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Abstract

The velocities of fusion-like residues produced at 15° in the reaction 313 MeV $^{16}O + ^{40}Ca$ have been measured in coincidence with alpha particles emitted over a wide range of angles. The maximum of the residue velocity distribution depends on the energy and angle of emission of the alpha particle. Analysis of this dependence indicates that a significant portion of the fast alpha particles at forward angles result from the fusion of ^{8}Be and the associated production of a ^{8}Be ejectile.

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Introduction

At bombarding energies exceeding the interaction barrier by 5 MeV/nucleon or more, the heavy residues formed in the fusion of an ^{16}O beam and a ^{40}Ca target emerge with an average velocity less than that expected for complete fusion.[1] This velocity shift and corresponding missing momentum are associated with the process of incomplete fusion,[2] and are general features of inclusive residue spectra in reactions between light projectiles and heavier targets.[1,3] The momentum missing from the residue is undoubtably carried by fast light particles (protons, neutrons, alpha particles) observed in inclusive reactions[4,5] at forward angles. In order to study the various reaction mechanisms that may contribute to incomplete fusion, a more detailed knowledge of the distribution of momentum among the heavy residues and the fast light particles is needed. To this end a coincidence measurement was performed with the detection of residues at 15° (lab) and alpha particles over a range of angles extending from 5° to 115°.

Experiment

A beam of ^{16}O ions at 313 MeV was provided by the 88-Inch Cyclotron at the Lawrence Berkeley Laboratory and used to bombard a Ca target (400 $\mu g/cm^2$) positioned in the 60-inch scattering chamber constructed at the Institute of Nuclear Physics, Cracow. The velocities and masses of the fusion-like residues (FLR) were measured at -15° by a time-of-flight spectrometer (1.3 m flight path, 0.3 msr solid angle, channel plate start detector, 100μ thick surface barrier stop detector). Alpha particles

were detected in the reaction plane at angles of -5°, 5°, 15°, 30° and 115°. The telescopes used to observe the alpha particles consisted of silicon surface barrier detectors having thicknesses of 40μ to 50μ for the first element and 600μ to 2000μ for the second silicon element. Solid angles subtended by the telescopes varied from 0.45 msr at -5° to 17.6 msr at 115°.

Results

Inclusive and coincidence velocity spectra for the FLR are shown in Figs. 1a-d. The dashed curves represent Gaussian fits to these spectra. Fig. 1a presents the inclusive spectrum at 15°. The arrow labeled V_I denotes the most probable or maxium value of the inclusive velocity distribution. The average velocity expected for the inclusive spectrum $d^2\sigma/dvd\Omega$ at this angle for complete fusion, according to the code LILITA, is denoted by V_{CF}. Note the downward shift in velocity ($V_I < V_{CF}$) of the maximum of the inclusive spectrum relative to the expectation for complete fusion.

Fig. 1b shows that the velocity spectrum is shifted upward relative to the inclusive spectrum when a coincidence is required with alpha particles at 115°. A coincidence with alpha particles at the forward angle of 5°, however, causes the peak of the velocity spectrum to shift downward from the value for the inclusive spectrum (Fig. 1c,d). The downward shift is much larger for a coincidence with alpha particles having an energy of 50 MeV or more, as may be seen by comparing Figs. 1c and 1d, and Figs. 2a and 2b. The same effect is present, though less pronounced, when the alpha particles are detected at 30° (see Fig. 3).

The corresponding energy spectra for the coincident alpha particles are given in Figs. 4 and 5. Although the inclusive alpha-particle spectra at these angles are rather featureless, the coincidence spectra at forward angles exhibit two groups, a low energy group due to evaporation from the heavy residue and a high energy part centered about 20 MeV per nucleon.[5)]

