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SEARCH FOR FRAGMENT EMISSION FROM NUCLEAR SHOCK WAVES*

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ABSTRACT

Energy spectra and angular distributions have been measured of ^{3}He and ^{4}He fragments emitted from Ag and U targets, bombarded with protons of 2.7 GeV, α particles and ^{16}O ions of 1.05 GeV/nucl. All cross sections increase drastically with higher projectile mass. In particular, the ^{3}He cross sections at about 150 MeV/nucl increase by three orders of magnitude upon going from protons to ^{16}O as projectiles. No sharp forward peaks are found in the angular distributions.

For a central collision of nuclei at relativistic energies, the interaction region is confined to a strongly localized overlap of projectile-target density. Recent theoretical investigations[1-6] have focused on the question of how large amounts of energy and momentum are transferred from projectile to target nucleons, and on the early events in the evolution of hot, high density regions as thermal equilibrium is approached. In particular, the formation of squirts of nuclear matter, or of nuclear shock waves[7] carrying large transverse momentum and compressional energy has been predicted[2-5]. These would be formed in central collisions if the projectile velocity exceeds the nuclear sound velocity $\nu_o \sim 0.2c$, and could lead to rarefaction emission of pre-equilibrium fragments upon the impinging of the compressional wave onto the nuclear surface. The energies of emitted nucleons and nuclear fragments should correspond to the nuclear shock compression propagation velocity ν_s, which may be as high as 0.6c [3,4]. The models are in disagreement about the angles in the lab system at which emission should occur, some predicting[3,4] a narrow peak at angles ranging from 25° to 45° depending systematically on the incident energy while others anticipate a broad range of forward angles for the fragments[5]. There is agreement, however, as to the expectation that such processes should have a high fragment multiplicity, with energies ranging far above the evaporative domain.

In an experiment with Lexan foil detectors, Crawford et al.[8] investigated fragments with $5 \leqslant Z \leqslant 8$ resulting from the interaction of a 2.1 GeV/nucl ^{12}C beam with Au. Non-evaporative tails in the spectra of B, C and N were observed but angular distributions showed no significant narrow forward peaks. Kullberg and Otterlund[9] have studied the emission of α

particles with $E \leq 50$ MeV/nucl produced in nuclear emulsions by cosmic ray nuclei with $E \geq 100$ MeV/nucl. The angular distributions deviate markedly from evaporation model predictions at forward angles around 45°. The authors observe that the high energy α particles result primarily from high multiplicity (star event) target fragmentations[10].

The most provocative experiment thus far is a recent study of prong angular distributions of star events produced in AgCl crystals upon bombardment with relativistic ^{16}O ions by Schopper et al.[11] and Baumgardt et al.[12]. They report the observation of narrow forward peaking in $d\sigma/d\theta$, with an angular width of about 20° (FWHM). The prongs analyzed in that experiment are due mostly to ^3He and ^4He target fragments in the detector sensitivity range from zero to 200 MeV/nucl, with no further discrimination with respect to energy and He isotope. These forward maxima are only pronounced when data with large prong multiplicity are selected.

We have therefore undertaken a study of target fragment energy spectra and angular distributions with a ΔE-E counter telescope that would identify fragments with $Z = 2$ and 3, $3 \leq A \leq 7$, and $15 \leq E/\text{nucl} \leq 150$ MeV that are produced in the interaction of proton, ^4He and ^{16}O beams with Ag and U targets at an incident energy of about 1GeV/nucl. The comparison of results obtained with these beams should accentuate features that are unique to heavy ion induced reactions. In this letter we want to concentrate on our results for ^3He, ^4He fragment production.

