumps for the reaction chamber,
- about 10 power supplies for NIM modules and 2 ones for CAMAC modules (with their crate controller)

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APPENDIX

E/A	Target	V_{CN} (MeV/amu)$^{1/2}$	E^k_{CN} (MeV)	E^*_{CN} (MeV)	T_{CN} (MeV)	A_R (MeV)	E^k_R (MeV)	$\bar{M}$
10	^{108}Ag	0.45	12	104	2.7	110	11	3.5
20	"	0.63	24	216	3.8	98	22	8
50	"	1	60	540	6	66	33	21
86	"	1.3	101	930	7.9	27	23	34
86	^{60}Ni	2.2	172	860	9.8	0	-	32
86	^{165}Ho	0.85	70	962	6.8	81	32	36

TABLE 1 : Typical numbers for CN reactions

V_{CN} is the lab velocity of the compound system, E^k_{CN} its kinetic energy, E^*_{CN} its excitation energy and T_{CN} the corresponding temperature.

A_R and E^k_R are the mass and kinetic energy of the residue :

$$A_R = A_{CN} - E^*_{CN}/10 \quad , \quad E^k_R = \frac{1}{2} A_R V^2_{CN}$$

$\bar{M}$ is the mean light charged particle multiplicity (assuming that 10 MeV are necessary for evaporating one nucleon, and that the ratios of evaporated protons, neutrons and α particles are $M_p/M_n/M_\alpha = 2/2/1$

E/A	$\theta_{max}(H)$	$E^k_{H\,min}$ (MeV)	E^*_H (MeV)	T_H (MeV)	A_{RH} (MeV)	$\overline{M}_H$	$E^k_{L\,max}$ (MeV)	E^*_L (MeV)	A_{RL}	$\overline{M}_L$	$\overline{M}$
10	37°	1.6	57	2	102	2.2	50	6	12	0	2.2
20	25°	6.7	158	3.3	93	6	57	16	10.5	0.6	6.6
50	16°	28	450	5.7	63	16.5	71	50	7	2	18.5
86	12°	55	800	7.8	28	30.	84	80	4	3	33

TABLE 2 : Typical numbers for DIC reactions (^{108}Ag target)

Assumption : the kinetic energy is completely damped

- $\theta_{max}(H)$ is the maximum angle of emission of the heavy fragment in the lab system (given by sin $\theta_{max} = V_H/V_{CN}$, V_H being the velocity of the heavy fragment in the c m s, due to coulomb repulsion).
- $E^k_{H\,min}$ is the lab kinetic energy of the heavy fragment, assuming a backward (180°) c.m emission, E^*_H its excitation energy, derived from eq. (3) assuming the same excitation energy per nucleon for heavy and light fragment, T_H the corresponding temperature, A_{RH} the mass of the heavy residue after evaporation ($A_{RH} = 108 - E^*/10$)
- $\overline{M}_H$ the charged particle multiplicity due to evaporation from the heavy fragment.
- The symbols $E^1_{L\,max}$, E^*_L , A_{RL}, $\overline{M}_L$ denote the same quantities as above, but relative to the light fragment.
- $\overline{M} = \overline{M}_H + \overline{M}_L$ is the overall light charged particle multiplicity associated with D.I.C. reactions

COUNTING RATES

- Compound nucleus (or DIC) cross section $\sigma = 10^{-25}$ cm^2

- Target thickness 1 mg/cm^2. For $A_t = 100$, this leads to $n = 6\ 10^{18}$ at/cm^2

- Beam intensity $I = 10^{10}$ ions/s

- Number of events $\sigma\ n\ I = 6\ 10^3$/s

- Probability for detecting one heavy residue in any of the 4 SSD :

$$P_R = \frac{\Omega R}{\Omega em} \simeq \frac{\Omega R}{\pi} = 3\ 6\ 10^{-3}$$

with $\Omega R = 4 \times 2\ 8\ 10^{-3}$ sr (solid angle for residue detection)

Ωem= solid angle in which the residues are emitted (assumed to be equal to π)

- Probability of detecting a q-fold coincidence between any of the N charged-particle telescopes (here N = 6)

$$P^q_{cp} \simeq \left(\frac{\Omega_{cp}}{4\pi}\right)^q \overline{M}^q C^q_N \begin{array}{l} \nearrow\ q=1 \quad 7.17\ 10^{-2} \\ \rightarrow\ q=2 \quad 2.14\ 10^{-3} \\ \searrow\ q=3 \quad 3\ 4\ \ 10^{-5} \end{array}$$

Ω_{cp} being the solid angle corresponding to one telescope (7 5 10^{-3} sr)

$\overline{M}$ the mean charged particle multiplicity ($\overline{M}$ = 20)