Discussion

It is useful to consider the results one would expect if all residues were the products of complete fusion followed by statistical evaporation. A coincidence with alpha particles evaporated at backward angles would cause the residue spectrum at forward angles to shift upward in velocity. The average increase in residue momentum (projected on the beam axis) represented by this shift would be equal and opposite to the average projected momentum of the coincident alpha particles. A coincidence with alpha particles at forward angles would cause a downward shift in the residue velocity distribution, the size of which would be determined by the same type of momentum balance. Now consider an ensemble of heavy nuclei prior to evaporation and having two components: a portion that moves with the velocity of the center of mass V_{CM} (as a result of complete fusion) and the remainder that moves slower, e.g., with $V = V_{ICF} < V_{CM}$, because only a portion of the projectle was captured. The average source velocity is now less than V_{CM}. Requiring a coincidence with the fragment of the projectile that did not fuse will

produce (in first order) a residue spectrum with a peak at the velocity V_{ICF}, and a width characteristic of the post-collision evaporation. A coincidence with an evaporated particle, however, will produce (again in first order), a velocity spectrum of residues containing components of both complete and incomplete fusion and shifted by an amount corresponding to the average momentum of the coincident evaporated particle. This assumes, of course, that the evaporative processes following complete and incomplete fusion are not too different.

It is thus clear that we must be able to account quantitatively for the shifts in the peaks of the velocity spectra in Fig. 1a expected on the basis of statistical evaporation in order to draw conclusions about incomplete fusion. A simple Monte Carlo evaporation model was constructed in order to estimate these effects. For this purpose it was assumed that the energies of the emitted particles could be approximated for each step of the evaporation cascade by the formulae: $(E_{CM} - E_{Coul})^{1/2} \exp[-(E_{CM} - E_{Coul})/T]$ where E_{CM} indicates the energy of light particle in the center of mass of the evaporating system, E_{Coul} denotes the height of the Coulomb barrier in the case of charged ejectiles, and T is the temperature. The energies of the recoil nucleus and the light particle were calculated for each step in the evaporation cascade and subsequently transformed to the laboratory system. The ratio of protons to neutrons to alpha particles was taken to be 1:1:1, since in our case we are dealing with a highly excited N = Z system. The result is unchanged if instead this ratio was chosen to be 1:4:1. The temperature, excitation energy and velocity of the initial ensemble of

heavy nuclei were chosen to be $T = 5.8$ MeV, $E_x = 238$ MeV and $v_{CM} = 1.75$ cm/ns, i.e., the values appropriate for complete fusion. The separation energies for the various particles were held constant throughout the decay process. The temperature was continuously adjusted during the evaporation process according to the formula $T = (U_x/a)^{1/2}$ where U_x denotes the excitation energy of the nucleus at each stage of the cascade and a is the level density parameter taken as A/8. Since the effects we wish to calculate are only kinematic, the above approximations are not too severe.

Using the above procedure, the ratios of the peak velocities for coincidence and inclusive residue spectra ($d^2\sigma/dVd\Omega$, as in Fig. 1) were calculated and then compared with the experimental values. This comparison is given in Table 1. The errors on the evaporation calculations are due to the statistics in the Monte Carlo method. Note that the results of evaporation calculations are given only in those cases for which the associated alpha particles have energies consistent with evaporation. In these cases the agreement is good, and may be understood in terms of a simple momentum balance between the residues and the alpha particles evaporated by the ensemble of highly excited nuclei produced in the collision through both complete and incomplete fusion.

The ratios 0.78, obtained for $E_\alpha > 50$ MeV and $\theta_\alpha = 5^o$ and 15°, respectively, obviously cannot be explained by the evaporation of an alpha particle. More remarkably, however, they cannot be explained in terms of a momentum balance between a residue and a single, beam velocity alpha particle. The reason is as follows. The postion of the peak in

the inclusive velocity distribution corresponds to an average ensemble velocity of 0.79 v_{CM} (see ref. 1). Requirement of a coincidence with a fast alpha particle at 5° produces a residue peak velocity that is lower than the inclusive peak velocity by the factor 0.78 ± 0.06. This corresponds to a source velocity of (0.78 ± 0.06) x 0.79 V_{CM} = 0.62 V_{CM}. The emission of one alpha particle at beam velocity or with the energy distribution given in Fig. 2a for E_α > 50 MeV would produce a source moving with an average velocity of 0.81 V_{CM} or 0.82 V_{CM}, respectively. To reproduce the measured value of 0.62 V_{CM}, the additional emission of either a second alpha particle (or four strongly correlated nucleons) having approximately the beam velocity is required.