The experiments were carried out at the Bevalac accelerator of the Lawrence Berkeley Laboratory[13]. The beams we used were protons of 2.7 GeV, α particles of 0.7 and 1.05 GeV/nucl and ^{16}O ions of 1.05 GeV/nucl. Average particle fluxes were 10^8 particles per beam burst. Targets of natural silver and uranium, about 200 to 300 mg/cm^2 thick, were mounted in a scattering chamber equipped with a detector telescope consisting of a 1 mm thick Si transmission detector as a ΔE detector and a 5 cm thick plastic scintillator (Pilot B) coupled to a 2.5 cm diameter phototube as an E detector. The telescope was mounted 25 cm from the target and subtended a solid angle of 5 msr. Signals from the detectors were used in a power law type particle identifier (PI) system. The PI and total energy signals as well as signals from the ΔE and E detectors were sent to a PDP 8 computer and stored event by event on magnetic tape. Isotopes from ^3He to ^7Li were well separated in the identifier spectrum.

The energy calibration of the spectra was obtained for each kind of particles from the ΔE signals in the surface barrier detector, using the known relation between energy loss in the ΔE counter and total kinetic energy. The overall energy resolution was better than 5%. The accessible energy range for ^3He and ^4He ions stopped in the second detector was $60 \leq E \leq 280$ MeV. However, owing to the good separation of ^3He and ^4He branches in the ΔE-E plot, it was possible to identify ^3He particles that were not completely stopped, following their spectra up to about 500 MeV.

The beam intensity was monitored with an ionization chamber calibrated with proton beams.[14] Assuming that its output is proportional to Z^2 (projectile), the relative cross sections for He particles, produced with the proton, ^4He and ^{16}O beams on the same target, should be accurate to better than 20%. The overall normalization of the absolute cross section scale was determined within ±50% by matching the present data to spectra obtained previously in the vicinity of the low energy evaporation peaks.[15]

Spectra are shown in Fig. 1 for ^{3}He and ^{4}He emission at 20° in the lab system from a U target bombarded with several projectiles and energies. For energies above 50 MeV/nucl, the cross sections increase by more than an order of magnitude as the projectile changes from p to ^{4}He, and from ^{4}He to ^{16}O. The ^{3}He spectrum from ^{16}O + U is remarkably flat, with cross sections about 1 mb/MeV•sr even at 150 MeV/nucl.

A comparison of ^{3}He and ^{4}He double differential spectra from the ^{16}O + U interaction is shown in fig. 2. The ^{4}He spectra decay much faster towards higher energies than the ^{3}He spectra, with the latter showing higher cross sections above about 30 MeV/nucl. It is obvious that the spectra cannot be understood by a simple evaporation process which would require a constant exponential decay. Approximating, nonetheless, the 90° spectra by a straight exponential in the region from 30 to 70 MeV/nucl, one obtains a "nuclear temperature" of 60 MeV for ^{3}He, and 38 MeV for α emission at these energies. These numbers are far too high to be compatible with a conventional evaporation process. The high energy end of the ^{3}He spectra would require an even higher temperature.

From fig. 2 it is obvious that the angular distributions for given energy bins both of ^{3}He and ^{4}He do not show pronounced maxima within the angular range accessible to this experiment. At about 20 MeV/nucl the differential cross sections decay slowly with increasing emission angle; at higher energy this decay is more pronounced. For ^{3}He produced from ^{16}O + Ag, the angular distributions are shown in fig. 3 for four successive bins of energy. We have plotted $d\sigma/d\theta = d\sigma/d\Omega \sin\theta$ here only in order to facilitate a comparison with the data of Baumgardt _et al._[12]. The peak in $d\sigma/d\theta$ has a width of about 60° (FWHM); its position shifts from

58° in the low energy bin to about 30° above 100 MeV/nucl where the angular distributions show little further change in shape. The same behaviour is observed for all other combinations of target, projectile and reaction product. No narrow forward peaking comparable with the 20° widths observed by Baumgardt et al. is found. If one assumes the correspondence reported by Kullberg and Otterlund[9] between high energy ^{4}He emission and high prong multiplicity, our data are in disagreement with those of Baumgardt et al. as far as the shape of angular distributions is concerned. The angular distributions of $d\sigma/d\Omega$, integrated over all energies, detected in this experiment are given in fig. 4 for ^{3}He and ^{4}He target fragments. They show forward peaking with leveling off towards angles $\theta \leqslant 40°$ in the lab system.

