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PARTICLE-PARTICLE ANGULAR CORRELATIONS IN PERIPHERAL HEAVY-ION REACTIONS*

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Angular correlations between fast alpha particles and outgoing heavy reaction products have been measured for the reactions (^{16}O,^{12,13,14}Cα) and (^{16}O,^{14}Nα) on ^{208}Pb and ^{197}Au targets at 140 and 310 MeV laboratory energy. For a wide range of energy losses, coincident particles are preferentially emitted on the same side of the beam axis. The results are compared with recent qualitative predictions.

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The production of light particles in quasi-elastic and deeply-inelastic heavy-ion collisions has attracted much interest experimentally [1-6] and theoretically [7,8]. For example, it was suggested [8] that fast alpha particles should be produced in quasi-elastic and deeply-inelastic reactions by the radial component of the dissipative force. Different light particle-heavy particle angular correlations are expected if these reactions involve positive and negative deflection angles of the heavy ion [8,9]. In this letter, we investigate these aspects of heavy-ion collisions by measuring the in-plane angular correlations for the reactions $^{197}Au(^{16}O,^{12,13}C\alpha)$, $^{197}Au(^{16}O,^{14}N\alpha)$ and $^{208}Pb(^{16}O,^{12,13}C\alpha)$ at 310 MeV laboratory energy and $^{208}Pb(^{16}O,^{12,13,14}C\alpha)$ at 140 MeV.

The experiments were performed at the 88-Inch Cyclotron of the Lawrence Berkeley Laboratory. Coincident reaction products from the bombardment of a ^{208}Pb target of 3 mg/cm^2 thickness by ^{16}O ions of 140 and 310 MeV laboratory energies and from the bombardment of a ^{197}Au target of 15 mg/cm^2 thickness by ^{16}O ions of 310 MeV were detected by two solid-state ΔE-E counter telescopes. Five parameter events (two ΔE signals, two E signals and the timing signal between the two telescopes) were stored on magnetic tape and analyzed off-line. For the ^{208}Pb target the data corresponding to three-body Q-values $Q_3 \lesssim -40$ MeV were found to be significantly affected by the very large cross sections for reactions on the oxygen impurity in the target (~30 μg/cm^2). To be certain of the reliability of the data only quasi-elastic events with $Q_3 \geqslant -20$ MeV were analyzed. (The results for more negative Q-values reported in ref. 10 are, therefore, unreliable.) For the measurements on the ^{197}Au target, carbon and oxygen impurities of 10 and 18 μg/cm^2 thickness still contributed significantly in the data for $Q_3 \lesssim -150$ MeV, especially for events correlated on opposite sides of the beam axis. Therefore, only events with $Q_3 \gtrsim -100$ MeV are discussed. The contamination of the spectra was subtracted by measuring the cross sections on a carbon target and assuming equal cross sections for the carbon and oxygen contaminants in the target. This correction was always smaller than 30% and was associated with an error of 25%. The accuracy of the absolute magnitude of the cross sections is within 20%; the relative error bars are statistical and include errors due to the subtraction of random and contaminant events.

In-plane angular correlations for alpha particles detected in coincidence with carbon and nitrogen nuclei are shown in fig. 1. For coincident particles detected on opposite sides of the beam axis, θ_α is defined to be negative. For alpha particles in coincidence with carbon nuclei the angular correlations are shown for three regions of the three-body reaction Q-value: $Q_3 \geqslant -20$ MeV (Group I, figs. 1a,d,e), -60 MeV $\leqslant Q_3 < -20$ MeV (Group II, fig 1b), and -100 MeV $\leqslant Q_3 < -60$ MeV (Group III, fig. 1c). For ^{14}N-α coincidences, events with $Q_3 \geqslant -30$ MeV (Group I, fig. 1a) and -80 MeV $\leqslant Q_3 < -30$ MeV (Group II, fig. 1b) are displayed. Over the entire range of Q-values considered here, coincident alpha particles and heavy ions appear with maximum probability on the same side of the beam axis, i.e., the angular correlations exhibit a pronounced maximum at positive angles θ_α. Only for the most quasi-elastic events in the $^{12}C + \alpha$ channel (Group I, see figs. 1a,d,e), two maxima are observed in the angular correlations which are expected from the kinematics of quasi-free break-up of an excited projectile or for direct knock-out reactions with $\ell \neq 0$. For these events the angular correlations are also broader than for the other reaction channels. For more negative Q-values (Groups II and III, see figs. 1b,c), the angular correlations observed in the ^{12}C-α channel are very similar to those observed in channels that cannot be trivially attributed to a projectile break-up mechanism. It should also be noted that, at 140 MeV, the ^{12}C-α cross sections are smaller than the ^{13,14}C-α cross sections indicating that pure projectile break-up is not the dominant reaction mechanism.

