Submitted to Physical Review Letters

LBL-5039
Preprint c.1

FINAL STATE INTERACTIONS IN THE PRODUCTION OF HYDROGEN AND HELIUM ISOTOPES BY RELATIVISTIC HEAVY IONS ON URANIUM

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July 1976

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

August 16, 1976

LBL-5039

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Phys. Rev. Lett., to be published

ERRATA

Lance Wilson has pointed out to us that factors of $\frac{1}{N!}$ and γ are missing from eq. 1. None of the conclusions are affected. However, the corrected equations are:

$$\frac{d^2n}{p^2dpd\Omega}(N) = \frac{1}{N!}\,\frac{d^2n}{p^2dpd\Omega}\left(\frac{d^2n}{p^2dpd\Omega}\,\frac{4\pi}{3}\,\gamma p_o^3\right)^{N-1} \quad (1)$$

$$\frac{d^2\sigma(x,y)}{dEd\Omega} = \left(\frac{d^2\sigma(\text{prot})}{dEd\Omega}\right)^{x+y} \frac{K(x,y)}{\left[m\sqrt{E(E+2m)}\right]^{x+y-1}} \quad (2)$$

$$K(x,y) = \left(\frac{4\pi p_o^3}{3\sigma_o}\right)^{x+y-1} \frac{1}{x!y!} \left(\frac{N_p + N_t}{Z_p + Z_t}\right)^y . \quad (3)$$

The p_o at the bottom of page 5 becomes, 140 MeV/c. Table I is corrected to:

Table I. Radius p_o (MeV/c) of the momentum sphere for coalescence.

^{20}Ne + U	d	t	^{3}He	^{4}He
250 MeV/nucleon	126	140	135	147
400 MeV/nucleon	129	129	129	142
2.1 GeV/nucleon	106	116	106	118
^{4}He + U				
400 MeV/nucleon	126	127	127	132

July 9, 1976
LBL-5039

FINAL STATE INTERACTIONS IN THE PRODUCTION OF HYDROGEN AND HELIUM ISOTOPES BY RELATIVISTIC HEAVY IONS ON URANIUM*

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ABSTRACT

Double differential cross sections have been measured for high energy p, d, t, ^{3}He, and ^{4}He particles emitted from uranium targets irradiated with ^{20}Ne ions at 250, 400, and 2100 MeV/nucleon and ^{4}He ions at 400 MeV/nucleon. By using the shape and yield of the proton energy spectra, the shape and yield of the d, t, ^{3}He, and ^{4}He energy spectra can be deduced at all measured angles for all incident projectile energies assuming that they are formed by coalescence of cascade nucleons using a model analogous to that of Butler and Pearson, and Schwarzschild and Zupančič.

Recently, we presented energy spectra and angular distributions for ^{3}He and ^{4}He fragments from uranium and silver targets bombarded with relativistic heavy ions.[1] The cross section for these high energy products were two and three orders of magnitude higher than those found for proton induced reactions at comparable incident velocity. The larger yield of high energy ^{3}He than ^{4}He raised doubts whether there was a common reaction mechanism which could explain the production of both. In high energy proton induced reactions, the observation of deuterons was explained by Butler and Pearson[2] as the coalescence of cascade nucleons. This model, which was modified by Schwarzschild and Zupančič,[3] assumes that among the many knock-on cascade nucleons there will be pairs that have small relative momenta. These nucleons can form a deuteron by interacting with each other and the nuclear field to which the excess momentum and energy are transferred. The model thus relates the energy spectra of the emitted complex particles to the proton and neutron spectra. We propose a slightly modified version of this model to explain our data on high energy light fragments emitted in relativistic heavy ion reactions. It is found that the energy spectra and angular distributions of the emitted composite particles fall off more steeply than those of the nucleons. Thus we conclude that calculations of nuclear matter ejected in relativistic heavy ion collisions should only be compared directly to data for the emission of nucleons.

