Some gross features of the interaction of semirelativistic ^{16}O and ^{12}C ions with ^{197}Au targets

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Fission and total observable cross sections have been measured for the interaction of 107 MeV/N ^{16}O and 86 MeV/N ^{12}C ions with ^{197}Au targets using various solid-state—nuclear-track detectors, e.g., mica and CR-39 plastic. Some results on the emission of light reaction products are also presented.

[NUCLEAR REACTIONS Semirelativistic heavy ions, Au targets, fission cross section, high multiplicities.]

I. INTRODUCTION

Reactions induced by semirelativistic heavy ions (20 MeV/N $\leq E \leq$ 200 MeV/N) have been extensively studied since heavy ion projectiles became available for experimental work. For example, the CERN SC gives beams of 107 MeV/N ^{16}O and 86 MeV/N ^{12}C. Some of the work on semirelativistic heavy ions has already been published (Refs. 1—6), and further references can be found therein. In this paper we report on some experiments using solid state nuclear track detectors (SSNTD's). Such detectors are simple to use and give certain overall features of new types of nuclear reactions quite readily; for example, the fission cross section can be measured using mica track detectors. In addition, plastic SSNTD's also register light charged particles—recently developed CR-39 reveals tracks due to incoming ^{12}C or ^{16}O ions and even protons. We can therefore measure more accurately the total observable interaction cross section and some multiplicity distributions of light fragments and their angular distributions.

The present paper deals with such an application of SSNTD's in studying some gross features in the interactions of 107 MeV/N ^{16}O and 86 MeV/N ^{12}C ions with ^{197}Au.

II. EXPERIMENTAL DETAILS

Four types of threshold detectors (CR-39, Makrofol E, Makrofol N, and muscovite mica) were employed in the present study. Table I summarizes the Z thresholds and the recommended etching conditions concerning these detectors. We established these characteristics of the particular batches of detectors employed in the present work, in particular for CR-39, the most recently developed, and most sensitive, detector. A series of calibration experiments was performed for this purpose. Such a fresh calibration was important, because in the past, it had been reported that different batches of the same detecting material yielded varying track registration characteristics.[7] A variety of charged particles having different energies and angles of incidence were employed for this purpose. Although the details of these investigations have been published,[12] some results are briefly summarized in Table II. Our calibration agrees fairly well with the results of others.[7,10,11]

In this work we employed the 2π-geometry technique used in low-energy heavy ion work.[8] Only fragments moving forward in the laboratory system were registered from the Au target (thickness 1.2 mg/cm^2) facing the beam. We used different solid state nuclear track detectors as backing. The stacks were exposed perpendicularly to 107 MeV/N ^{16}O and 86 MeV/N ^{12}C ions at the CERN SC. The incident beam was defocused so that its cross section at the detector was about 25 cm^2 in area. For fluence measurement purposes, the total number of tracks on the detector was determined by integration over the beam

TABLE I. Z thresholds and recommended etching conditions for various SSNTD's.

Detector	Z thresholds	$\frac{Z}{\beta}$ limit	Recommended etching conditions (Refs. 10—12)
CR-39	$Z=1$ (proton)	<10	6N NaOH, 70±1 °C 35 min for fission fragments 2 h for energetic $^4_2$He ions 5 h for energetic protons
Makrofol E	$Z=2$ (alpha)	≃160	6N NaOH 40 min 50 °C
Makrofol N	$Z=8$ $A=16$ (oxygen)		6N NaOH 60 min 60 °C
Muscovite mica	$Z=16$ $A=32$ (sulphur)	≃800	48% HF 15 min 23 °C

TABLE II. Induction times [the minimum etching time required to enlarge the etch pit diameter to optically observable size (1–2 μm)] for the development of etch pits due to various ions in CR-39 (Homalite) plastic track detector etched in 6N NaOH kept at 70±1 °C.

