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PARTICLE-PARTICLE ANGULAR CORRELATIONS FOR QUASI-ELASTIC AND DEEPLY-INELASTIC SCATTERING IN THE REACTION ^{208}Pb(^{16}O,Cα) AT 20 MeV/A*

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Abstract:

In-plane angular correlations of the ^{208}Pb(^{16}O,Cα) reaction at 315 MeV incident energy provide evidence for the dominance of positive and negative classical deflection angles for quasi-elastic and deeply-inelastic reactions, respectively. The data exhibit features which are qualitatively consistent with a fast projectile fragmentation process combined with neutron pick-up by the heavy fragment.

The occurrence of two broad peaks in the energy spectra of particles produced in peripheral heavy-ion reactions has been established for a large variety of entrance channels.[1-7] In a classical model,[8,9] the high energy ("quasi-elastic") peak is believed to originate from "grazing" trajectories, corresponding to the Coulomb rainbow of the deflection function. The low energy ("deeply-inelastic") peak, on the other hand, has been attributed to more penetrating trajectories, corresponding to either the nuclear rainbow of the deflection function[9] or to orbiting.[8,10] The observation of highly energetic light particles resulting from direct (non-compound) processes,[11] should yield different light particle-heavy particle correlations for different particle trajectories and, consequently, for the quasi-elastic and the deeply-inelastic components of the energy spectra. In this letter, we report the first experimental measurement of different correlations between heavy and light reaction products associated with quasi-elastic and deeply-inelastic processes, which were induced by ^{16}O ions on ^{208}Pb at 20 MeV/A incident energy. These correlations present convincing evidence for the occurrence of negative deflection angles in deeply-inelastic processes.

The experiment was performed at the 88-Inch Cyclotron of the Lawrence Berkeley Laboratory. A ^{208}Pb target of 4 mg/cm^2 thickness was bombarded by $^{16}O^{6+}$ ions of 315 MeV incident energy. The heavy reaction products (Li to O) were identified with a solid-state detector telescope ($\Delta E, E = 70\ \mu m$, 3000 μm) positioned at laboratory angles of $\Theta_C = 13°$ and 20°. Using a second solid-state detector telescope (ΔE, E = 300 μm, 5000 μm), coincident light particles (H to Li) were detected in the reaction plane. Fast coincidences between the telescopes were determined with a time-to-amplitude converter. Five-parameter events (two ΔE and E signals, and the timing signal) were stored on magnetic tape and analysed off-line. The accuracy of the absolute magnitude of the cross sections is within ± 15%. The relative error bars are statistical and include errors due to the subtraction of random events.

The largest heavy particle-light particle coincidence cross sections are observed for the $^{208}Pb(^{16}O,C\alpha)$ reaction. Cross sections for the reactions $^{208}Pb(^{16}O,N\alpha)$ and $^{208}Pb(^{16}O,O\alpha)$ are smaller by factors of about 6 and 50, respectively. Since the singles cross sections for C and N are of comparable magnitude, this enhancement of C-α coincidences suggests that a reaction mechanism related to projectile fragmentation[12] plays a significant role at 20 MeV/A. On the other hand, integration over the alpha particle cross-section in the reaction plane yields the same ratio of ^{13}C to ^{12}C cross sections (approximately 0.6) as observed in the single particle inclusive experiment.[12] The observed similarities of the ^{12}C-α and ^{13}C-α angular correlation implies that the same primary production mechanism holds for both carbon isotopes. Since the cross sections for ^{13}C-τ coincidences are smaller than for ^{13}C-α by a factor of 10, the $^{208}Pb(^{16}O,C\alpha)$ reaction therefore does not proceed by a pure projectile fragmentation mechanism. It is conceivable that a significant neutron pick-up by the heavy-ion from the target nucleus occurs during the reaction.[13]