The displacement in peak position with the fragment emission energy for a given target-projectile combination and incident energy (fig. 3) is at variance with present simple hydrodynamic models of nuclear shock wave fragmentation which, for a central collision of a light projectile with a heavy target nucleus, predict a fixed emission angle[3]. However, preliminary numerical calculations[5] of the two dimensional relativistic hydrodynamics for the ^{16}O + Ag interaction result in an angular distribution of fragments emitted with $20 \leqslant E/nucl \leqslant 200$ MeV that is in qualitative agreement with our data.

In summary, our data present evidence for the non-evaporative emission of ^{3}He and, to a somewhat lesser extent, ^{4}He products in collisions between relativistic heavy ions. The cross sections for these products are more than two orders of magnitude higher than those found for proton induced reactions at comparable incident velocity[16]. This points towards a cooperative mechanism that cannot be explained by geometrical considerations or by an independent superposition of nucleon induced knockon cascades.

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FOOTNOTE AND REFERENCES

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16. At incident proton energies of about 30 GeV, a high yield of ^3H and ^3He has also been observed that was interpreted as an emission from

hadronic fireballs (R. Hagedorn and J. Ranft, Nuovo Cimento Suppl. 6, 169 (1968)). At our incident energies of about 1 GeV/nucl., the centre of mass energy of a *single* nucleon-nucleon scattering system is too low to allow for such emissions.