Ions	Energy	Induction time (min) $D \gtrsim 1$ μm	$D \gtrsim 2$ μm
Fission fragments	From ^{252}Cf spontaneous fission	24	35
^{16}O	at Bragg Peak	31	48
^{12}C	at Bragg Peak	39	59
^{4}He	0.9 MeV	58	103
^{4}He	4.1 MeV	63	115
Protons	0.5 MeV	116	185
Protons	4.2 MeV	180	275

profile. Good results were obtained for heavy ion fluxes of approximately $(2-8)\times 10^6$ cm^{-2}.

After the exposures, the gold targets were dissolved in aqua regia. The etching of mica and Makrofol was carried out according to Table I and revealed fission tracks. The etching of CR-39 detectors was carried out in stages in an aqueous solution of 6N NaOH, kept at 70±1 °C for various time intervals. Fission fragments were revealed after 35 min of etching and the counting was carried out. The etching was then continued further and the lighter reaction products were revealed as tracks on prolonged etching.

III. RESULTS

A. Fission cross sections

Fission fragments are registered in mica and revealed as "correlated" binary events or "uncorrelated" events (i.e., single tracks). In the latter case, it is assumed that one heavy fragment is emitted into the backward hemisphere and thus cannot be registered with our 2π-geometry technique. Single fission tracks with track length $l \geq 2$ μm are included in the calculated fission cross section.

From the densities of heavy reaction products found on the muscovite mica detectors, the fission cross sections σ_f for the reactions 107 MeV/N ^{16}O plus ^{197}Au and 86 MeV/N ^{12}C plus ^{197}Au were computed. Table III shows σ_f for the above-mentioned two target-projectile combinations. Katcoff and Hudis,[9] using thin gold targets, obtained a fission cross section of 340±60 mb for the 143 MeV/N ^{14}N plus ^{197}Au combination. Thus, our results fit well into the known pattern of fission cross sections in this energy range.

B. Emission of light fragments ($A \leq 32; Z \leq 16$) and total observable interaction cross section

The use of more sensitive detectors, i.e., CR-39, revealed a large number of high-multiplicity events. The tracks were traced back to the point of interaction by means of their angle of incidence. The multiplicity of charged particles m (the number of reaction products per interaction) for each event was determined. Multiplicities as high as 14 were observed. Figures 1 and 2 give examples of events with $m=4$ and 5, respectively, observed in the 107 MeV/N ^{16}O+^{197}Au interaction.

The distribution of track multiplicity along with the background in the CR-39 detector itself for the reaction 107 MeV/N ^{16}O+^{197}Au is shown on the left-hand side of Fig. 3. The right-hand side of the figure shows the background subtracted distribution. The peak at multiplicity 4 is somewhat artificial, since very energetic light reaction products have energies above the detection limit of the detector. Low-multiplicity events ($m=2$) are given only as a lower limit. Figure 4 gives the same information for the system 86 MeV/N ^{12}C+^{197}Au. The maximum of the distribution is in the latter case shifted slightly to lower multiplicities, which might be due to the higher total kinetic energy of the ^{16}O induced reaction (1.0 GeV). The shift to higher multiplicities in the ^{16}O-induced reactions can be exemplified by the cross sections for $m \geq 6$, which for ^{16}O+^{197}Au is σ $(m \geq 6)=525\pm99$ mb and for C+^{197}Au is σ $(m \geq 6)=290\pm84$ mb. The calculated total reaction geometrical cross section is 4.2 b for the ^{12}C+^{197}Au system.

TABLE III. Experimental details and cross sections for ^{16}O+^{197}Au and ^{12}C+^{197}Au interactions. σ_f denotes fission cross section; σ_t denotes total observable interaction cross section.