Energy spectra observed for coincident carbon and alpha particles at two representative pairs of angles ($\Theta_C = 13^\circ$, $\Theta_\alpha = \pm 28^\circ$) are shown in Fig. 1. (For coincident particles detected on opposite sides with respect to the beam, a negative sign is used for Θ_α). Here, E_C and E_α denote the laboratory energies of the carbon and alpha particles. For comparison, Fig. 2 shows the singles carbon spectra[7] observed at the laboratory angles of $\Theta_C = 15^\circ$ and 25°. Several points are worth noting:

(i) The carbon spectrum observed in coincidence with α-particles at $\Theta_\alpha = 28^\circ$ is dominated by a large quasi-elastic peak, whereas the deeply-inelastic component of the spectrum appears as a rather structureless continuum. The singles spectra at forward angles exhibit similar features. However, for $\Theta_\alpha = -28^\circ$, the quasi-elastic and deeply-inelastic components of the coincident carbon spectrum are of comparable magnitude.

(ii) Both the carbon energy spectrum, E_C, and the summed energy spectrum, $E_C + E_\alpha$, are dominated by a very sharp quasi-elastic peak for $\Theta_\alpha = 28^\circ$. About 50% of the coincident events correspond to energy losses to the residual nucleus of less than 20 MeV; for $\Theta_\alpha = -28^\circ$, on the other hand, no dominant quasi-elastic peak is observed and more than 50% of the coincident events correspond to energy losses of more than 100 MeV.

(iii) The energy spectrum of coincident α-particles extends to higher energies for $\Theta_\alpha = 28^\circ$ compared to $\Theta_\alpha = -28^\circ$. At both angles, the α-particle energies are higher than expected for evaporation processes from an equilibrated target residue.

In-plane angular correlations for coincident carbon and alpha particles are shown in Figs. 3 and 4 for $\Theta_C = 13^\circ$ and 20°, respectively. The correlations are presented for the three different energy intervals indicated on Fig. 1: $E_\alpha + E_C \geqslant 290$ MeV (group I), $E_\alpha + E_C = 215 - 290$ MeV (group II) and $E_\alpha + E_C \leqslant 215$ MeV (group III). The following points are of interest:

(i) The angular correlations are not symmetric about the direction of the outgoing heavy particles (see, in particular, the correlation for group I shown in Fig. 3). This asymmetry can not be reconciled with the formation of an excited projectile in statistical equilibrium which subsequently decays on a time scale long compared to the interaction time. Therefore the light particle emission must occur in the field of the target nucleus.

(ii) The angular correlations are peaked in narrow angular intervals suggesting that the coincident α-particles are produced on a time scale even shorter than the rotational period of the di-nuclear complex.

(iii) It is already evident from Fig. 1 that different angular correlations are observed for quasi-elastic events (represented by groups I and II) and deeply-inelastic events (group III). For quasi-elastic events, the angular correlations exhibit maxima at positive angles. For deeply-inelastic events, on the other hand, the maxima of the angular correlations are located at significantly smaller or even negative angles. This effect is particularly evident for the correlations shown in Fig. 4. (Although in this letter we discuss only C-α coincidences, similar results were obtained for the angular correlations of a variety of different light and heavy reaction products detected in coincidence. A detailed discussion will be given in a forthcoming paper).

The observed angular correlations provide experimental support for the hypotheses[8,9] that quasi-elastic processes correspond to grazing trajectories (i.e. to the region of the Coulomb rainbow of the classical deflection function) and that deeply-inelastic processes correspond to more penetrating trajectories which are deflected to smaller angles by the attractive nuclear potential.[14] In particular, the correlations shown in Fig. 4 present experimental evidence for the association of negative deflection angles[8] with deeply-inelastic, heavy-ion collisions. Such evidence can not be directly obtained from single particle inclusive experiments[9] in which positive and negative deflection angles are indistinguishable.[15]

In conclusion, we have shown that a measurement of the angular correlation between light and heavy reaction products lends strong support for the association of negative deflection angles with deeply-inelastic collisions and positive deflection angles with quasi-elastic collisions. At the incident energy of 20 MeV/A, our coincidence experiments imply a reaction mechanism closely related to projectile fragmentation, in which, however, there is evidence for neutron pick-up by the heavy fragment. The majority of the light particles observed in coincidence with a heavy fragment appear to be produced on a time scale commensurate with direct reactions.

