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### Publication Date

1977-07-01

0 0 0 0 4 8 0 0 3 4 4

Submitted to Physics Letters

7/03/77  
LBL-6551  
Preprint c-1

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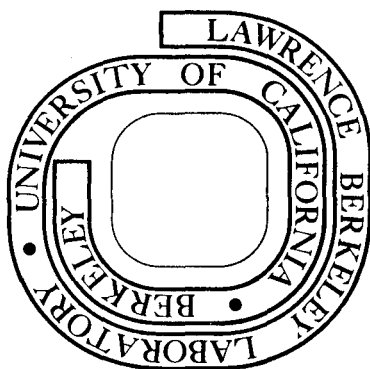
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July 1977

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

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LBL-6551  
c-1

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## INFLUENCE OF INTRINSIC NUCLEON MOTION ON ENERGY SPECTRA

AND ANGULAR DISTRIBUTIONS FOR  $^{16}\text{O}$ -INDUCED

## REACTIONS AT 20 MEV/A\*

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July 1977

## ABSTRACT

Energy spectra and angular distributions for peripheral reactions induced by  $^{16}\text{O}$  on  $^{208}\text{Pb}$  at 20 MeV/A can be explained in terms of the intrinsic nucleon motion of the excited projectile, in a manner similar to the interpretation of projectile fragmentation reactions at 2.1 GeV/A.

\* Work performed under the auspices of the U.S. Energy Research and Development Administration.

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Both at low and relativistic energies, the energy spectra produced in heavy-ion reactions are often dominated by a broad peak in the continuum centered at energies well above the Coulomb barrier. At low energies  $[(E-V_c)/A \lesssim 5 \text{ MeV/A}]$ , this peak is often attributed to two-body reactions [1-4] populating a high density of final states in the residual nucleus. At relativistic energies, the other hand, the continuum is produced by fragmentation of the projectile [5] in the field of the target nucleus, either by the fast liberation of clusters [6,7] or by the slow decay of the excited projectile [6,8]. At these energies, the intrinsic motion of the nucleons inside the projectile has been found to be important for understanding the momentum (or energy) distributions of the observed fragments [6,8,9]. In this letter, we show that the energy spectra and angular distributions observed [10] in peripheral reactions of  $^{16}\text{O}$ -ions on  $^{208}\text{Pb}$  at 20 MeV/A incident energy also can be well understood in terms of the intrinsic nucleon motion in the projectile.

For projectile fragmentation reactions at relativistic energies, the momentum distributions in the projectile rest frame were well described by Gaussian distributions predicted by simple models [5,6]

$$\frac{d^3\sigma}{dp^3} \sim e^{-\frac{(\vec{p}-\vec{p}_0)^2}{2\sigma^2}} \quad (1)$$

where

$$\sigma^2 = \sigma_0^2 \frac{m_f(m_p - m_f)}{(m_p - 1)}. \quad (2)$$

Here,  $m_f$  and  $m_p$  are the masses of the observed fragment and the projectile, respectively. For  $^{16}\text{O}$  ions of 2.1 GeV/A, the value of  $\sigma_0 = 86 \text{ MeV/c}$  has

been determined experimentally [5]. The centroid of the momentum distribution depends on the observed fragment and can be related to the momentum transfer due to the excitation of the projectile [7]. The momentum  $\vec{p}_0$  is found to be opposite to the beam direction and  $p_0 \ll \sigma$ . Using eq. (1), a rest frame R can be found in which fragments of mass  $m_f$  are emitted isotropically [5], i.e.

$$\frac{d^3\sigma}{dp_R^3} \sim e^{-p_R^2/2\sigma^2} \quad (3)$$

In the laboratory system, the velocity  $v_R$  of the rest frame R is slightly smaller than the projectile velocity  $v_p$ . Denoting the laboratory energies of fragments at rest in the frame R and in the projectile rest frame by  $E_R$  and  $E_p$ , respectively, one obtains [10] from the model of ref. [7]:

$$E_R \approx E_p - \gamma_p \frac{m_f}{m_p} E^* \quad (4)$$

where  $\gamma_p = (1 - v_p^2/c^2)^{-1/2}$  and  $E^*$  is the excitation energy of the projectile in its rest frame. As shown in fig. 1, the centroids of the observed energy distributions for an incident energy of 20 MeV/A are in good agreement with the kinetic energies  $E_R$  expected from eq. (4), if  $E^*$  is taken to be the minimum energy required to dissociate the projectile into the observed fragment together with nucleons, except for the case of carbon which was assumed to be produced together with an alpha particle. (The predicted locations for  $^{15}\text{N}$ ,  $^{12}\text{C}$ ,  $^{11}\text{B}$ ,  $^9\text{Be}$  and  $^{7,6}\text{Li}$ , which are the isotopes produced with the largest cross sections, are shown.) Furthermore, for the lighter fragments (Li, Be, B), the values of  $\Delta E = E_p - E_R$  at 2.1 GeV/A are observed to be approximately three times greater than at 20 MeV/A [10], as predicted by eq. (4).