Experimentally, we have measured the energy spectra from 30 to 120 MeV/nucleon at several laboratory angles for protons, deuterons, tritons, ^{3}He, and ^{4}He emitted from uranium bombarded with 250, 400, and 2100 MeV/nucleon ^{20}Ne beams and a 400 MeV/nucleon ^{4}He beam from the Bevalac. The hydrogen and helium isotopes were identified as to their charge and mass in a ΔE-E telescope consisting of a 2-mm thick silicon ΔE counter (300 mm^2) and a 10-cm long plastic scintillator (Pilot B, coupled to a 2.5 cm diameter phototube) as an E detector. The natural uranium target had a thickness of 240 mg/cm^2 and its normal was 55° to the beam. The energy of each particle was determined from its energy loss in the silicon ΔE counter after the particle charge and mass were determined using a two dimensional contour display of the analogue particle identification function vs. the energy loss in the plastic scintillator. The relative cross sections, which are accurate to within 20%, were obtained by normalizing to a monitor telescope fixed at 90° with respect to the beam. The absolute cross sections were obtained by normalizing to previously measured data.[4]

Double differential cross sections for the various emitted particles are presented in Figs. 1 and 2. Although many more angles have been measured, only some of the spectra are shown. Similar to the ^{4}He and ^{16}O induced reactions,[1] the energy spectra of all products are smooth and show no peaks. The slopes of the energy spectra become steeper with increasing angle and also with increasing mass of the emitted particle.

Schwarzschild and Zupančič[3] predict that the deuteron density in momentum space is proportional to the proton density times the probability of finding a neutron within a small sphere of radius p_o around the proton momentum. A straightforward generalization to more complex particles leads to:

$$\frac{d^2n}{p^2dpd\Omega}(N) = \frac{d^2n}{p^2dpd\Omega}\left(\frac{d^2n}{p^2dpd\Omega}\ \frac{4\pi}{3}\,p_o^3\right)^{N-1} . \qquad (1)$$

N is the mass number of the emitted fragments, p is the momentum per nucleon, $\frac{d^2n}{p^2dpd\Omega}$ is the number of nucleons per event per element of momentum space, and $\frac{d^2n}{p^2dpd\Omega}$ (N) is the number of coalesced clusters with N nucleons per event per element of momentum space.

We apply this formalism to heavy ion induced reactions assuming that the protons and neutrons have the same momentum distribution and that their relative yield is equal to the neutron-to-proton ratio in the projectile plus target. We get:

$$\frac{d^2\sigma(x,y)}{dEd\Omega} = \left(\frac{d^2\sigma(\text{prot})}{dEd\Omega}\right)^{x+y} \frac{K(x,y)}{[\sqrt{E(E + 2m_{\text{prot}})}(E + m_{\text{prot}})]^{x+y-1}} \tag{2}$$

$$K(x,y) = \left(\frac{4\pi p_o^3}{3\sigma_o}\right)^{x+y-1} \binom{x + y}{x} \left(\frac{N_p + N_t}{Z_p + Z_t}\right)^y \tag{3}$$

where E is the laboratory kinetic energy per nucleon, x is the number of protons and y is the number of neutrons in the cluster, N_p and Z_p are respectively the neutron and proton number of the projectile, and N_t and Z_t are respectively the neutron and proton number of the target. The quantity σ_o is the nucleus-nucleus total reaction cross section calculated in Ref. 5 as 4.1 b for ^{20}Ne + U and 2.6 b for ^{4}He + U.

In Fig. 3 we show measured double differential cross sections for d, t, ^{3}He, and ^{4}He compared to calculations based on Eq. (2) and the measured proton spectra shown in Fig. 2. For each projectile, incident energy, and fragment we extract one value for p_o, the radius of the momentum sphere for coalescence. These values are listed in Table I. The values are much smaller than those found in Ref. 3 and are of reasonable magnitude as they are a fraction of the Fermi momenta of the clusters. This simple phase-space calculation of coalescence involves only one adjustable parameter for each fragment, the value of p_o, for calculating absolute cross sections, energy spectra, and angular distributions. The p_o values are remarkably uniform even though absorbed into this parameter are the many factors, including correlations, not explicitly accounted for in this very simple model.

In conclusion we have found strong evidence for final state interactions in the production of high energy fragments (30 to 120 MeV/nucleon) in relativistic heavy ion induced reactions. This result could suggest that future work concerning the possible detection of density effects in these collisions should concentrate on the nucleon and meson spectra since the energy spectra of the composite particles can be obtained from Eq. (2) and are shifted in energy and angle relative to the nucleons. On the other hand, we have data showing that the particle multiplicity increases with the size of the fragment. Thus the observation of the larger composit particles might be a way of selecting central collisions, and may be a sensitive probe of density effects. We do not, however, have an understanding of the detailed mechanism leading to coalescence. Equation (2) leads to a different fragment energy dependence than that found in the original work of Butler and Pearson,[2] and further theoretical work is needed to understand the difference between the two models. Earlier experimental results of Crawford et al.[6] on high energy boron to oxygen fragments are also consistent with this model. The high-energy tails in the energy spectra of helium to beryllium fragments from uranium irradiated by 5 GeV protons[7] can now be understood by this mechanism with the reasonable value of p_o of about 90 MeV/c. This eliminates the previously postulated apparent temperatures of 20 MeV needed to explain these tails. This model could also aid in the understanding of the scaling effect seen in the production of d, t, ^{3}He, and ^{4}He by high energy pions and protons.[8]

We are grateful to H. Grunder and the Bevalac staff for their support and to W. Swiatecki and W. D. Myers to helpful discussions. One of us (P.J.J.) gratefully acknowledges a scholarship from the Danish Research Council.