In order to gain further insight into the nature of the reaction mechanism, we have made a three-body kinematic analysis [11] of the data, event by event, and determined the mean values $\langle E_{c.m.}(\alpha)\rangle$, $\langle E_{12}\rangle$ and $\langle E_{23}\rangle$. The sub-indices denote, 1, the heavy fragments (C and N nuclei), 2, the coincident alpha particles and, 3, the target residues; $E_{c.m.}(\alpha)$ is the energy of the alpha particle in the center-of-mass system and E_{ik} is the total kinetic energy of particles i and k in their common center-of-mass system. (If particles i and k result from a decay of the nucleus $(i+k)$ with excitation energy E^*, then $E_{ik} = E^* - S_{ik}$, where S_{ik} is the separation energy [11].) These quantities are shown in fig. 2 for the ^{197}Au(^{16}O,^{12,13}Cα) reaction at 310 MeV.

The values of $\langle E_{c.m.}(\alpha)\rangle$, $\langle E_{12}\rangle$ and $\langle E_{23}\rangle$ associated with ^{12}C and ^{13}C reaction products are very similar for all groups of the three-body reaction Q-value. The values of $\langle E_{12}\rangle$ exhibit a strong variation with θ_α (fig. 2b). Because of the large widths of the spectra, the mean values of $E_{c.m.}(\alpha)$ and E_{23} are not very precisely defined by the statistics of the present experiment. However, the general trend of smaller mean values $\langle E_{c.m.}(\alpha)\rangle$ and $\langle E_{23}\rangle$ for more negative Q-values and for alpha particle emission angles further removed from the maximum of the angular correlation is apparent. From the angular dependence of these mean values we infer that the alpha particles do not originate from a sequential decay of the ejectile [7] or from a transfer process followed by alpha particle emission from the system 2 + 3, in contrast to observations [2,5] at lower energies.

The narrow widths of the angular correlations (fwhm ≈ 30° - 50°; see fig. 1) indicate that the α-particles are emitted on a time scale shorter than the rotational periods of the systems (1 + 3) and (2 + 3). The values of $\langle E_{c.m.}(\alpha) \rangle$ are largest at forward angles, and correspond at all angles to energies well above the Coulomb barrier (≈20 MeV) of the system (2 + 3). At forward angles, the alpha particles are emitted with velocities close to the projectile velocity; here $\langle E_{12} \rangle$ is only slightly larger than the Coulomb barrier (≈3 MeV) of the system (1 + 2). These observations suggest that the alpha particles are mainly produced in a fast, non-equilibrium process at an early stage of the collision, where the rate of energy dissipation in deeply-inelastic collisions has already been shown to be largest [12].

It has been suggested [8] that such fast alpha particles are produced by the radial component of the dissipative force. In the piston model [8] schematically illustrated in fig. 3a, the alpha particles are predicted to be emitted from the side of the target nucleus opposite to the point of impact. If quasi-elastic and deeply-inelastic collisions are then associated with positive and negative deflection angles of the heavy ion [9], this theory of alpha particle production leads to angular correlations which peak at negative angles θ_α for quasi-elastic collisions and at positive angles θ_α for deeply-inelastic collisions [8]. For the reactions studied in the present work, the results are opposite to these predictions, since the angular correlations for quasi-elastic events (see figs. 1a,d,e), which are not associated with projectile break-up reactions, exhibit a maximum at positive angles θ_α. The same pattern holds for more inelastic events (see figs. 1b,c).

