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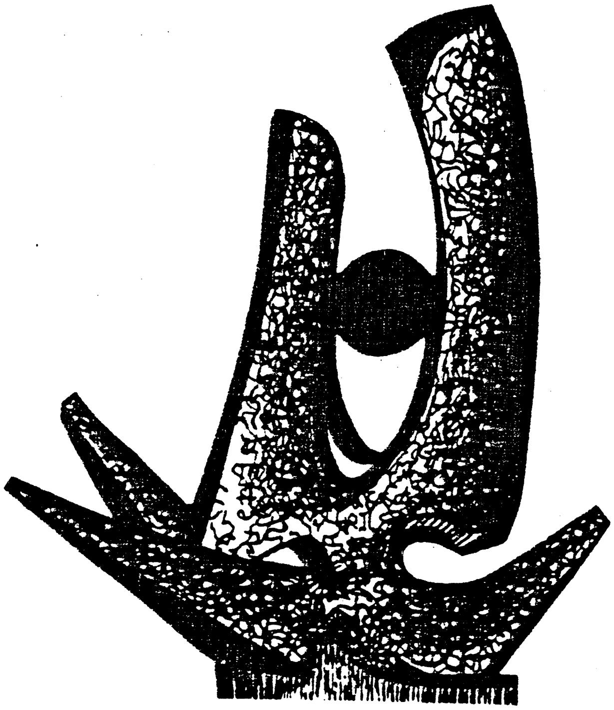

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Breakup of 11 MeV/A-^{7}Li by ^{159}Tb

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Abstract

Previously measured double differential cross sections of α particles and tritons from the breakup of 11 MeV/u-^{7}Li by ^{159}Tb were well accounted for by an opaque-nucleus model of Serber incorporating the spectral distortion in the field of the target nucleus.

Disintegration of light nuclei in the fields of targets has been reported for isotopes such as d, ^{3}He, α and ^{6,7}Li.[1-5] A simple method to describe projectile disintegration was presented by Serber which explained the production of fast neutrons from breakup of 190 MeV-deuterons very well. Up till now, however, the method has been used with the assumption that the target is transparent to breakup fragments[2,3] even though the assumption has not been verified experimentally.

On the other hand, recent exclusive studies[7-10] of the breakup of ^{3}He, α and ^{6,7}Li clearly indicated existence of a breakup fusion(BF)-type process, in which one of the breakup fragments is absorbed by the target nucleus. This suggests that, in the framework of Serber[6], the target is more likely to act as a completely opaque nucleus rather than as a transparent nucleus to breakup fragments. A fragment is stripped off by the target when it strikes the target, while it goes into the exit channel when it misses. This absorptive nature seems reasonable especially for the breakup of low-energy projectiles because fusion, which dominates low-energy heavy-ion reactions, might be expected to take place between the breakup fragments and the target.

The best procedure for analyzing these data is that formalism of the distorted wave Born approximation (DWBA) applicable to the breakup fusion-type process which is being developed.[11-14] Such DWBA analysis seems to be just at its beginning stage and a simpler calculation is still useful.

In this report, an opaque-nucleus version of the Serber model is adapted to reproduce experimental spectra of α particles and tritons from the breakup of ^{7}Li. Distortion of the breakup spectra in the field of a target nucleus is also included.

Breakup of 11 MeV/u-^{7}Li by ^{159}Tb was studied in singles and in coincidence with γ rays from residual nuclei. Details of the experiment was reported in Ref. 10. Fig. 1(a) shows exclusive α spectra measured at 30° for various reaction channels corresponding to a process in which, whatever the mechanism is, the remainder of the projectile (a triton) has been absorbed by the target nucleus. The spectra from the three channels of α4n, α3n and α2n can be added together forming a prominent bump centered around the beam velocity. Previous analysis showed that these channels should be considered to represent breakup-fusion of ^{7}Li. The small bump in singles seen at low energies is near the Coulomb barrier between an α particle and the residual nucleus and has been attributed to the complete fusion of ^{7}Li and ^{159}Tb. In addition, another interesting channel of α5n which lies between the Coulomb energy bump and the beam velocity-energy bump was observed. This channel might be mainly attributed to a process closer to equilibrium in which interaction between a projectile and a target lasts longer and more intimately than in projectile breakup. Thus, at 30°, an exclusive spectrum of α particles resulting from breakup-fusion (shaded area in Fig. 1(b)) was obtained by summing over α4n, α3n and α2n channels. A comparison of the yield of α particles in coincidence with any γ ray (dotted-dashed curve in Fig. 1(a)) with singles α particles (dotted curve in Fig. 1(a)) shows a significant amount of missing strength (dashed line in Fig. 1(b)). This cross section can be attributed to a

breakup process in which the ^{159}Tb target is thought to remain almost at ground state. It should be noted that at 30° in the present reaction, a spectral shape and yield of α particles from that process are very close to those of BF α particles.