The most likely and reasonable explanation of the observed large velocity shifts is that a significant number of the fast alpha particles detected at 5° and at 15° result from the decay of a ^{8}Be that has been produced by an incomplete fusion reaction. Not only would this explanation account well for the observed ratios in Table 1, it is anticipated both by earlier studies of incomplete fusion reactions[2)] and by the predictions of several reaction models.[2,6)]

Two factors give the present experiment additional sensitivity to the observation of ^{8}Be. The first is the production of two fast alpha particles from the decay of ^{8}Be, which increases by a factor of two the probability of observing one of the resultant alpha particles. The other reason is associated with the choice of angles for the time of flight spectrometer and the alpha particle telescope. From the energy and angle of the observed fast alpha particle one may calculate the initial

direction of the heavy residue in the case of either ^{12}C capture (alpha particle ejectile) or ^{8}Be capture (^{8}Be ejectile). This angle can then be compared with the angle of the time of flight spectrometer. The difference needs to be made up by recoil from evaporated particles. For an alpha particle detected at 5°, the angles between the initial direction of the residue and the residue detector are 13.3^{o} and 10.4^{o} for single alpha particle emission or ^{8}Be emission, respectively. If the alpha particle is detected at 15°, however, these same angles are 10.2^{o} and 2.2^{o}. Thus when both detectors are at 15° on opposite sides of the beam, the kinematics of the reaction favors the observation of ^{8}Be rather than a single alpha particle. This may be the reason for the (suggested) slightly larger shift in velocity (0.72 ± 0.07 versus 0.78 ± 0.06) at $\theta_{\alpha} = 15^{o}$ than at $\theta_{\alpha} = 5^{o}$. Better counting statistics, however, would be required to establish the existence of a larger velocity shift at 15°.

Summary

The velocity spectra of fusion-like residues have been measured at 15° in the reaction 313 MeV $^{16}O + ^{40}Ca$ both in singles and in coincidence with alpha particles. The shifts in the peak velocity for inclusive and coincidence spectra can in most cases be explained by the momentum balance associated with the evaporation of alpha particles by a sample of heavy residues containing both complete and incomplete fusion components. The velocity shifts associated with fast alpha particles at forward angles, however, are too large to be explained solely by an incomplete fusion process that produces a single beam velocity alpha

particle. The results can be explained by assuming that the observed alpha particle is predominantly the decay product of ^{8}Be. Various other experiments and reaction models suggest this is a likely explanation. Direct proof of this can be obtained by the detection of the two alpha particles that comprise the ^{8}Be.

Acknowledgements

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References

1. Y. Chan, M. Murphy, R. G. Stokstad, I. Tserruya, S. Wald, and A. Budzanowski, Phys. rev. C27, 447 (1983).

2. K. Siwek-Wilczynska, E. H. du Marchie van Woorthuysen, C. van Popta, R. H. Siemssen, and J. Wilczynski, nucl. Phys. A330, 150 (1979); J. Wilczynski, K. Siwek-Wilczynska, J. van Driel, S. Gonggrijp, D. C. J. M. Hageman, R. V. F. Janssens, J. Lukasiak, R. H.Siemssen, and S. Y. Van der Werf, Nul. Phys. A373, 109 (1982).

3. H. Morgenstern, W. Bohne, K. Grabish, D. G. Kovar, and H. Lehr, Phys. Lett., 113B, 463 (1982); Phys. Rev. Letts. 52 1104 (1984), V. Viola, Jr., B. B.Back, K. L. Wolf,T. C. Awes, C. K. Gelbke, and H. Breuer, Phys. Rev. C26 178 (1982).

4. R. Vandenbosch, Proceedings of the Conference on Nuclear Physics with Heavy Ions (Prospects at Energies below 20 MeV/nucleon), Stony Brook, N.Y., 1983. Nucl. Sci. Conf. Series 6 Ed, P. Braunmunzinger, Harwood Acad. Publ. Co. (1984).

5. P. L. Gonthier, H. Ho, M. N. Namboodiri, J. B. Natowitz, L. Adler, S. Simon, K. Hagel, S. Kniffen, and Khodai, Nucl. Phys. A411, 289 (1983); J. B. Natowitz, Nucl. Phys. A387, 65 (1982).