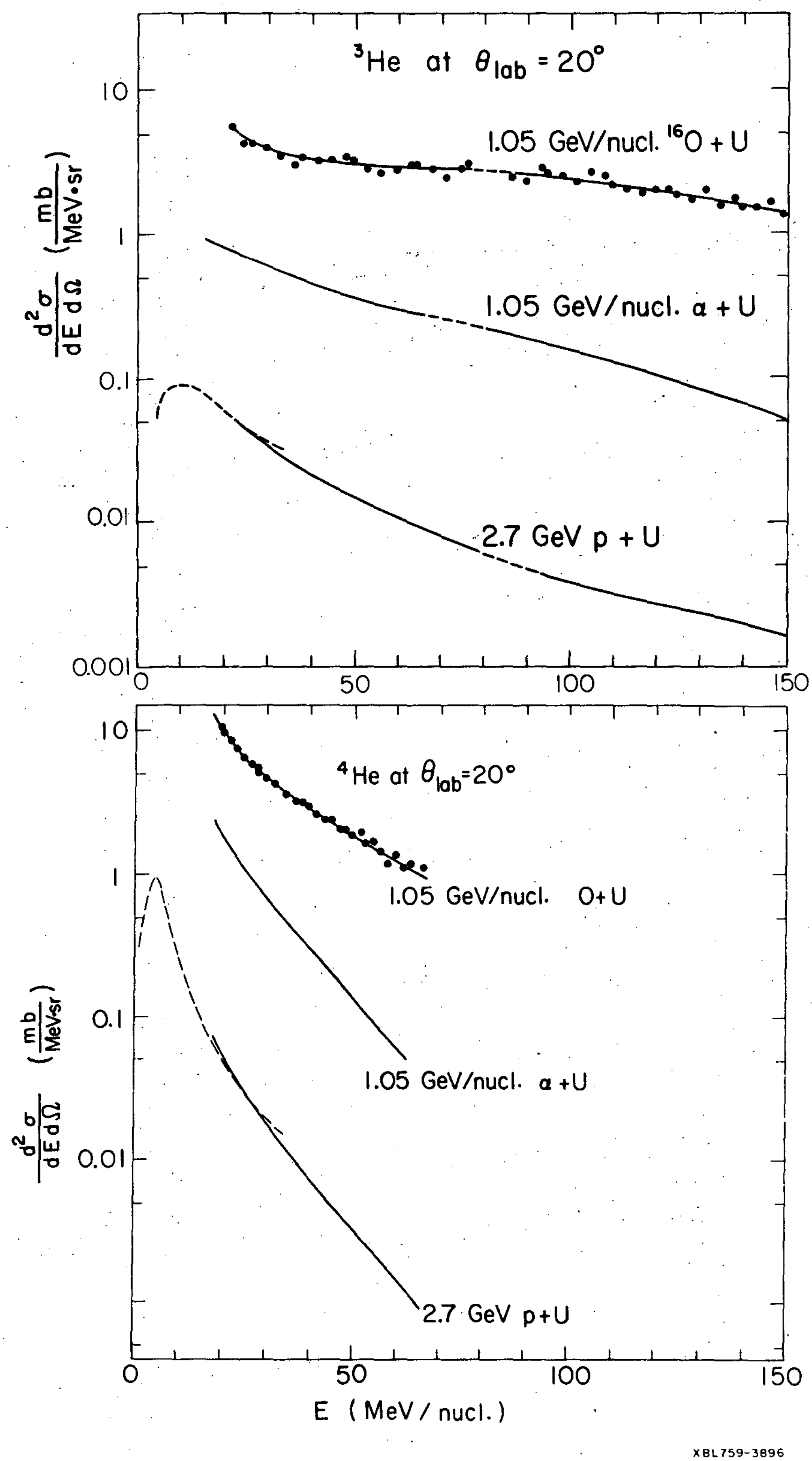
FIGURE CAPTIONS

Fig. 1. Comparison of ^{3}He (upper part) and ^{4}He (lower part) spectra at 20° (lab) obtained upon bombardment of a uranium target with protons of 2.7 GeV, α particles and ^{16}O ions with 1.05 GeV/nucl. The data points shown for ^{16}O + U spectra are interpolated by an average curve; similar curves represent the data for the other spectra. For p + U these curves are matched to low energy evaporation spectra (dashed lines) obtained previously (ref. 15).

Fig. 2. Double differential cross sections for ^{3}He (upper part) and ^{4}He (lower part) produced by ^{16}O of 1.05 GeV/nucl. on uranium as a function of laboratory angle. Data points are shown at 20° and 50° to indicate the statistical quality of the data.

Fig. 3. Differential cross sections per unit angle, $d\sigma/d\theta$, of ^{3}He fragments emitted in various energy domains between 20 and 150 MeV/nucl from ^{16}O + Ag at 1.05 GeV/nucl incident energy. Curves are drawn to guide the eye.

Fig. 4. Angular distributions of ^{3}He and ^{4}He fragments observed with ^{4}He and ^{16}O projectiles on Ag and U targets. Curves are drawn to guide the eye.



^{3}He at θ_{lab} = 20°
1.05 GeV/nucl. ^{16}O + U
1.05 GeV/nucl. α + U
2.7 GeV p + U
$\frac{d^2\sigma}{dE\,d\Omega}$ $\left(\frac{mb}{MeV \cdot sr}\right)$
10
1
0.1
0.01
0.001
0
50
100
150
^{4}He at θ_{lab}=20°
1.05 GeV/nucl. O+U
1.05 GeV/nucl. α +U
2.7 GeV p+U
E (MeV/nucl.)
XBL759-3896