The application of the Serber model[6] to the calculation of the double differencial cross sections of breakup fragments is straightforward. Consider the breakup of projectile a into fragments b and x. Let the fragment b stand for an observed fragment. The momentum distribution of b in a is given by $|\psi(\vec{p})|^2$, where $\psi(\vec{p})$ is the Fourier transform of the relative wave function $\psi_a(\vec{r})$ between b and x in a. The laboratory momentum $\vec{p}_b$ of b is given by a coupling of $\vec{p}$ and the momentum $\vec{p}_o$ due to incident motion of the projectile, i.e., $\vec{p}_b=\vec{p}+\vec{p}_o$. Let the wave function $\psi_a(\vec{r})$ be a Yukawa-type, i.e., $\psi_a(\vec{r})=(\alpha/2\pi)^{1/2}e^{-\alpha r}/r$, where $\alpha=(2\mu\varepsilon)^{1/2}/\hbar$ with the reduced mass μ and separation energy ε of the fragment from the projectile. Taking into account the fact that for a transparent nucleus, the Fourier transformation can be allowed in full $\vec{r}$ space, the double differencial cross section $d^2\sigma/d\Omega_b\cdot dE_b$ for the transparent nucleus is given by:

$$\frac{d^2\sigma}{d\Omega_b dE_b} \propto m_b p_b |\psi(\vec{p})|^2 = m_b p_b \frac{(2\mu\epsilon)^{1/2}}{(2\mu\epsilon + p^2)^2} \qquad (1)$$

, where $p^2=p_b^2+p_o^2-2p_bp_o\cos\theta$, m_b is mass of b and θ is the laboratory angle. Note that $d\vec{p}=d\vec{p}_b\propto m_bp_bd\Omega_bdE_b$.

In the case of an opaque nucleus, the Fourier transformation has to be done with the restriction that b misses the target, while x strikes and is stripped off by the target.[6] After integrating the momentum distribution along the circumference of the target nucleus, the double differential cross section is written as:

$$\frac{d^2\sigma}{d\Omega_b dE_b} \propto m_b P_b \frac{(2\mu\epsilon)^{1/2}}{(2\mu\epsilon + P^2)^2} \left[\frac{(2\mu\epsilon + P^2)^{1/4}\, P_{1/2}(S)}{(2\mu\epsilon + P^2 - P_b^2 \sin^2\theta)^{3/4}} \right] \quad (2)$$

, where $P_{1/2}(s)$ is Legendre function of the argument:

$$S = \frac{2\mu\epsilon + P^2 - \frac{1}{2} P_b^2 \sin^2\theta}{(2\mu\epsilon + P^2)^{1/2}(2\mu\epsilon + P^2 - P_b^2 \sin^2\theta)^{1/2}} \quad (3)$$

Comparing Eq. (1) with Eq. (2), one can see that the difference between the transparent nucleus and the opaque nucleus is the factor in the square bracket in Eq. (2).

Eq. (2) was used to calculate the exclusive spectrum of α particles resulting from BF process. Two additional effects due to the field of the target were taken into account: (i) Coulomb/ nuclear deflection and (ii) barrier height difference between the entrance and exit channels. The average deflection angle θ_o requires replacement of θ with $\theta-\theta_o$. θ_o was previously[10] found to be 10° from the requirement that maximum of the most probable energy of the breakup spectrum should be realized at θ_o. It should be, however, noted that the value is considerably smaller than the classical grazing angle (23°) for the system, suggesting necessity of the nuclear attractive force which pulls the trajectory toward a forward angle. This is consistent with the results of angular correlation measurements of the ^{232}Th(^{7}Li,αf) and (^{7}Li,tf) reactions

which show that BF likely takes place at angular momenta between the critical values for complete fusion and for the grazing trajectory.