6. B. G. Harvey and H. Hoymer, preprint LBL-16882.

Table 1

Ratios of the most probable velocity of the fusion-like residues observed in coincidence with alpha particles to those observed in singles. The experimental ratios and the corresponding ratios calculated with a Monte Carlo evaporation model are given where a comparison is possible.

θ_α		E_α(MeV) >50	<50	>30	<30	all
5°	experiment	.78±.06	.93±.06			.80±.04
	evap. calc.		.90±.02			
15°	experiment	.72±.07	.95±.03			.83±.03
	evap. calc.		.92±.02			
30°	experiment			.95±.02	.96±.03	.96±.03
	evap. calc.				.94±.02	
115°	experiment					1.17±.04
	evap. calc.					1.10±.04

Figure Captions

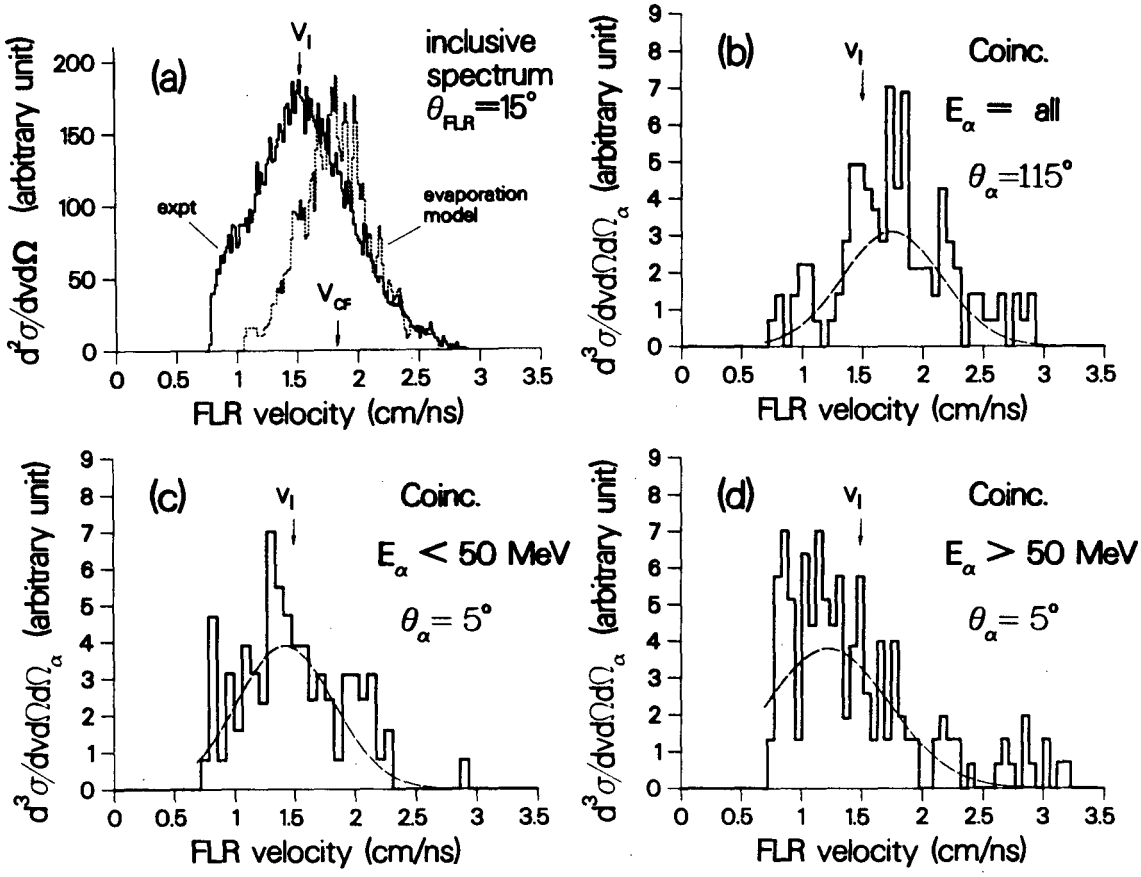
Fig. 1. Velocity spectra of the fusion-like residues. Solid line, experiment; dashed line, Gaussian fits. a) inclusive spectrum; the complete fusion spectrum, as predicated by the statistical model code, Lilita, is indicated by the dotted curve; b) in coincidence with alpha particles emitted at 115°; c) in coincidence with alpha particles of energies smaller than 50 MeV emitted at 5°; d) in coincidence with alpha particles of energies higher than 50 MeV emitted at 5°. Arrows indicate: V_I, peak position in the inclusive spectrum; V_{CF}, peak velocity expected for complete fusion.