Fig. 1

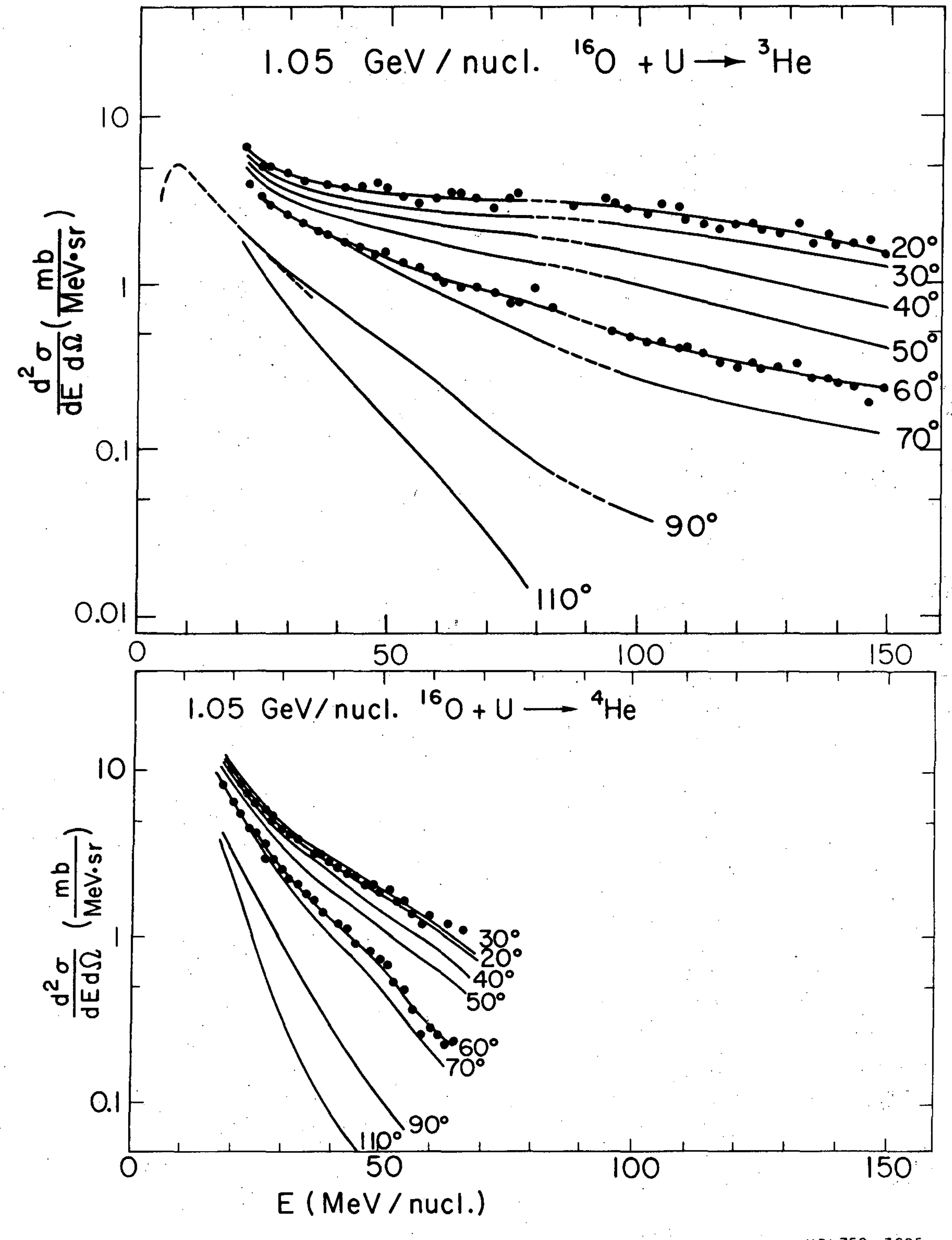