Projectile	Target-detector combination	Fluence #/cm^2	Total number of events and area scanned	Cross sections[a] $(\sigma_f$ or $\sigma_t)/10^{-24}$ cm^2
^{16}O (107 MeV/N)	^{197}Au on CR-39	1.57×10^6	118 events in 6.92 cm^2	$\sigma_t=3.09\pm0.29$
^{16}O (107 MeV/N)	^{197}Au on mica	6.50×10^6	81 events	$\sigma_f=0.36\pm0.04$
^{12}C (86 MeV/N)	^{197}Au on CR-39	1.31×10^6	81 events in 6.19 cm^2	$\sigma_t=2.92\pm0.33$[b]
^{12}C (86 MeV/N)	^{197}Au on Makrofol N	7.73×10^6	93 events in 8.62 cm^2	$\sigma_f=0.34\pm0.04$

[a]The uncertainty quoted is purely statistical; in addition, we have a (10–20) % systematic error.
[b]The total calculated geometrical cross section $\sigma_{\rm th}=\pi r_0^2(A_T^{1/3}+A_p^{1/3})^2$ with $r_0=1.43$ is $\sigma_{\rm th}=4.2$ b.

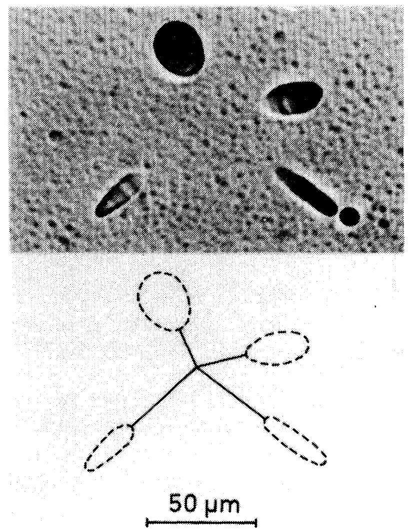

FIG. 1. A photograph (along with a sketch of the expected trajectories of the fragments and the point of origin) showing the emission of four fragments in an interaction of 107 MeV/N ^{16}O ions with ^{197}Au. The CR-39 detector was etched for 5 h in $6N$ NaOH kept at 70 ± 1 °C (similar conditions apply for Fig. 2). Most likely, all etch pits are due to light particles ($A<32$).

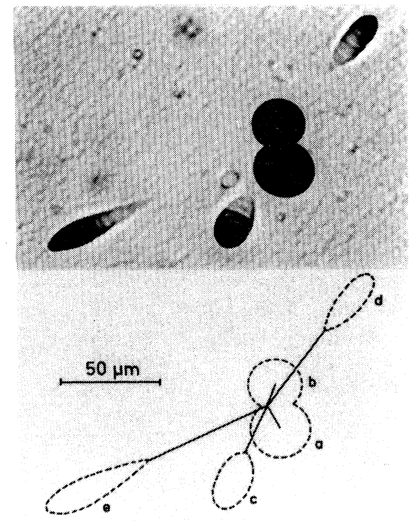

FIG. 2. A five-prong event resulted in the interaction of 107 MeV/N ^{16}O ions with ^{197}Au. Our calibration curves indicate that two of the fragments (etch pits "a" and "b") are most probably due to particles heavier than oxygen ions.

From the total number of events we have calculated the total observable interaction cross sections for the reactions as shown in Table III. These numbers include all reactions where at least one slow light and/or one heavy fragment are produced. Reactions where only fast ($E/A\geq5$ MeV) light fragments are produced are not developed under the used etching procedure. The total observable interaction cross section is about (30 ± 20) % smaller than the total geometrical cross section, as shown in Table III. This discrepancy is to be expected, due to the limitations of the experimental method and the simplicity of the calculations based on a simple geometrical model. We also measured the angle relative to the beam axis for all tracks observed in CR-39 ($Z\geq1$) and derived an overall angular distribution, as shown in Fig. 5. The track method gives information down to 0°, and we observe a strongly forward peaked distribution where the majority of reaction products are emitted in a cone subtending only 20° around the beam axis. The cutoff at 80° is due to the limitation of the 2π-detection technique employed. Our results give only an indication of the overall picture of light-particle production. More detailed results can only be obtained by counter experiments. At this stage it is premature to compare our results with any theoretical model.