Fig. 2. Velocity spectra of FLR in coincidence with alpha particles emitted at 15°.

Fig. 3. Velocity spectra of FLR in coincidence with alpha particles emitted at 30°.

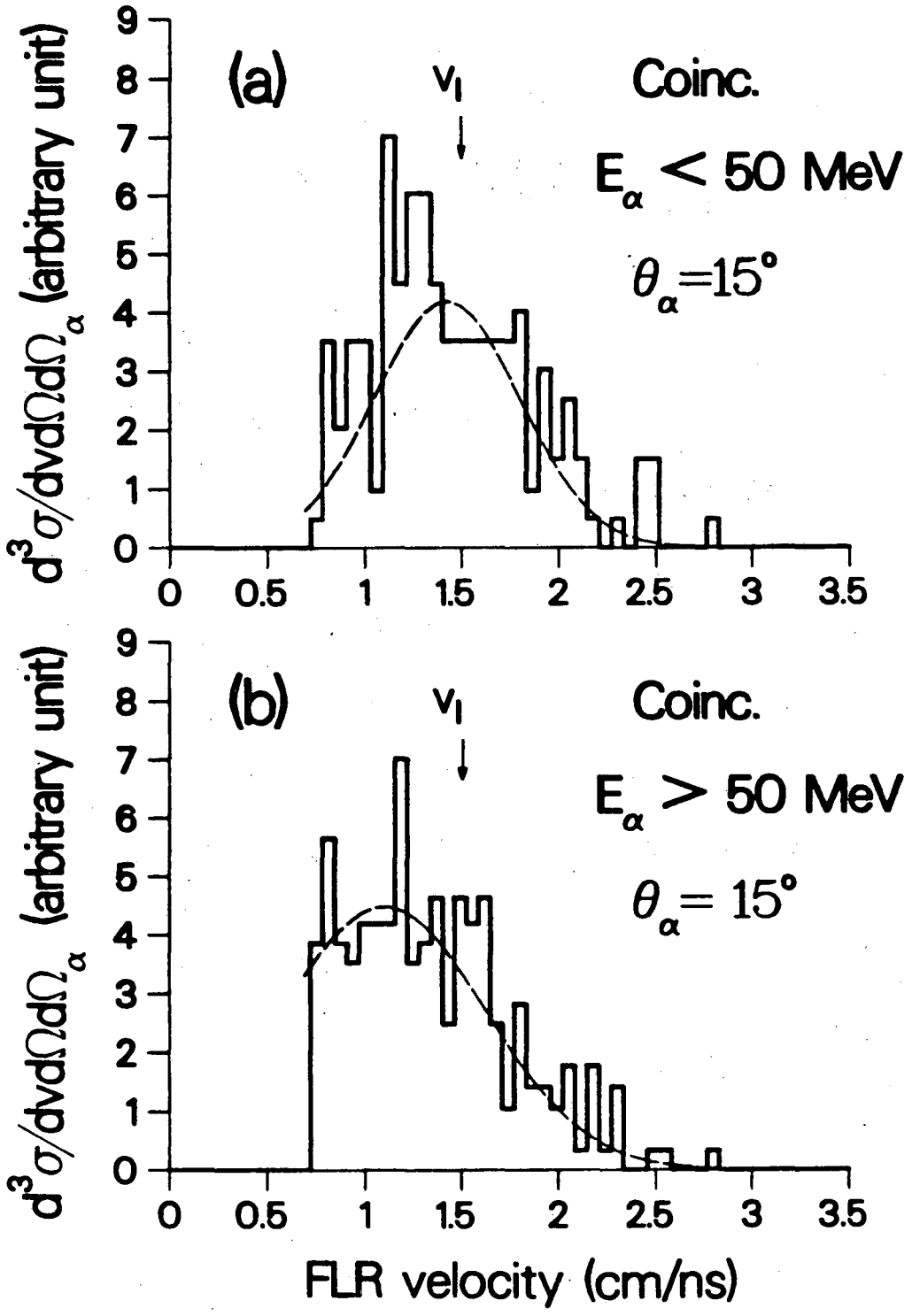
Fig. 4. Energy spectra of alpha particles emitted at 5° and 115°. Inclusive spectra are indicated by the solid line. The dashed line denotes spectra in coincidence with FLR detected at 15°.