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[*] This work was done with support from the U. S. Energy Research and Development Administration, and from the Bundesminister für Forschung und Technologie, W. Germany.

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Table I. Radius p_o (MeV/c) of the momentum sphere for coalescence.

^{20}Ne + U	d	t	^{3}He	^{4}He
250 MeV/nucleon	99	104	100	103
400 MeV/nucleon	102	96	96	100
2.1 GeV/nucleon	84	86	79	83
^{4}He + U				
400 MeV/nucleon	100	94	91	93

FIGURE CAPTIONS

Fig. 1. Double differential cross sections for fragments from the irradiation of uranium by 400 MeV/nucleon ^{20}Ne ions.

Fig. 2. Double differential cross sections for protons emitted from the irradiation of uranium by ^{20}Ne ions at 250 and 400 MeV/nucleon.

Fig. 3. Experimental points and calculated lines for the double differential cross sections of fragments from the irradiation of uranium by ^{20}Ne ions at 250 and 400 MeV/nucleon.

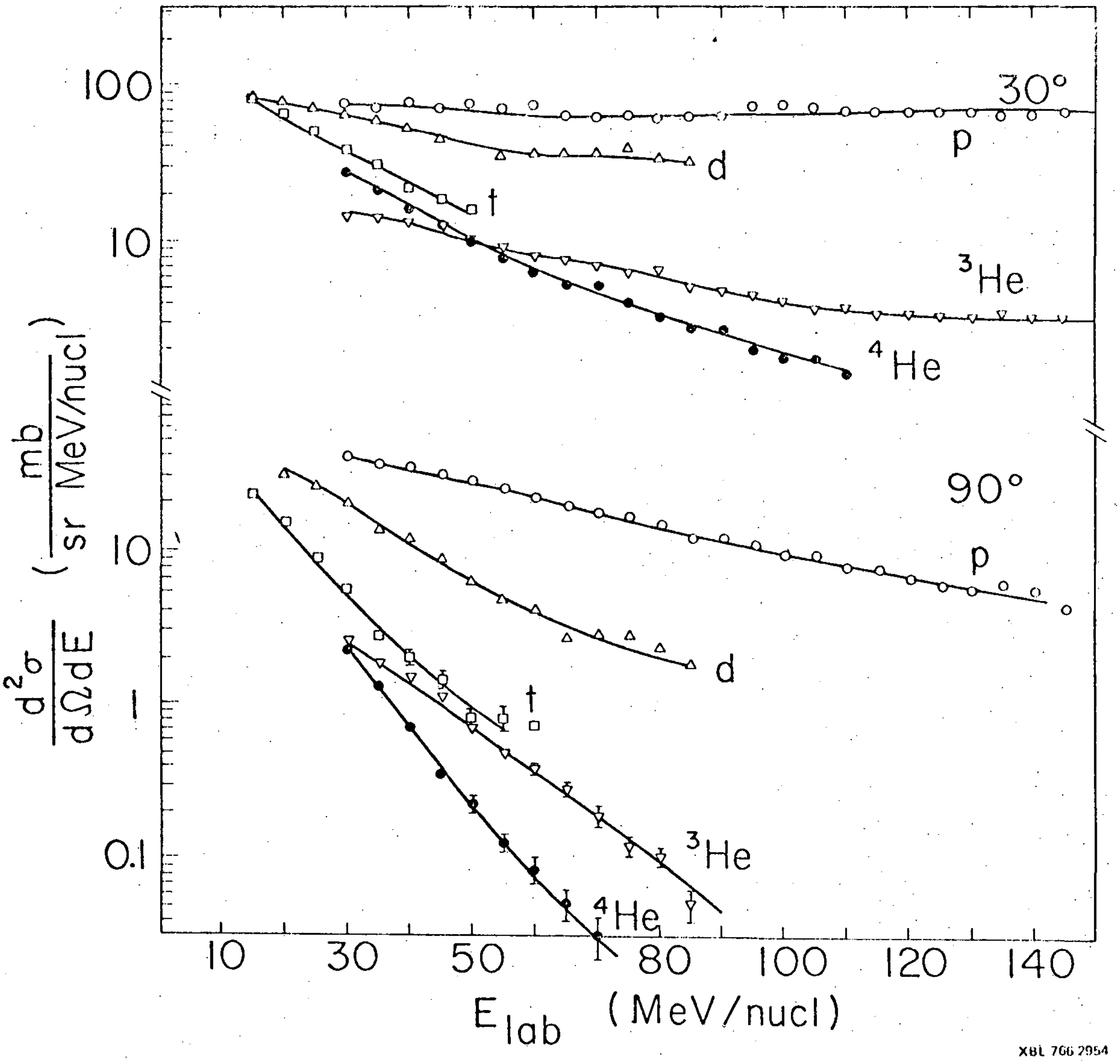
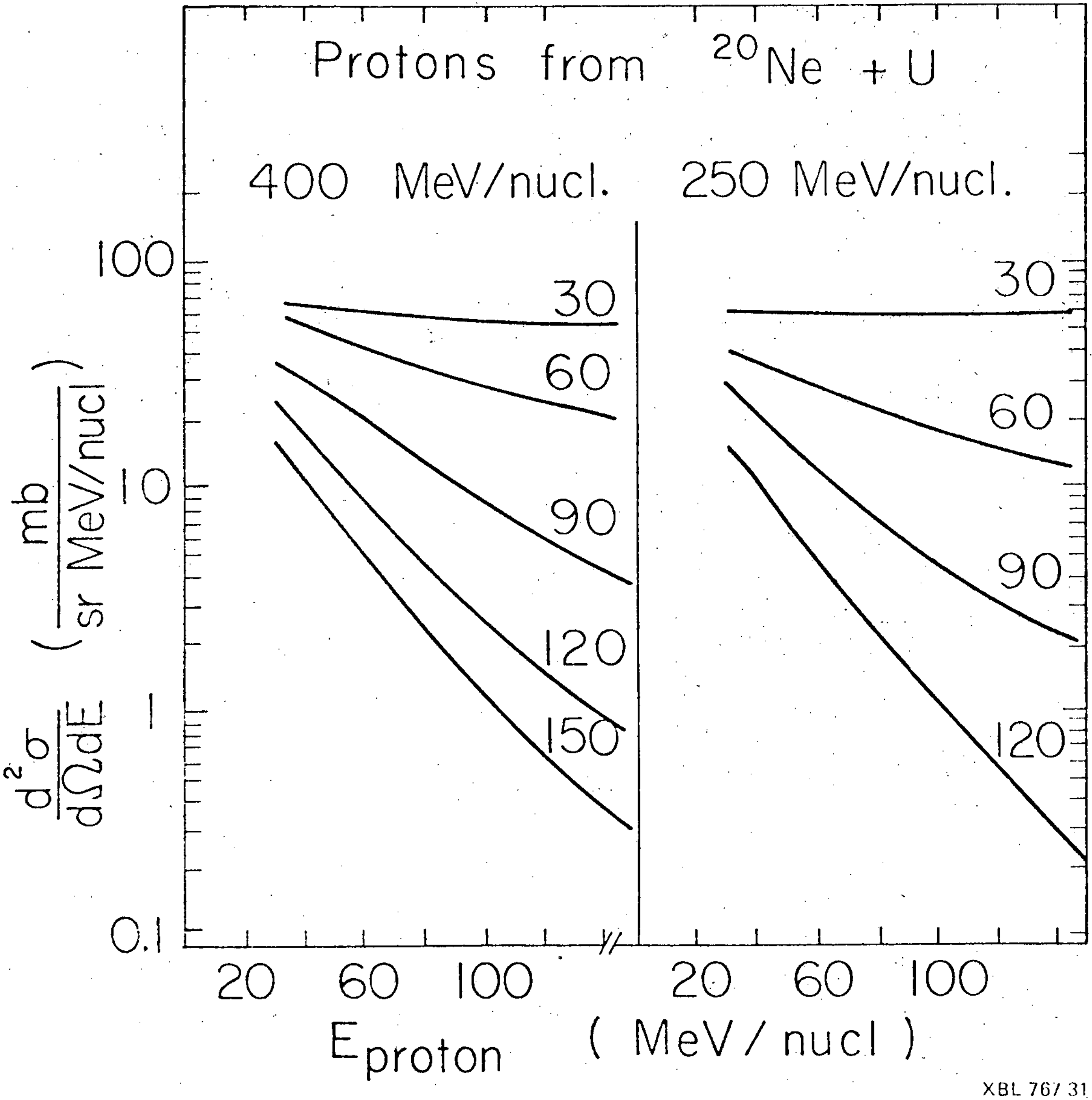