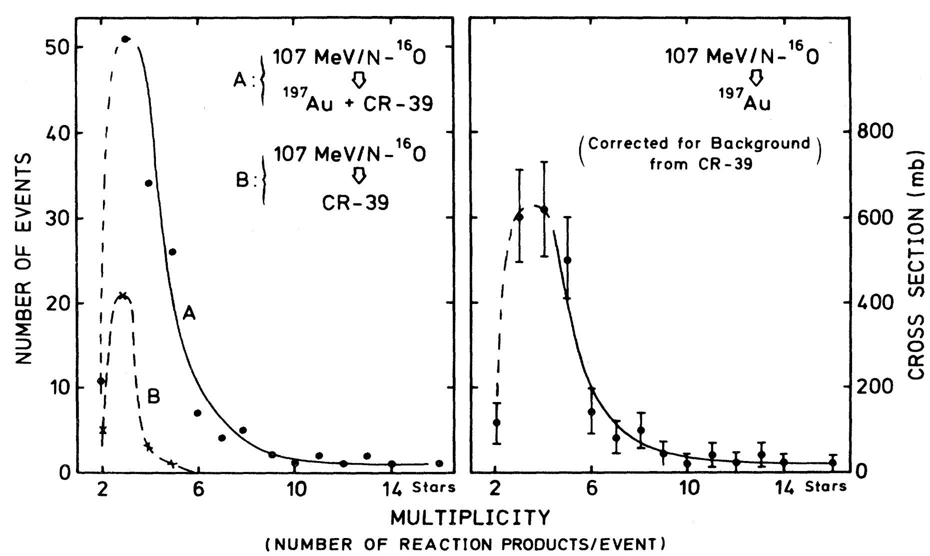

FIG. 3. Cross sections for the production of events of different multiplicities in the interaction of 107 MeV/N ^{16}O ions with ^{197}Au.

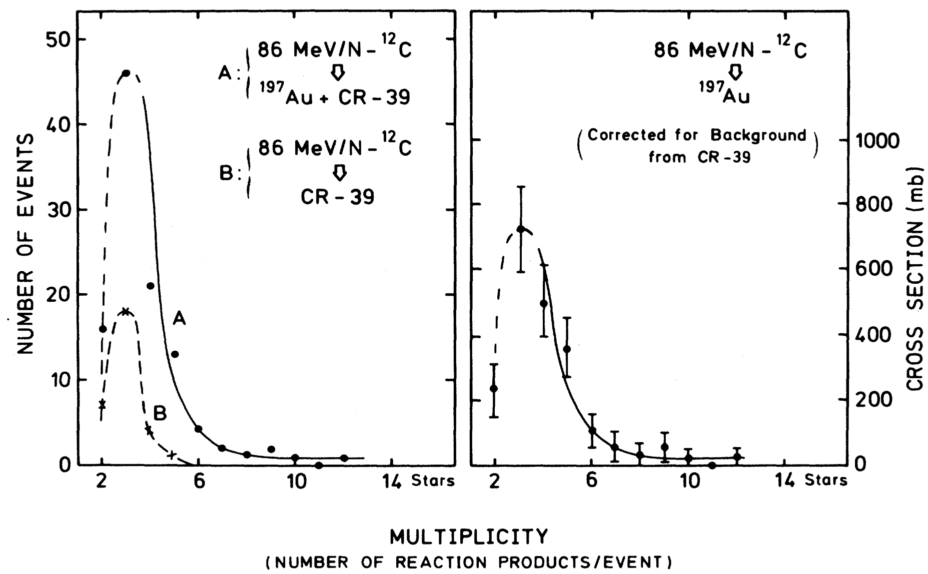

FIG. 4. Cross sections for the production of events with different multiplicities in the 86 MeV/N ^{12}C plus ^{197}Au interaction.