Fig. 5. Energy spectra of alpha particles emitted at 15° and 30°.



XBL 855-2631

Fig. 1.



XBL 855-2629

Fig. 2.

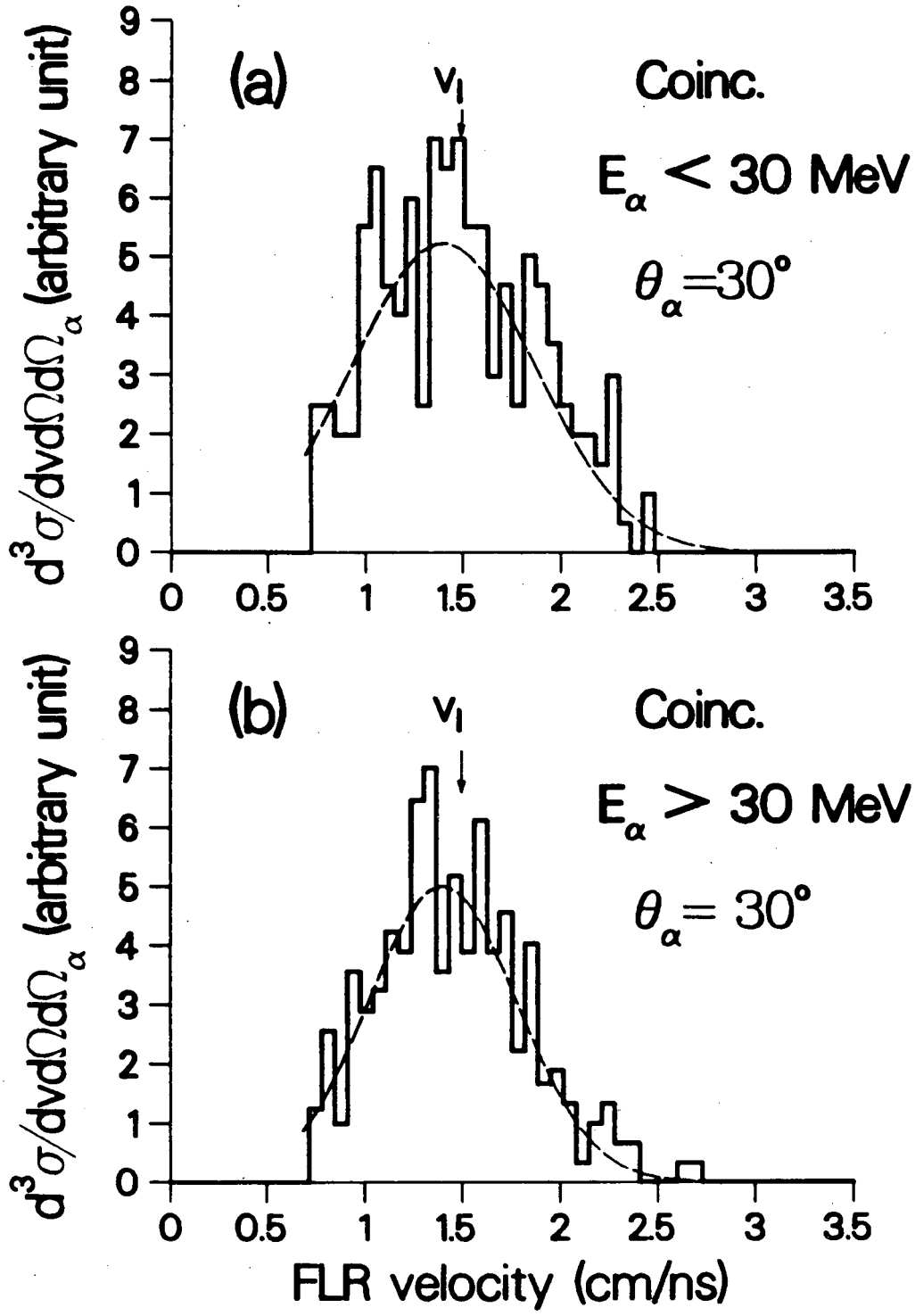
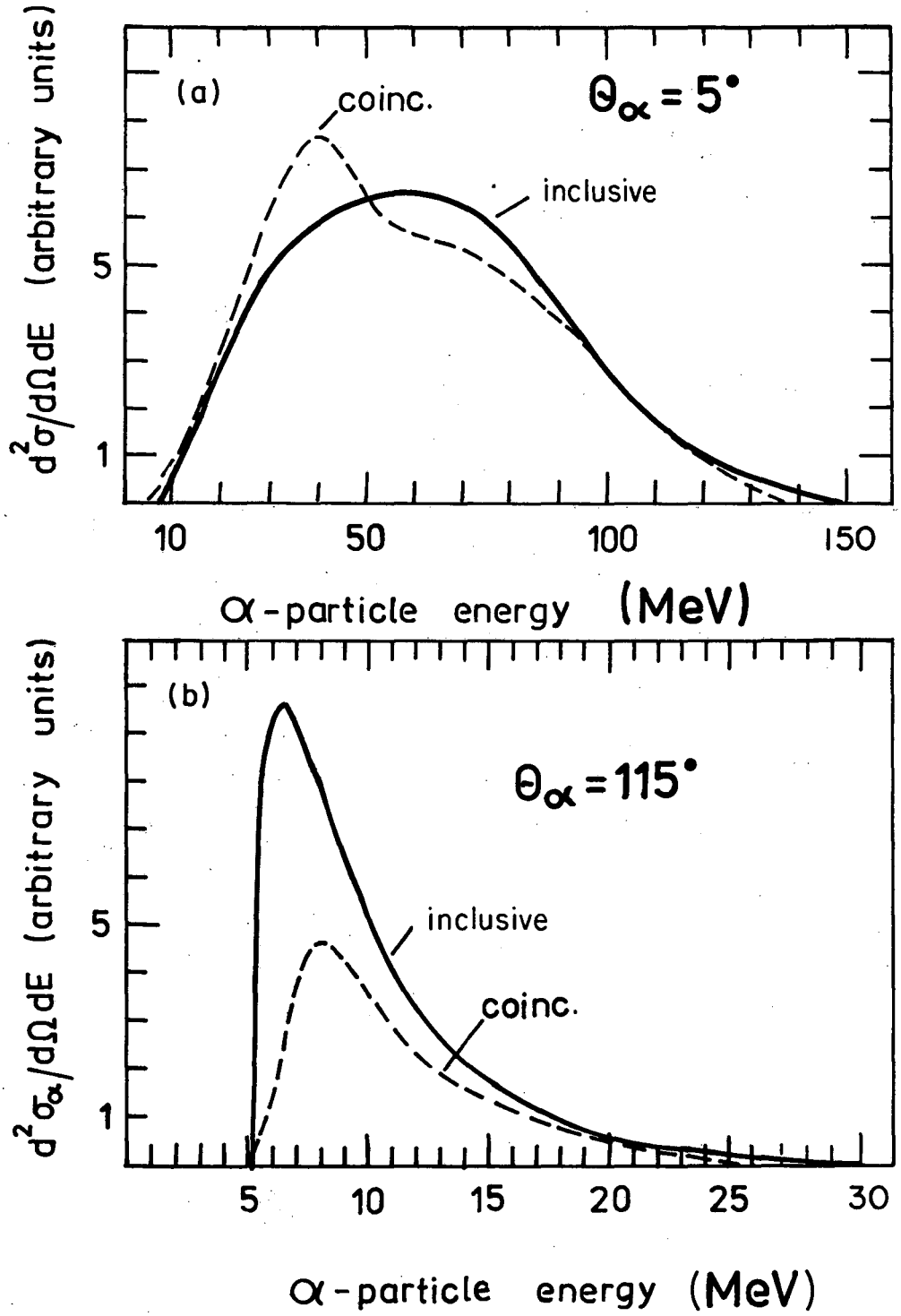


Fig. 3.