It has been pointed out [6,7,11] that the momentum distributions can result from a fast statistical projectile fragmentation process and that the width  $\sigma_0$  can be connected to the Fermi momentum  $p_F$  of the projectile by

$$\sigma_0 = p_F / \sqrt{5} \quad (5)$$

For an  $^{16}\text{O}$  nucleus, the value of  $p_F = 230$  MeV/c has been determined from electron scattering [12], which implies, from eq. (5), a value of  $\sigma_0 = 103$  MeV/c compared to the value of 86 MeV/c obtained [5] from  $^{16}\text{O}$  projectile fragmentation studies at 2.1 GeV/A. However, the observed momentum distributions also can be explained [6] by the assumption that the excited projectile decays after attaining thermal equilibrium at a temperature  $T$ . The width  $\sigma_0$  is then given by [6]

$$\sigma_0^2 = m_N T(m_p - 1)/m_p \quad (6)$$

where  $m_N$  is the nucleon mass. The results at 2.1 GeV/A correspond to  $T = 8.5$  MeV, almost equal to the average nucleon binding energy. Although it is not possible to distinguish between the processes implied by eqs. (5) and (6) from the experimental momentum distributions alone [6], in both cases the intrinsic motion inside the projectile determines the main features of the momentum distributions of the observed fragments at relativistic energies.

Very similar assumptions give a rather satisfactory description of the observed widths of the energy spectra and angular distributions at 20 MeV/A. Transformation of eq. (2) into the laboratory system yields

$$\frac{d^2\sigma}{d\Omega dE_L} \sim m_f \sqrt{2m_f E_L} \exp\left[-\frac{m_f}{\sigma^2} (E_L - 2a E_L^{1/2} \cos \theta + a^2)\right] \quad (7)$$

with

$$a^2 = m_f v_R^2 / 2, \quad (8)$$

where  $E_L$  is the laboratory energy. The laboratory scattering angle  $\theta_L$  of the outgoing particles was shifted by  $10^\circ$  (i.e.  $\theta_L = \theta + 10^\circ$  in eq. (7)) in order to include the Coulomb repulsion from the target nucleus in an approximate way. The resulting energy spectra and angular distributions are compared to the experimental data in figs. 1 and 2. The solid curves were calculated using  $\sigma_0 = 103$  MeV/c (the value corresponding to eq. (5)) and the dotted lines were calculated using  $\sigma_0 = 80$  MeV/c (corresponding, from eq. (6), to  $T = 7.3$  MeV, which has been used previously to reproduce the isotope-production cross sections [12]). For each element, the curves were calculated for the isotope produced with the largest cross section; the parameters  $a^2$  were chosen to reproduce the position of the maxima of the energy spectra (see Table I). These energies correspond closely to the values  $E_R$  predicted for fragmentation processes. Since the width  $\sigma$  depends most strongly on isotope number for  $m_f \approx m_p$  [see eq. (2)], calculations have also been performed for  $^{14}\text{N}$  fragments using  $\sigma_0 = 103$  MeV/c (see dashed lines). Although an exact description of the experimental data cannot be expected from such a simple approach, the widths of the energy spectra and the slopes of the angular distributions are reproduced remarkably well.

The applicability of the simple model developed for projectile fragmentation reactions at relativistic energies to reactions at 20 MeV/A is in accordance with the observed similarities [13] of cross sections at these energies. The angular distributions and the energy spectra at both energies appear to be dominated by the intrinsic nucleon motion in the projectile. It is intriguing, however, that the distributions at 20 MeV/A



are qualitatively similar to those encountered in reactions at lower incident energies [10], where so far the effects of intrinsic motion on the energy spectra and angular distributions have not been treated explicitly.