For the second effect, we will confine ourselves to the Coulomb energy difference. There is a difference between the Coulomb deceleration of the projectile a in the entrance channel and Coulomb acceleration of the fragment b in the exit channel. This requires replacing E_a and E_b with $E_a-Z_a \cdot V_c$ and $E_b-Z_b \cdot V_c$, respectively, where V_c is the Coulomb energy per unit charge , E_i is laboratory kinetic energy of i (i=a or b) and Z_i is the atomic number of i (i=a or b). V_c is about 8 MeV,[10] (corresponding to the radius parameter of 1.5 fm). The distortion of the actual breakup spectra due to the field of the target nucleus is shown later.

The calculation shown by the solid curve in Fig. 1(b) was normalized such that the data and calculation had the same peak yield. The shape of the experimental spectrum is in rough agreement with the present calculation. This rough agreement should be acceptable because we should take into account the fact that the model works best near a detection angle given by $\theta_o=\theta_o+(2\mu\epsilon)^{1/2}/p_o$ with $\epsilon=2.47$ MeV, which is the range of 10-20°.

It is also interesting to see the angular dependence of the spectra for the opaque nucleus. The calculated spectra of α particles and tritons are shown in Fig. 2 along with the experimental singles spectra. For convenience, it was assumed that at 30°, approximately 50% of the triton singles originated from BF. This assumption might not be reasonable since the spatial spreading of an α particle in ^{7}Li differs from that of a triton, giving rise to different capabilities of the target nucleus to absorb the α particle and the triton. As expected, spectra of both α particles and tritons detected within the plausible angular range are well reproduced by Eq. (2). Note that low energy side of the beam-velocity α particles should be mainly attributed to the process mentioned earlier(see α5n channel). The largest discrepancy occurs for the α particles at 10° where the calculated yield is larger than the singles yield. This discrepancy is not very serious because the angular distribution function is very steep in this region.

As a summary, we can show the spectral distortion due to the Coulomb/nuclear field of the target. The spectra calculated with Eq. (2) with (solid curves) and without (dash-dotted curves) the distortion effect are shown in Fig. 3 for both cases of α particles and tritons at 15°. The effect gives rise to a slight shift of peak position of α (t) spectrum toward high (low) energy and a considerable narrowing of the both spectra, significantly modifying the spectral shapes. Also shown in Fig. 3 are spectra of α particles and tritons for the transparent nucleus calculated using Eq. (1) (dashed curves). Although, as pointed out by Serber, the opaque-nucleus model predicts a slightly narrower breakup spectrum than the transparent-nucleus model does, the resultant spectral narrowing is much weaker than that caused by the field of the target. This fact seems to suggest that in the breakup of low-energy projectiles by high-Z targets, one can neither justify the opaque nucleus nor the transparent nucleus on the basis of only the spectral shapes of breakup fragments.

In conclusion, the opaque-nucleus model of Serber was applied to breakup of 11 MeV/u-^{7}Li by ^{159}Tb. Experimental double differential cross sections of both α particles and tritons were accounted for in a consistent way by the model incorporationg the distortion of the spectra in the field of the target nucleus.

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Figure Captions

Fig. 1(a); Energy spectra of α particles measured at 30° for the ^{159}Tb(^{7}Li, αxn)$^{162-x}$Dy reaction channels. The dotted curve and the dash-dotted curve stand for singles α particles and coincident α particles with any γ ray, respectively. The thin solid curves are to guide the eye. Fig. 1(b); Experimental (shaded area) and calculated (thick solid curve) spectra of α particles at 30° for breakup-fusion of ^{7}Li. The opaque-nucleus model of Serber was used (see text). The dashed curve stands for the difference between the singles spectrum and the coincidence spectrum.

Fig. 2 Experimental (solid circles) and calculated (solid curves) spectra of α particles and tritons from the breakup of 11 MeV/u-^{7}Li by ^{159}Tb. The opaque-nucleus model was used (see text).