One possible interpretation of these observations is illustrated in fig. 3b, and involves the emission of fast alpha particles mainly from the region of initial impact along the direction of the classical Coulomb trajectories of the incoming projectile [1]. In a macroscopic friction model, these alpha particles could be associated with the tangential rather than the radial friction force. The experimental angular correlations are then consistent with positive deflection angles for the entire region of Q-values considered in this experiment.

In conclusion, we have shown that, in the present reaction, the emission of fast alpha particles is an important aspect of peripheral heavy-ion collisions. Although a detailed understanding of the production mechanism of fast alpha particles is not yet available, the study of pre-equilibrium alpha particle emission may provide new insight into the energy dissipation mechanisms of heavy-ion collisions.

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FIGURE CAPTIONS

Fig. 1. In-plane angular correlations for ^{16}O-induced reactions on ^{197}Au at 310 MeV (parts a-c) and on ^{208}Pb at 310 MeV (part d) and at 140 MeV (part e). Three different regions of Q-values are displayed. Group I (parts a,d,e): $Q_3(C\text{-}\alpha) \geq -20$ MeV, $Q_3(N\text{-}\alpha) \geq -30$ MeV. Group II (part b): $-60 \text{ MeV} \leq Q_3(C\text{-}\alpha) < -20$ MeV, $-80 \text{ MeV} \leq Q_3(N\text{-}\alpha) < -30$ MeV. Group III (part c): $-100 \text{ MeV} \leq Q_3(C\text{-}\alpha) < -60$ MeV. Only the ^{12}C-α correlations corresponding to Group I exhibit two maxima as expected from the kinematics of a quasi-free break-up reaction.

Fig. 2. Mean values of the center-of-mass energy $E_{c.m.}(\alpha)$ of coincident alpha particles and the excitation energies E_{12} and E_{23} of the systems 12 and 23, respectively, observed in the reactions ^{197}Au(^{16}O,^{12,13}Cα) at 310 MeV.

Fig. 3. Schematic illustration of angular correlations between fast alpha particles and heavy fragments in quasi-elastic (QE) and deeply-inelastic (DI) collisions. In (a) alpha particle production by radial friction [8] leads to alpha particles and heavy fragments from deeply-inelastic scattering preferentially on the same side of the nucleus, and on opposite sides for quasi-elastic scattering. The inverse correlations are illustrated in (b), where the alpha particles are assumed to be produced mainly at the initial stage of the collision, and to follow the Coulomb trajectory of the incident ion.