Footnotes and References

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13. At relativistic energies, nucleon pickup processes are expected to be of negligible importance. The importance of neutron pickup from the ^{208}Pb target (N/Z = 1.5) at 20 MeV/A could, e.g., be related to the observation[12] of larger relative cross sections for neutron-rich isotopes at 20 MeV/A as compared to 2.1 GeV/A.

14. The diffractive spreading of the wave packets is, however, still an important effect.[7]

15. The present interpretation relies on the assumption that the light particles are produced on a time scale short enough to retain some "memory" of their point of origin. It should, however, be kept in mind that the light particle can equally well be deflected in the nuclear field of the target nucleus. Although such an interpretation of the angular correlation patterns for quasi-elastic and deeply-inelastic scattering can not be categorically ruled out, we believe it less likely since the difference between the coincidence α-spectra (see Fig. 1) are less dramatic than for the carbon spectra, and in addition, the position of the maximum α-particle coincidence cross section decreases from $\Theta_\alpha \approx -5^\circ$ to $\Theta_\alpha \approx -20^\circ$ for an increase of the detection angle for deeply-inelastic carbon nuclei from $\Theta_C = 13^\circ$ to $\Theta_C = 20^\circ$ (compare Figs. 3 and 4).

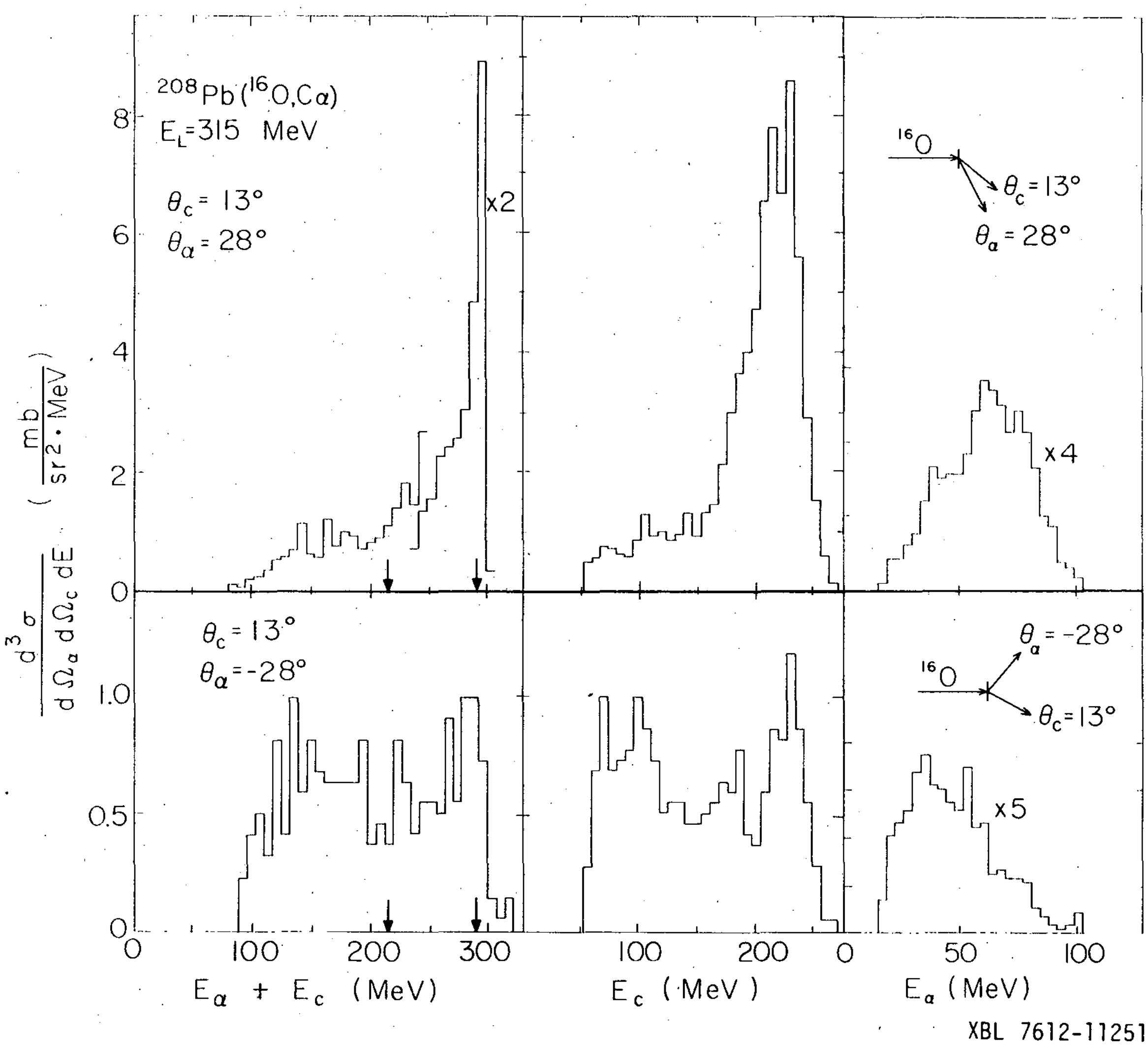
Figure Captions

Fig. 1. Summed energy spectra, $E_\alpha + E_C$, carbon energy spectra, E_C, and alpha-particle energy spectra, E_α, observed for the reaction $^{208}Pb(^{16}O,C\alpha)$ at 315 MeV incident energy. Outgoing carbon nuclei were detected at the laboratory angle $\Theta_C = 13^\circ$ in coincidence with alpha particles observed at the angles of $\Theta_\alpha = \pm 28^\circ$.

Fig. 2. Energy spectra for the reaction $^{208}Pb(^{16}O,C)$ at 315 MeV incident energy measured at the laboratory angles of 15° and 25°.