Fig. 3 Comparison of spectra calculated with (solid curves: θ_o=10°, V_c=8 MeV) and without (dash-dotted curves: θ_o=0°, V_c=0 MeV) the spectral distortion effect in the opaque-nucleus model. The dashed curves are calculated spectra in the transparent-nucleus model, including the distortion effect. For comparison of spectral shapes, the calculated spectra are normalized such that they have the same peak yield. The solid circles stand for experimental singles spectra of α particles and tritons.

MSU-84-215

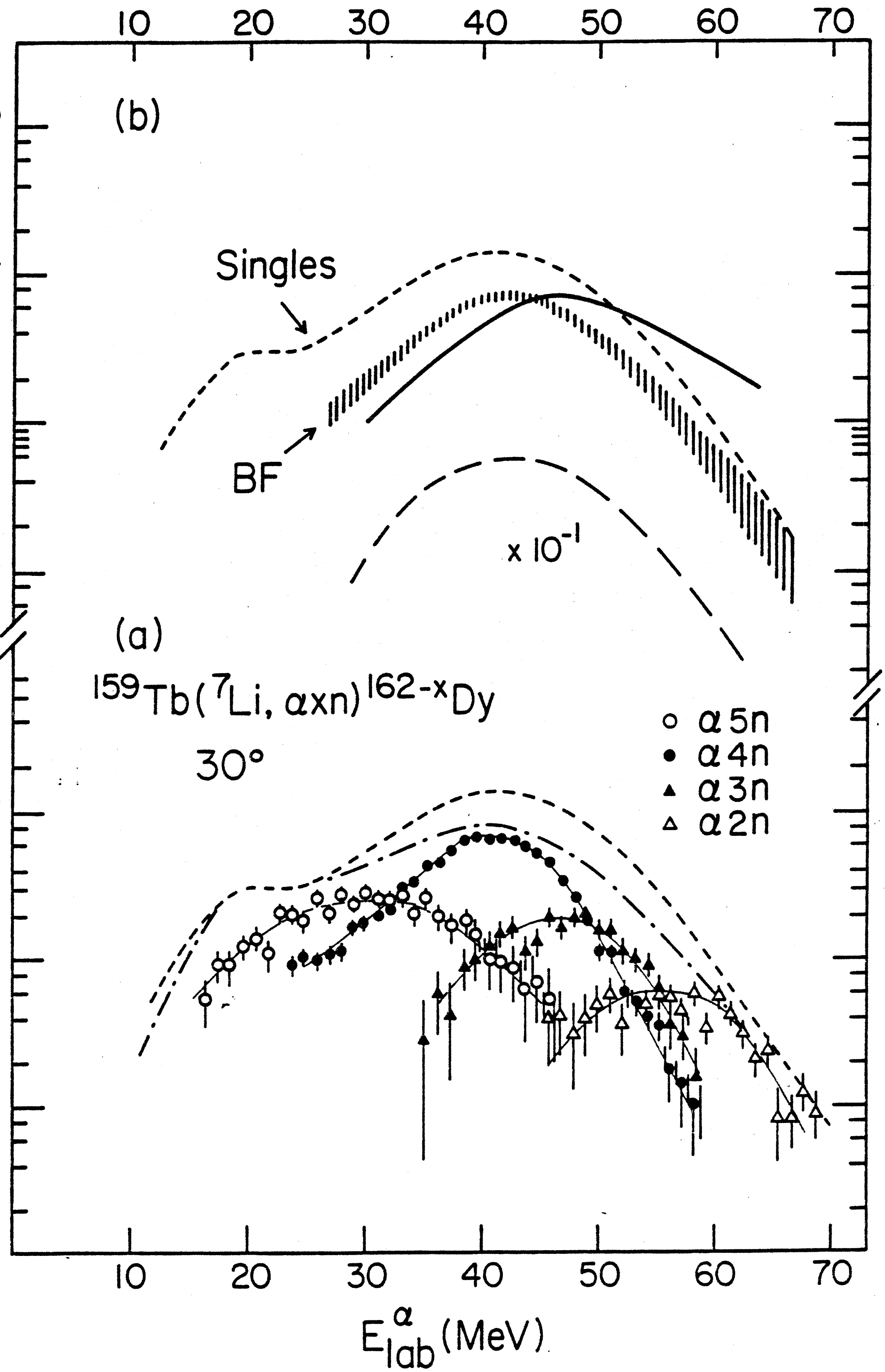


Fig. 1

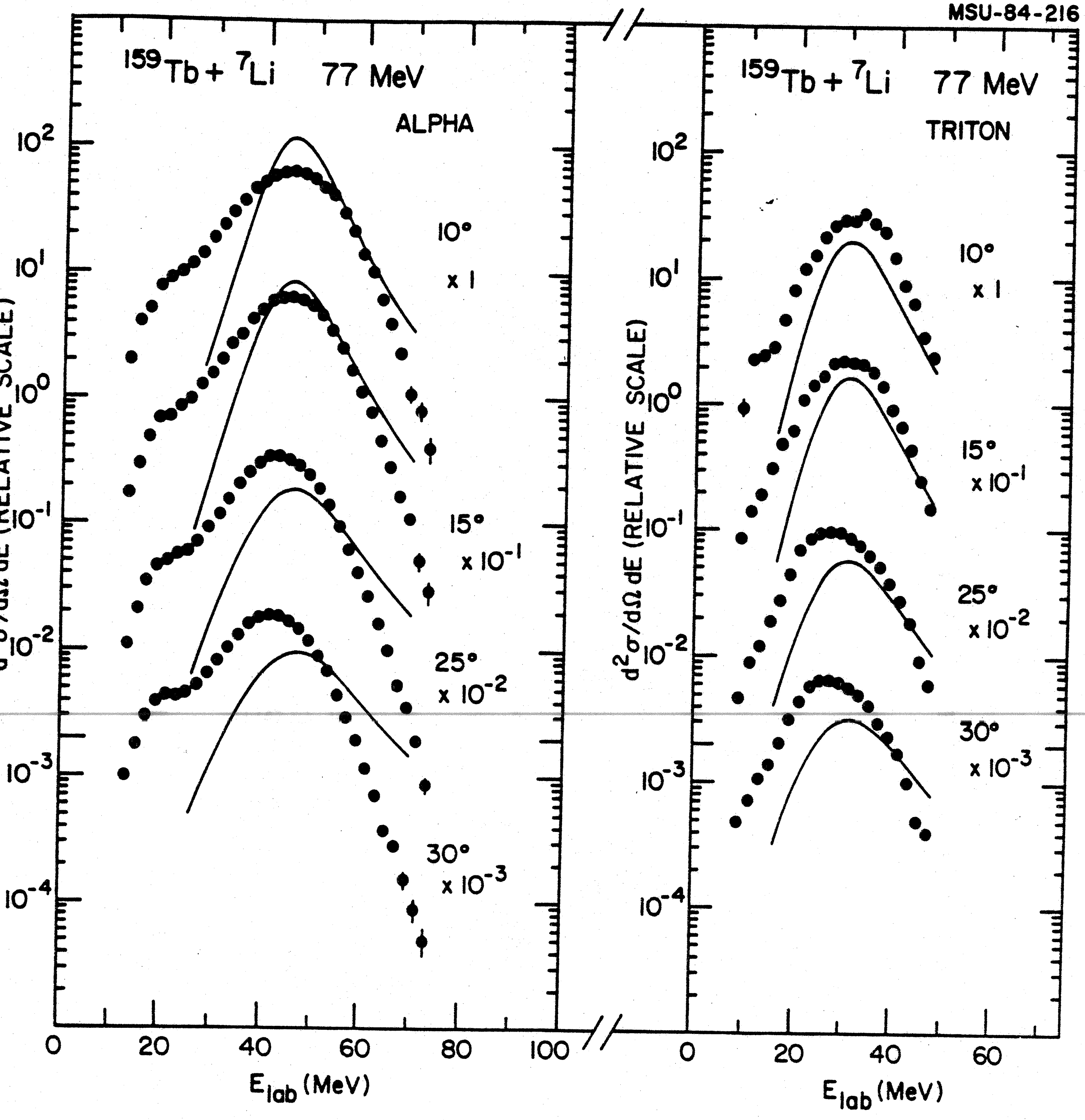
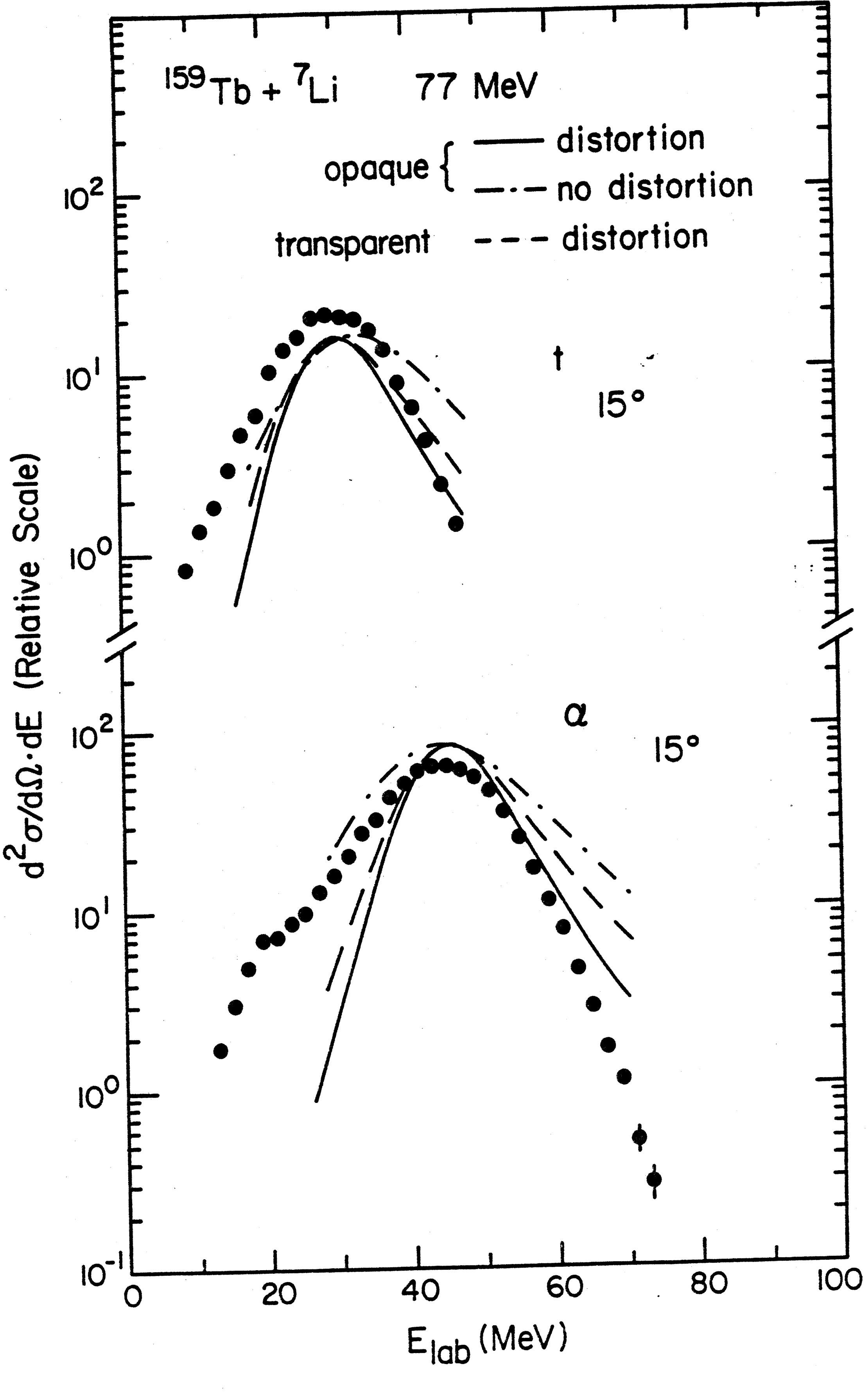

MSU-84-216
$^{159}Tb + ^{7}Li$ 77 MeV
ALPHA
TRITON
$d^2\sigma/d\Omega\,dE$ (RELATIVE SCALE)
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10° x 1
15° x 10^{-1}
25° x 10^{-2}
30° x 10^{-3}
0
20
40
60
80
100
E_{lab} (MeV)

Fig. 2



^{159}Tb + ^{7}Li 77 MeV
opaque
distortion
no distortion
transparent
distortion
t
15°
α
15°
10^2
10^1
10^0
10^{-1}
$d^2\sigma/d\Omega\cdot dE$ (Relative Scale)
0
20
40
60
80
100
E_{lab} (MeV)

Fig. 3