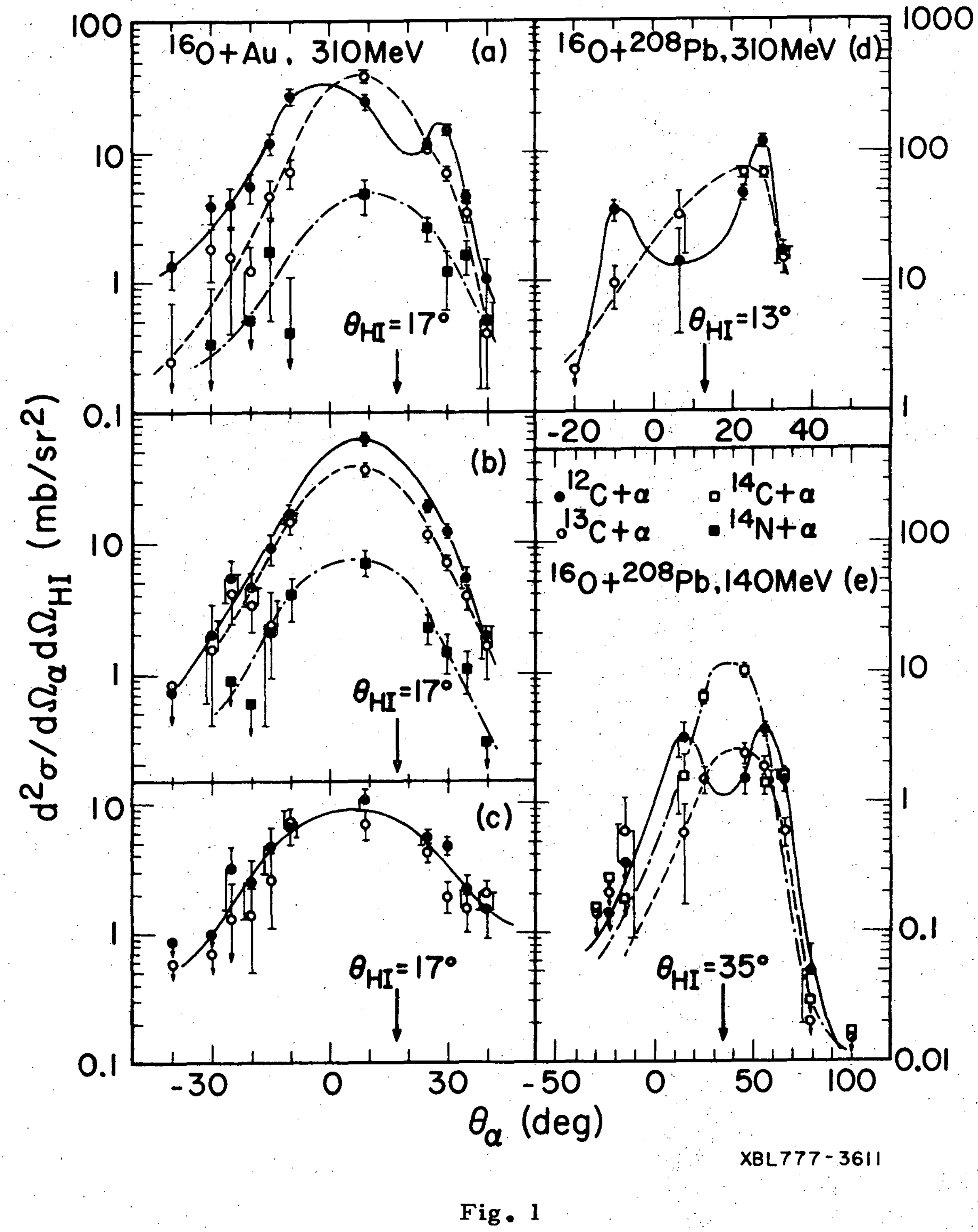
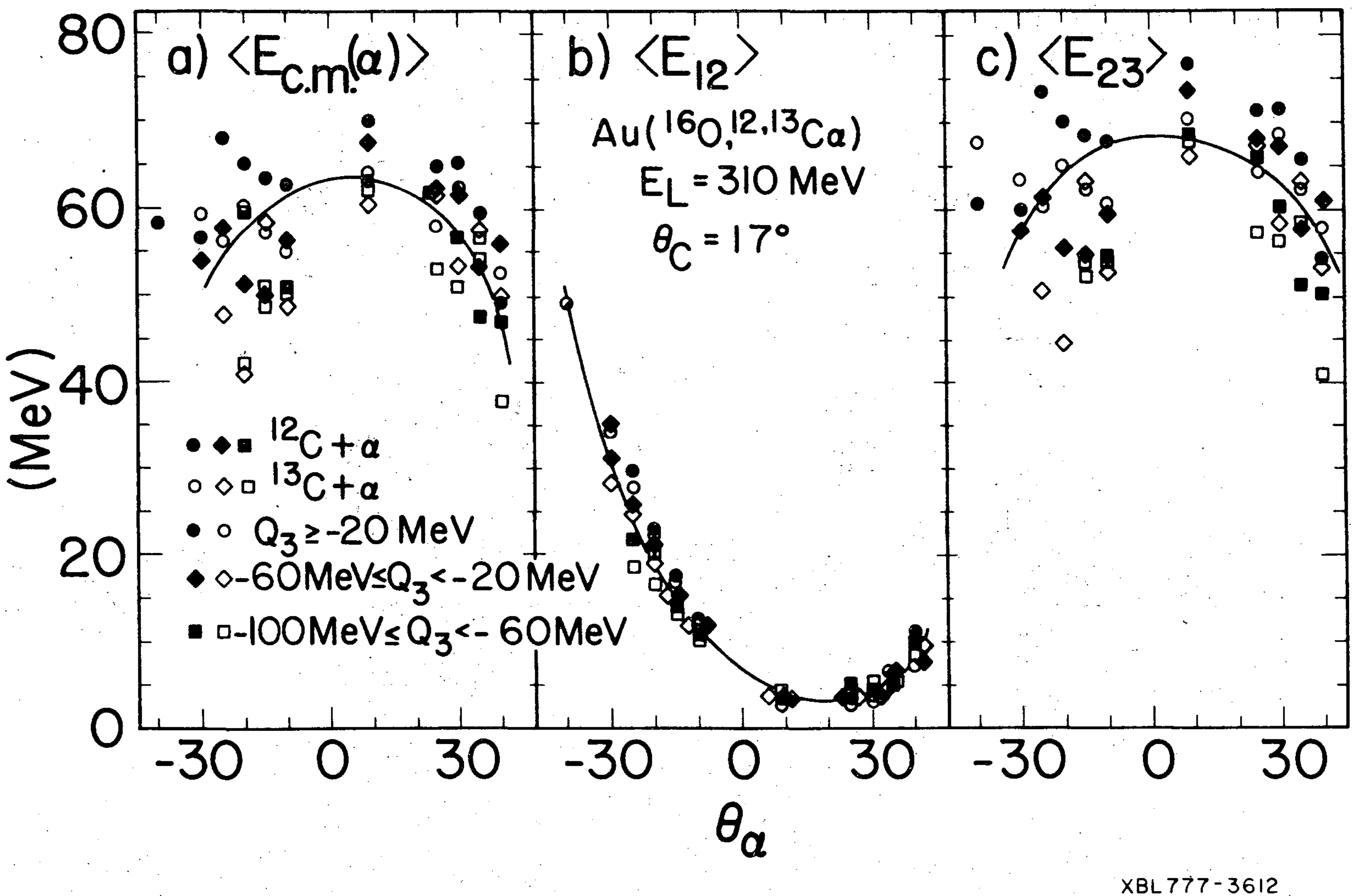
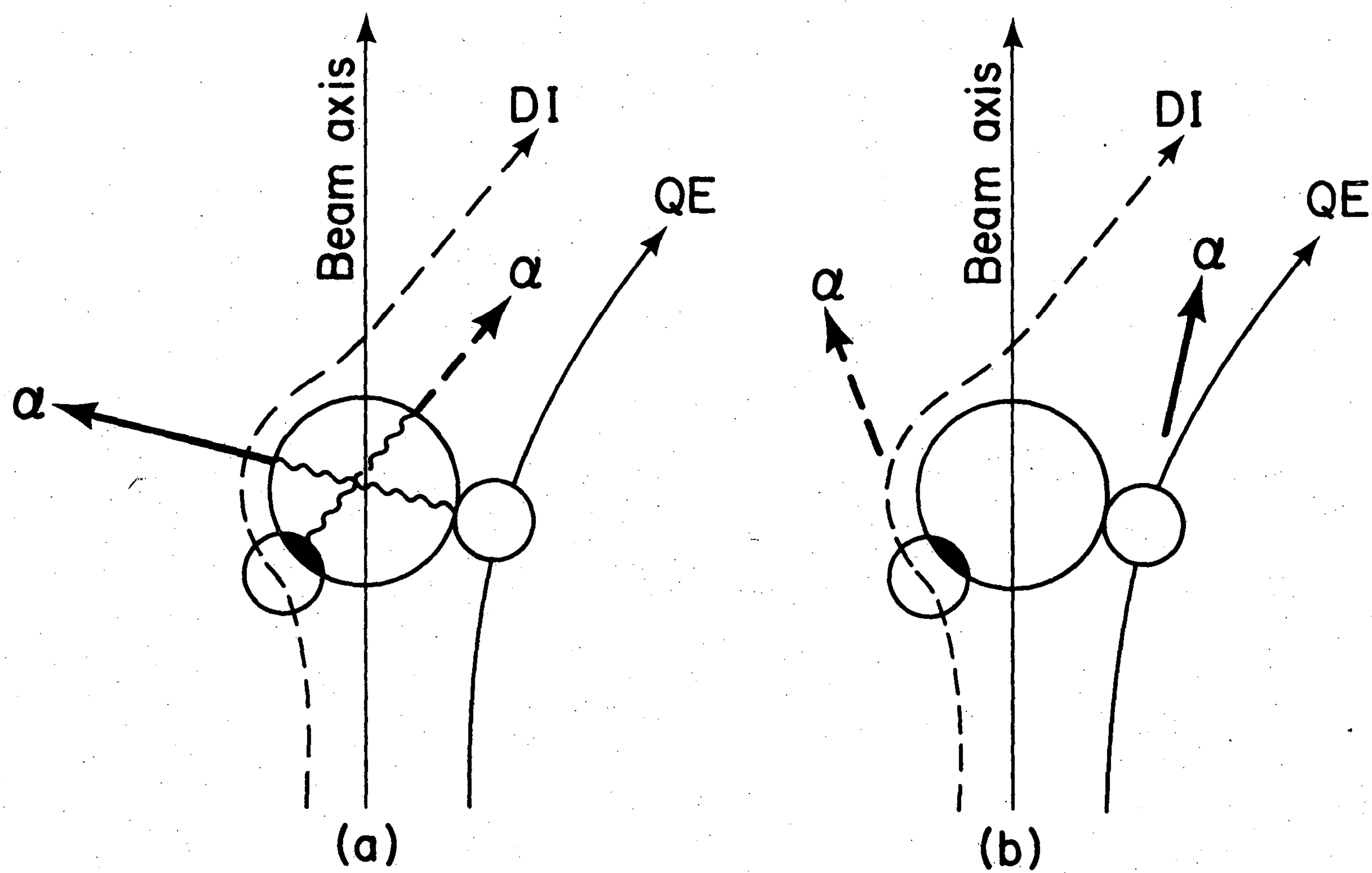

^{16}O+Au, 310MeV (a)
θ_{HI}=17°
(b)
θ_{HI}=17°
(c)
θ_{HI}=17°
^{16}O+^{208}Pb, 310MeV (d)
θ_{HI}=13°
-20 0 20 40
^{12}C+α
^{14}C+α
^{13}C+α
^{14}N+α
^{16}O+^{208}Pb, 140MeV (e)
θ_{HI}=35°
$d^2\sigma/d\Omega_\alpha d\Omega_{HI}$ (mb/sr^2)
θ_α (deg)
-30 0 30
-50 0 50 100
100 10 1 0.1
1000 100 10 1 0.01
XBL777-3611

Fig. 1



a) ⟨E c.m.(α)⟩
b) ⟨E12⟩
c) ⟨E23⟩
Au(16O,12,13Cα)
EL = 310 MeV
θC = 17°
12C + α
13C + α
Q3 ≥ -20 MeV
-60MeV ≤ Q3 < -20 MeV
-100MeV ≤ Q3 < -60MeV
(MeV)
80
60
40
20
0
-30
0
30
θα
XBL 777-3612

Fig. 2



XBL 774-695

Fig. 3

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