C^q_N the binomial coefficients $C^q_N = \frac{N!}{q!\,(N-q)!}$

- Number of detected events :

q-fold coincidences between light c.p counters only :

$$Cq = \sigma NI.P^q_{cp}$$

events in which a residue is detected in coincidence with a q-fold light c p. coincidence :

$$C_{Rq} = \sigma NI\ P^q_{cp}\ P_R$$

(see table 3 in text)

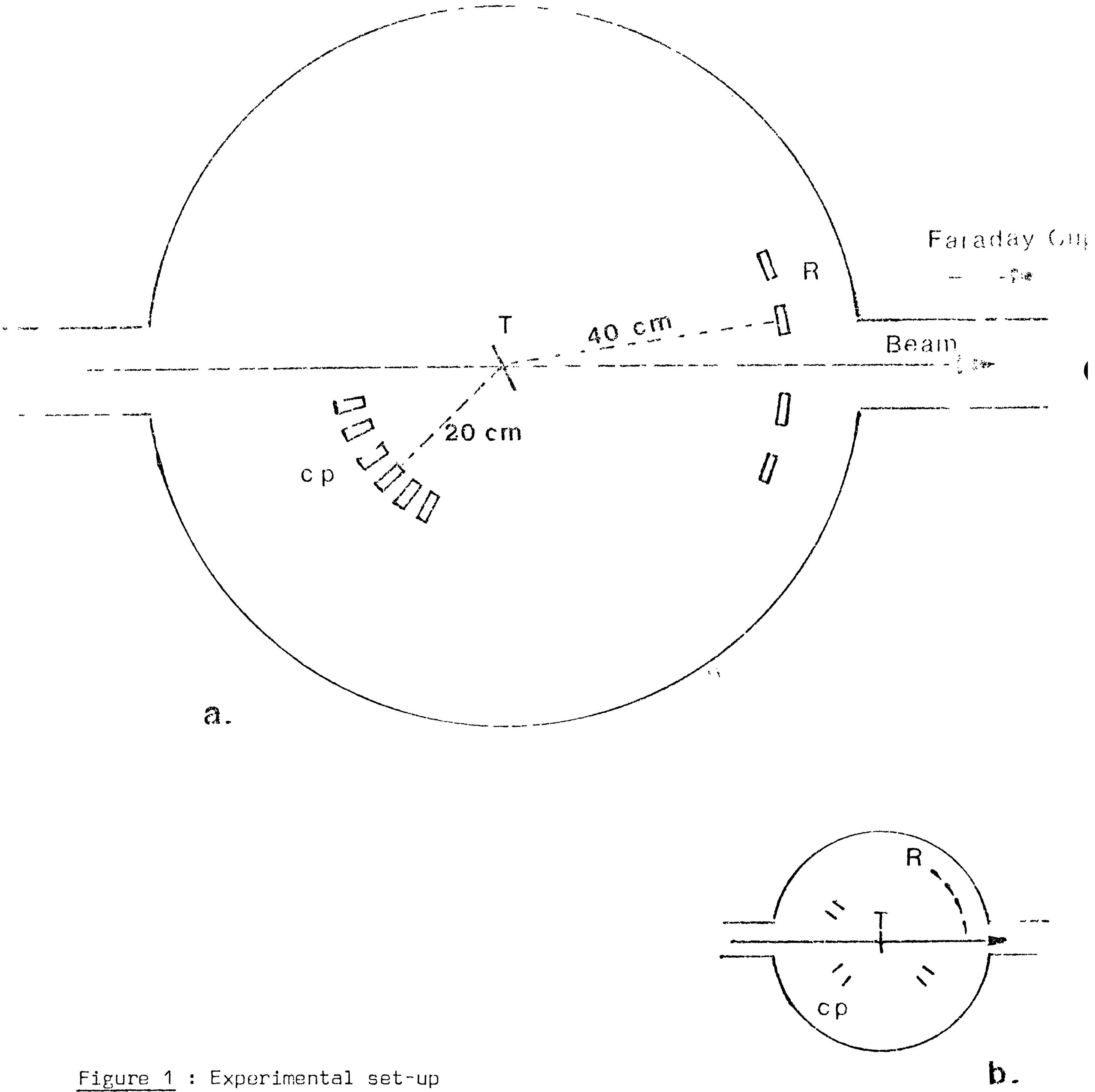

Figure 1 : Experimental set-up

a) for angular distributions of light charged particles (H,He) The angles θ_R are fixed (± 5 to 20°), and the angles $\theta_{c\,p}$ are varied from 10 to 170°.

b) for angular distributions of heavy fragments The angles $\theta_{c.p}$ are fixed and the angles θ_R are varied from 5° to 60°

The symbol T denotes the target, R the four SSD used to measure the residues at the angles θ_R, c p the six telescopes used to detect the light particles in coincidence, at the angles θ_{CP} The multiplicity measurements are performed at the same time as the angular distributions.