XBL 855-2630



XBL 845-8910

Fig. 4.

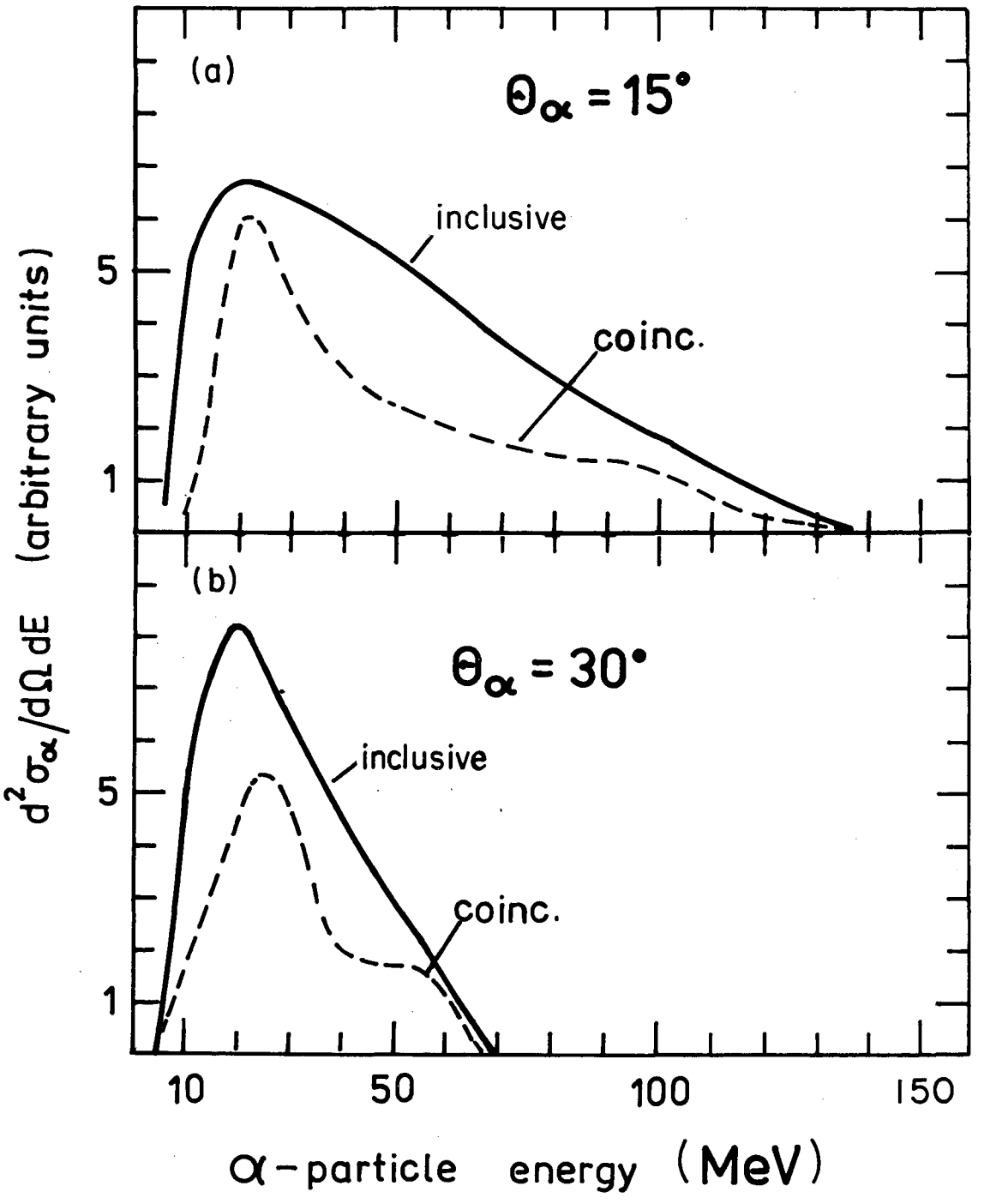


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Fig. 5.

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