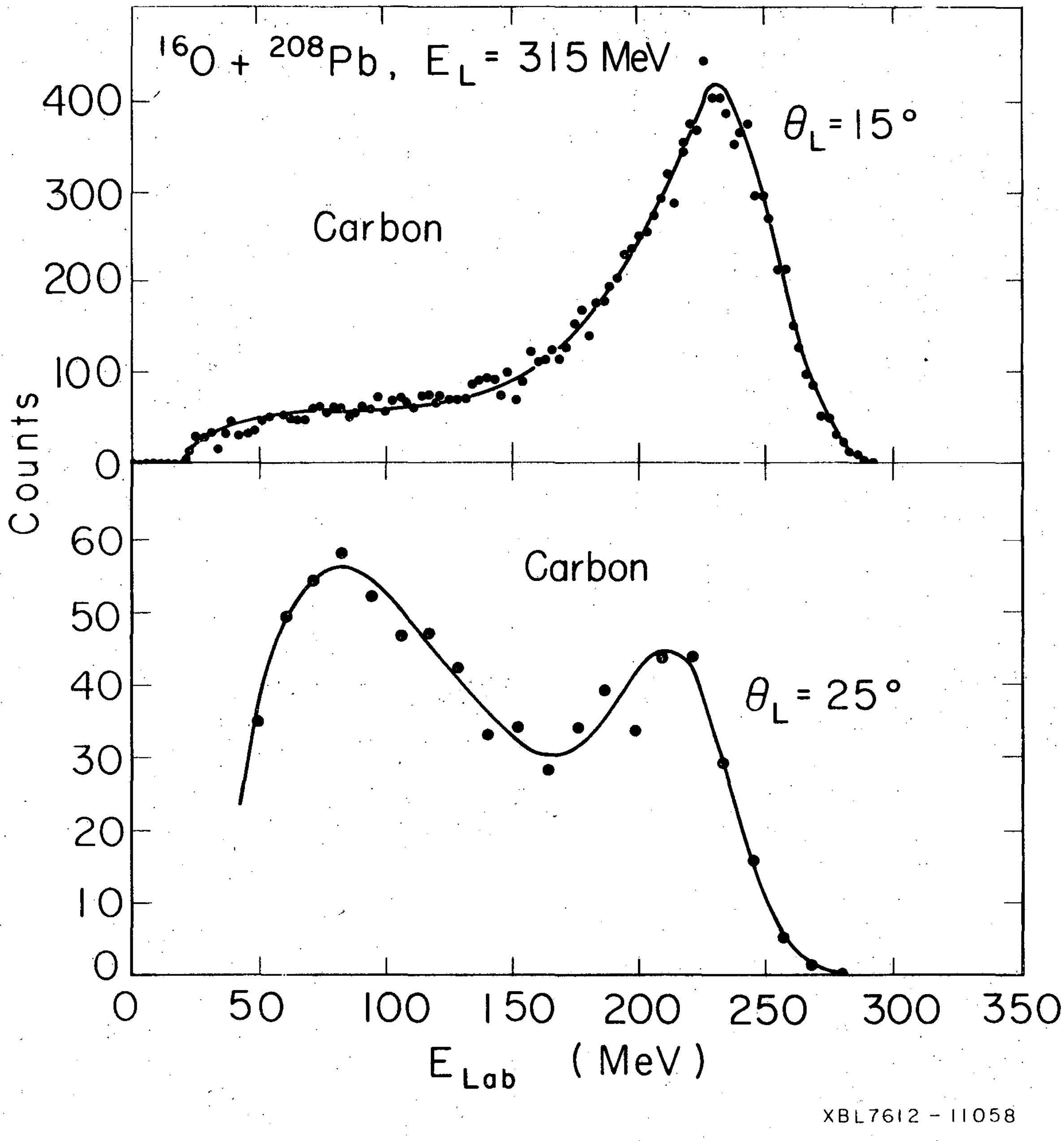
Fig. 3. In-plane angular correlations of the reaction $^{208}Pb(^{16}O,C\alpha)$ at 315 MeV incident energy. Outgoing carbon nuclei were detected at the laboratory angle of $\Theta_C = 13^\circ$.

Fig. 4. In-plane angular correlations of the reaction $^{208}Pb(^{16}O,C\alpha)$ at 315 MeV incident energy. Outgoing carbon nuclei were detected at the laboratory angle of $\Theta_C = 20^\circ$.