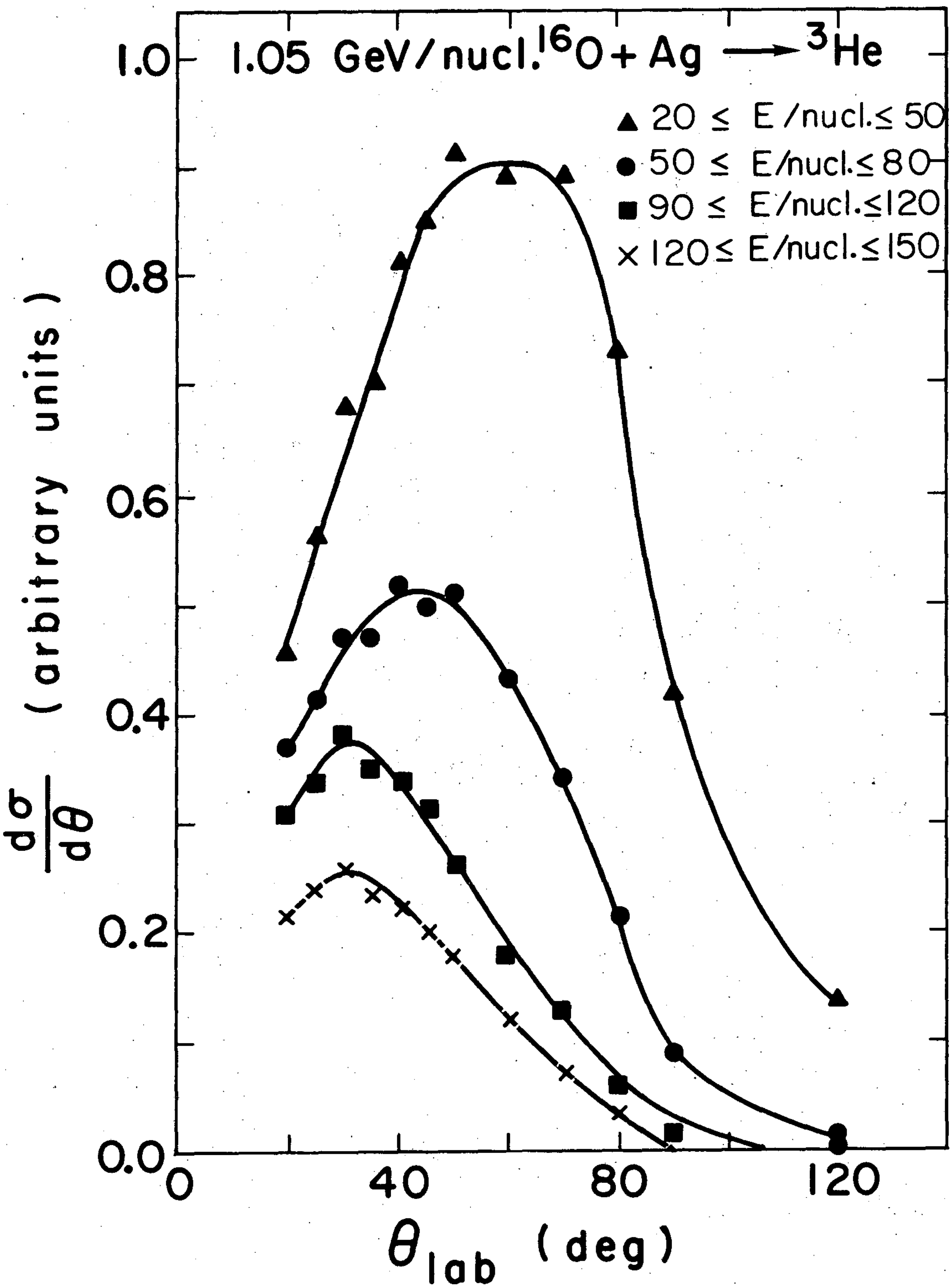