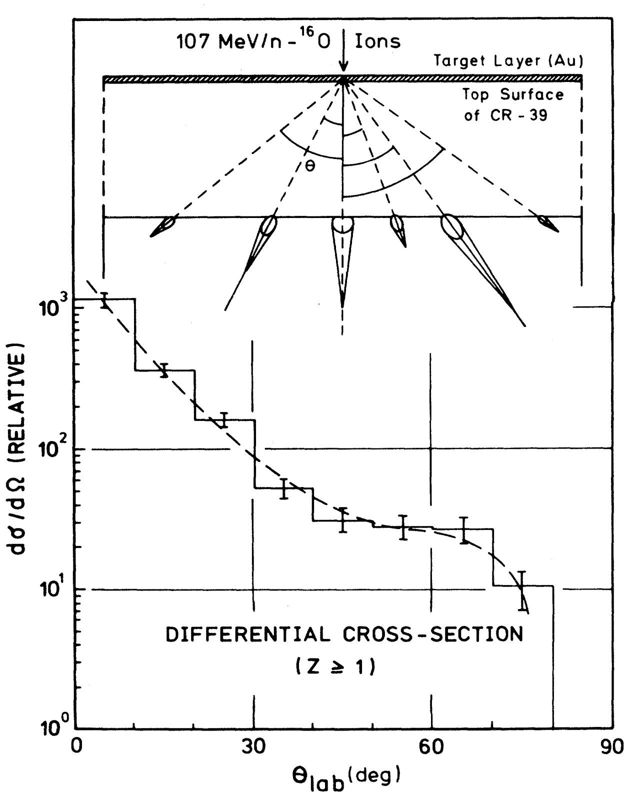

FIG. 5. Angular distribution for the reaction products ($Z \geq 1$) formed in the interaction of 107 MeV/N ^{16}O ions with ^{197}Au. A strong forward peaking is quite evident. (E/A's $\lesssim 5$ MeV/N are registered.)

IV. SUMMARY

We have used SSNTD's for the study of the interactions of the semirelativistic heavy ions (86 MeV/N ^{12}C and 107 MeV/N ^{16}O) with gold targets. From measurements with mica detectors we derived fission cross sections in good agreement with previous results. The total observable interaction cross sections were derived by counting the number of events found in CR-39 detectors. From the latter experiments we also obtained charged particle multiplicity distributions. We observe multiplicities up to 14, and the more energetic system (107 MeV/N ^{16}O) has the highest multiplicity, as is to be expected. The charge distribution shows that protons and light fragments ($Z \leq 16$) are the most abundant reaction products. The overall angular distribution is thus representative for such products and demonstrates the strong forward peaking of the system after interaction.

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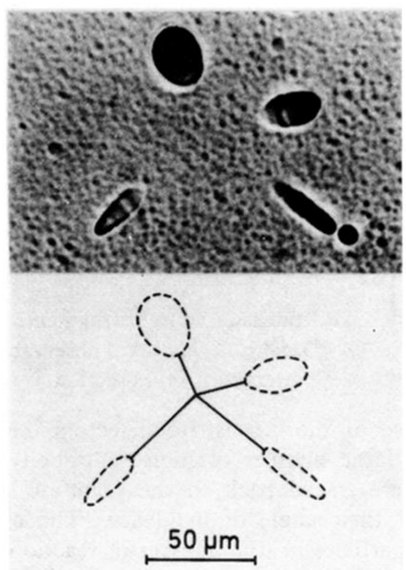

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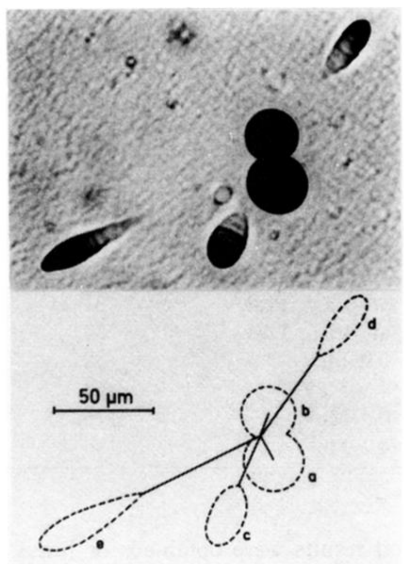

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