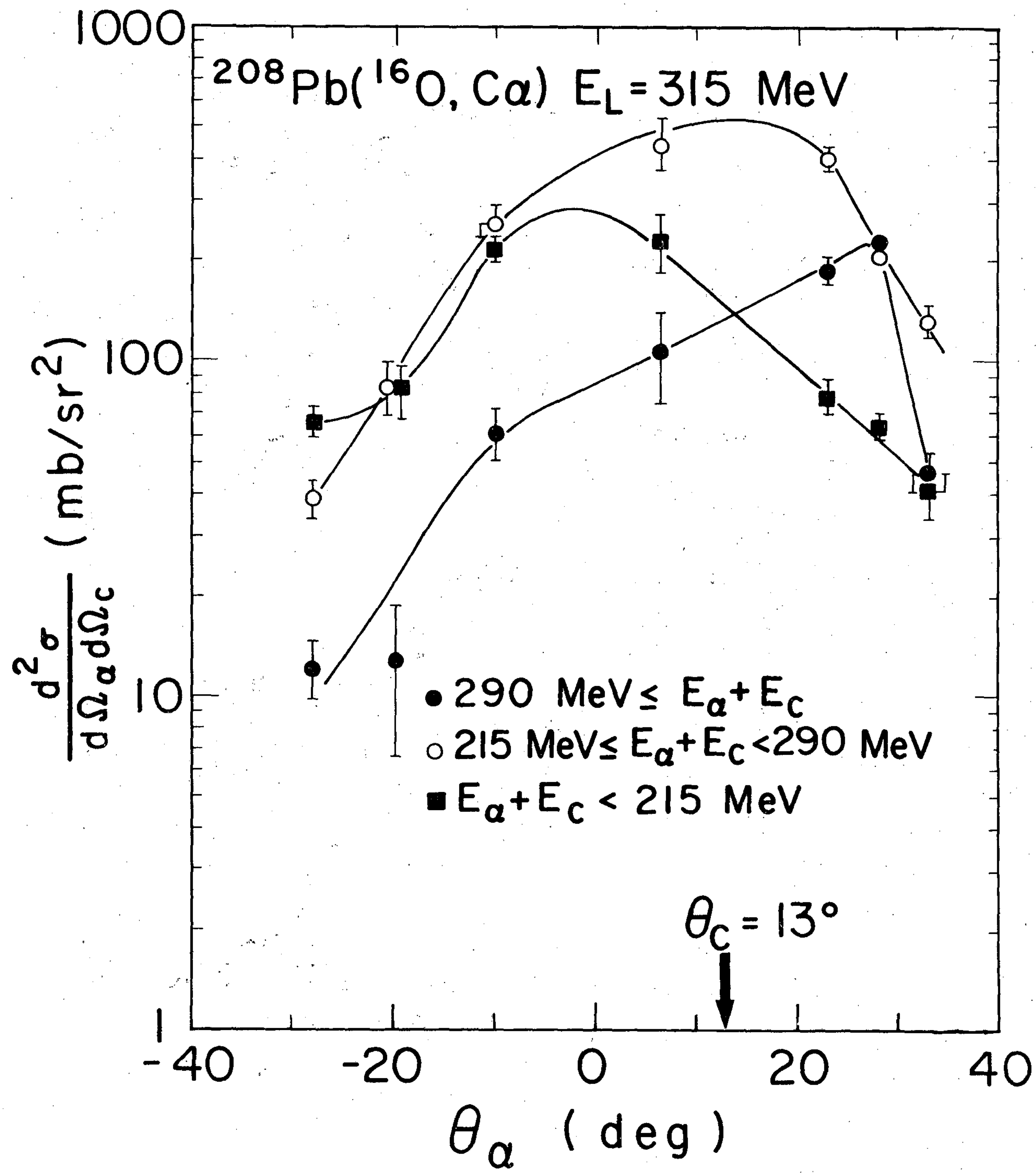
$^{208}Pb(^{16}O,C\alpha)$
E_L=315 MeV
θ_c = 13°
θ_α = 28°
x2
x4
^{16}O
θ_c = 13°
θ_α = 28°
θ_c = 13°
θ_α = -28°
θ_α = -28°
θ_c = 13°
x5
$\frac{d^3\sigma}{d\Omega_\alpha d\Omega_c dE}$ $\left(\frac{mb}{sr^2 \cdot MeV}\right)$
$E_\alpha + E_c$ (MeV)
E_c (MeV)
E_α (MeV)
XBL 7612-11251