1.05 GeV / nucl. $^{16}O + U \rightarrow {}^{3}He$
1.05 GeV/ nucl. $^{16}O + U \rightarrow {}^{4}He$
$\frac{d^2\sigma}{dE\,d\Omega}\left(\frac{mb}{MeV\cdot sr}\right)$
10
1
0.1
0.01
0
50
100
150
20°
30°
40°
50°
60°
70°
90°
110°
E (MeV / nucl.)
XBL759-3895

Fig. 2



XBL758-3792

Fig. 3

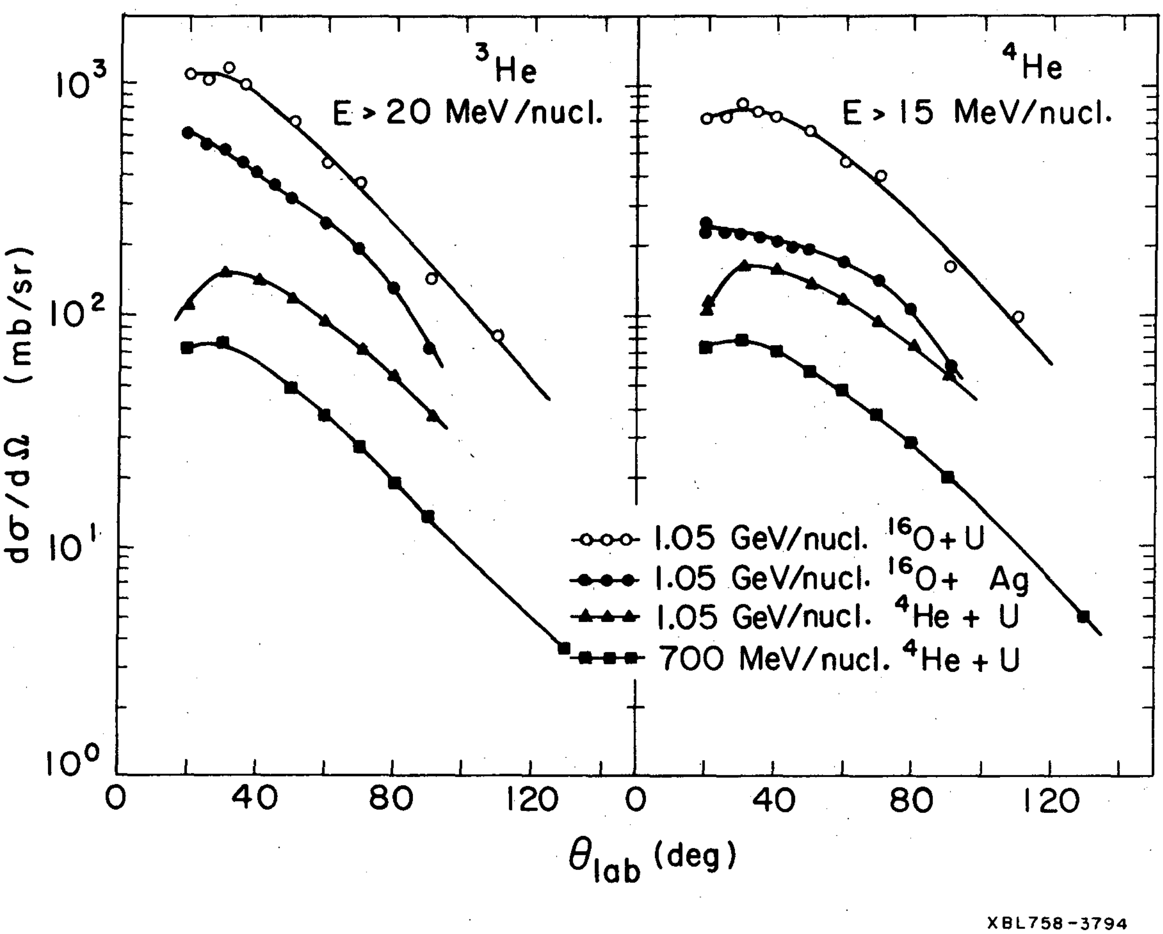

3He
E > 20 MeV/nucl.
4He
E > 15 MeV/nucl.
1.05 GeV/nucl. 16O + U
1.05 GeV/nucl. 16O + Ag
1.05 GeV/nucl. 4He + U
700 MeV/nucl. 4He + U
dσ/dΩ (mb/sr)
θlab (deg)
XBL758-3794

Fig. 4

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