30°
p
d
t
^{3}He
^{4}He
90°
p
d
t
^{3}He
^{4}He
100
10
1
0.1
$\frac{d^2\sigma}{d\Omega dE}$ $\left(\frac{mb}{sr\ MeV/nucl}\right)$
10
30
50
80
100
120
140
E_{lab} (MeV/nucl)
XBL 766 2954

Fig. 1



XBL 767 3114

Fig. 2

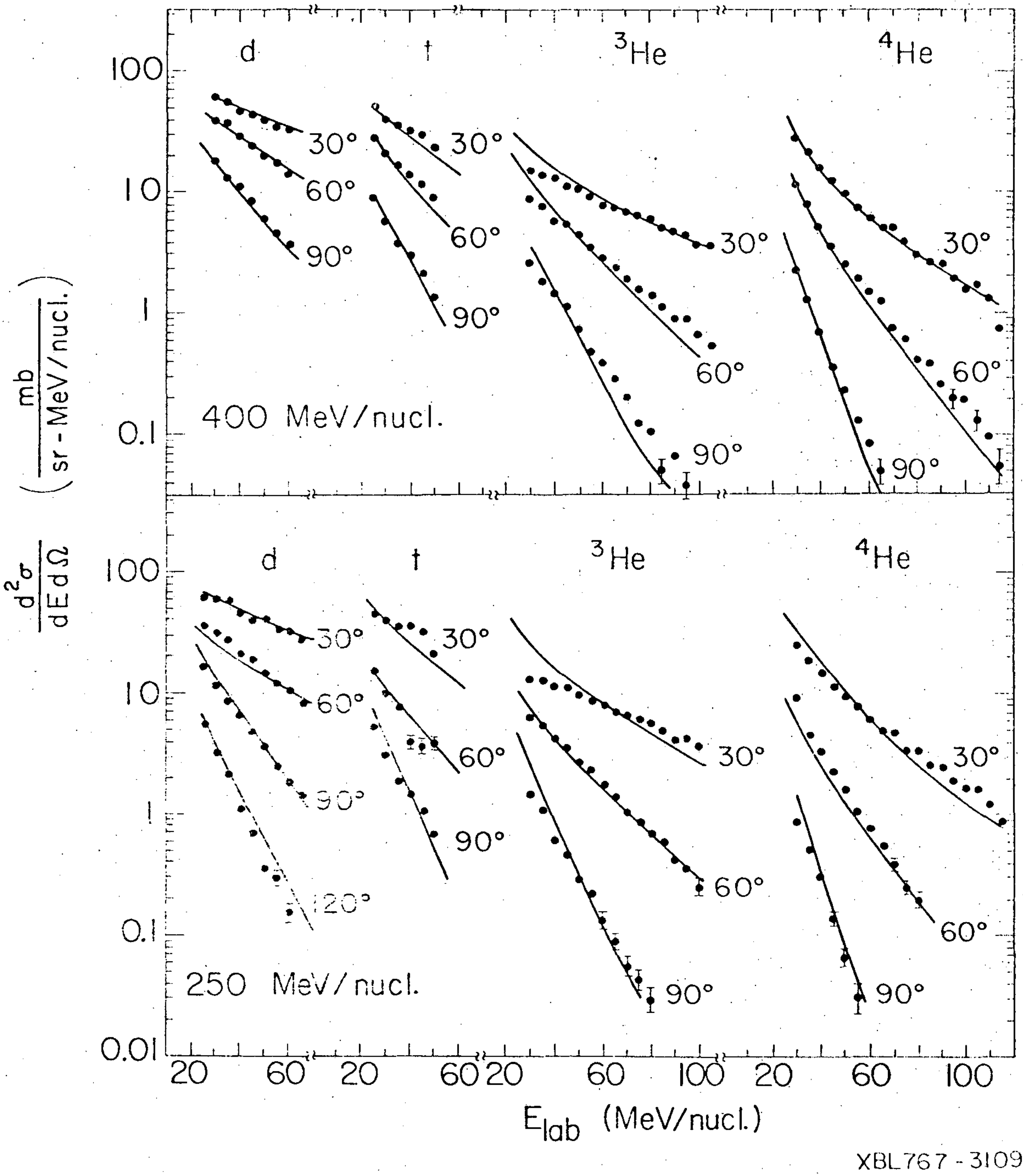


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Fig. 3

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