Fig. 1



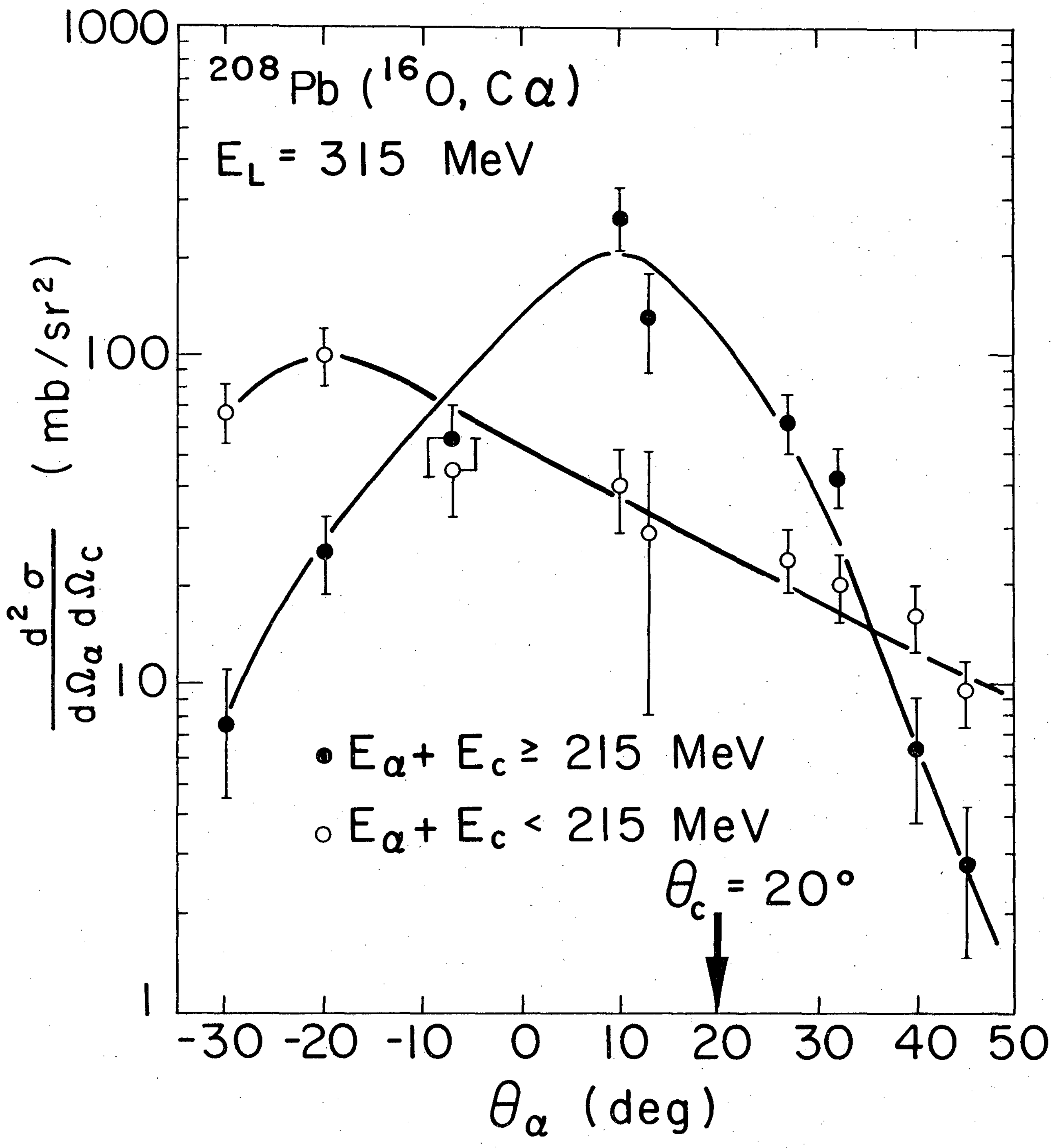
^{16}O + ^{208}Pb, E$_L$ = 315 MeV
θ$_L$ = 15°
Carbon
Carbon
θ$_L$ = 25°
Counts
400
300
200
100
0
60
50
40
30
20
10
0
0
50
100
150
200
250
300
350
E$_{Lab}$ (MeV)
XBL7612 - 11058

Fig. 2



XBL 7612-4547

Fig. 3



XBL 7612-11125

Fig. 4

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