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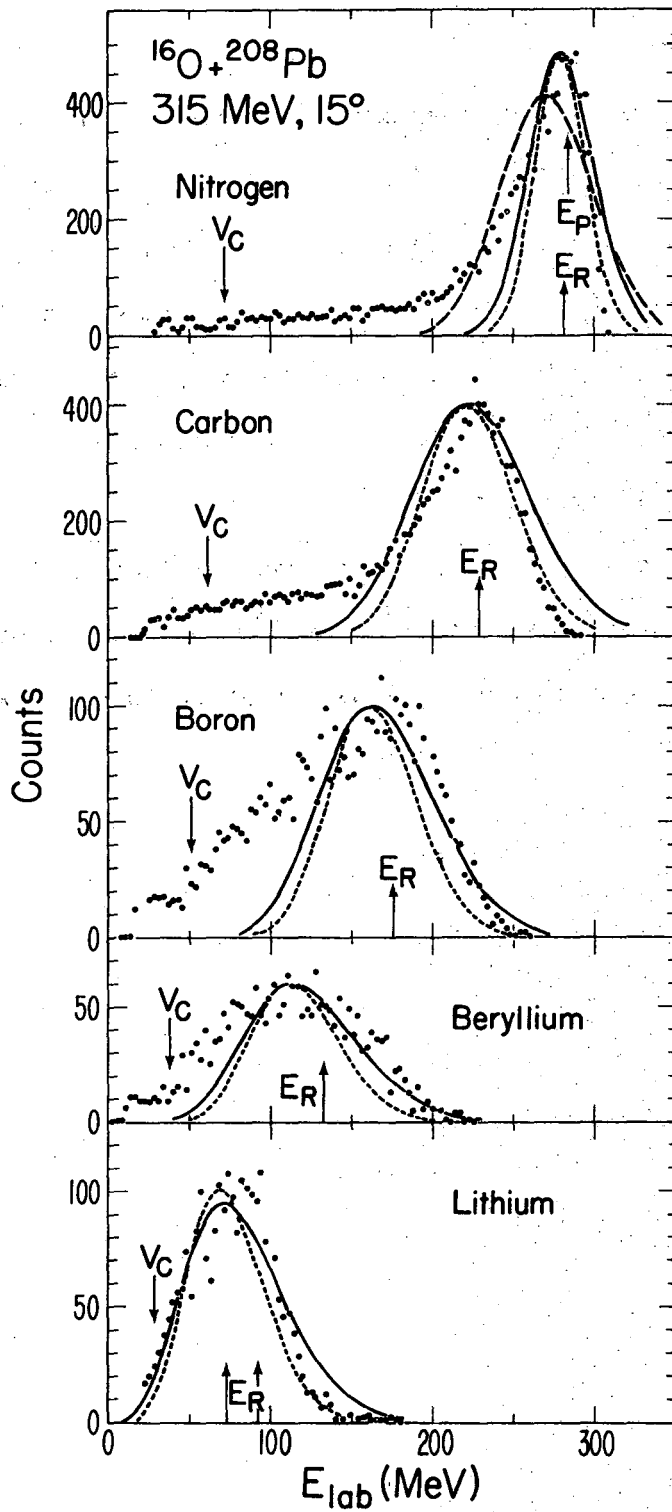
Table I. Parameters used for the calculated curves in figs. 1 and 2. The widths  $\sigma_0 = 103$  MeV/c and  $\sigma_0 = 80$  MeV/c have been used for the solid and dotted curves, respectively.

Element	N	C	B	Be	Li
$m_f$ (amu)	15 (14)	12	11	9	7
$a^2$ (MeV)	280 (270)	220	160	110	65

## FIGURE CAPTIONS

Fig. 1. Energy spectra [10] of reaction products N, C, B, Be, Li measured in the bombardment of  $^{208}\text{Pb}$  by  $^{16}\text{O}$ -ions of 315 MeV at the laboratory angle of  $15^\circ$ . The curves are calculated from eq. (7) as explained in the text. The arrows denoted by  $V_C$  and  $E_R$  correspond to the exit-channel Coulomb barrier and the energy predicted for a fragmentation of the projectile into the observed fragment together with individual nucleons and alpha particles.

Fig. 2. Angular distributions [10] of reaction products N, C, B, Be, Li measured in the bombardment of  $^{208}\text{Pb}$  by  $^{16}\text{O}$  ions of 315 MeV. The curves are calculated from eq. (7) as explained in the text.



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Fig. 1

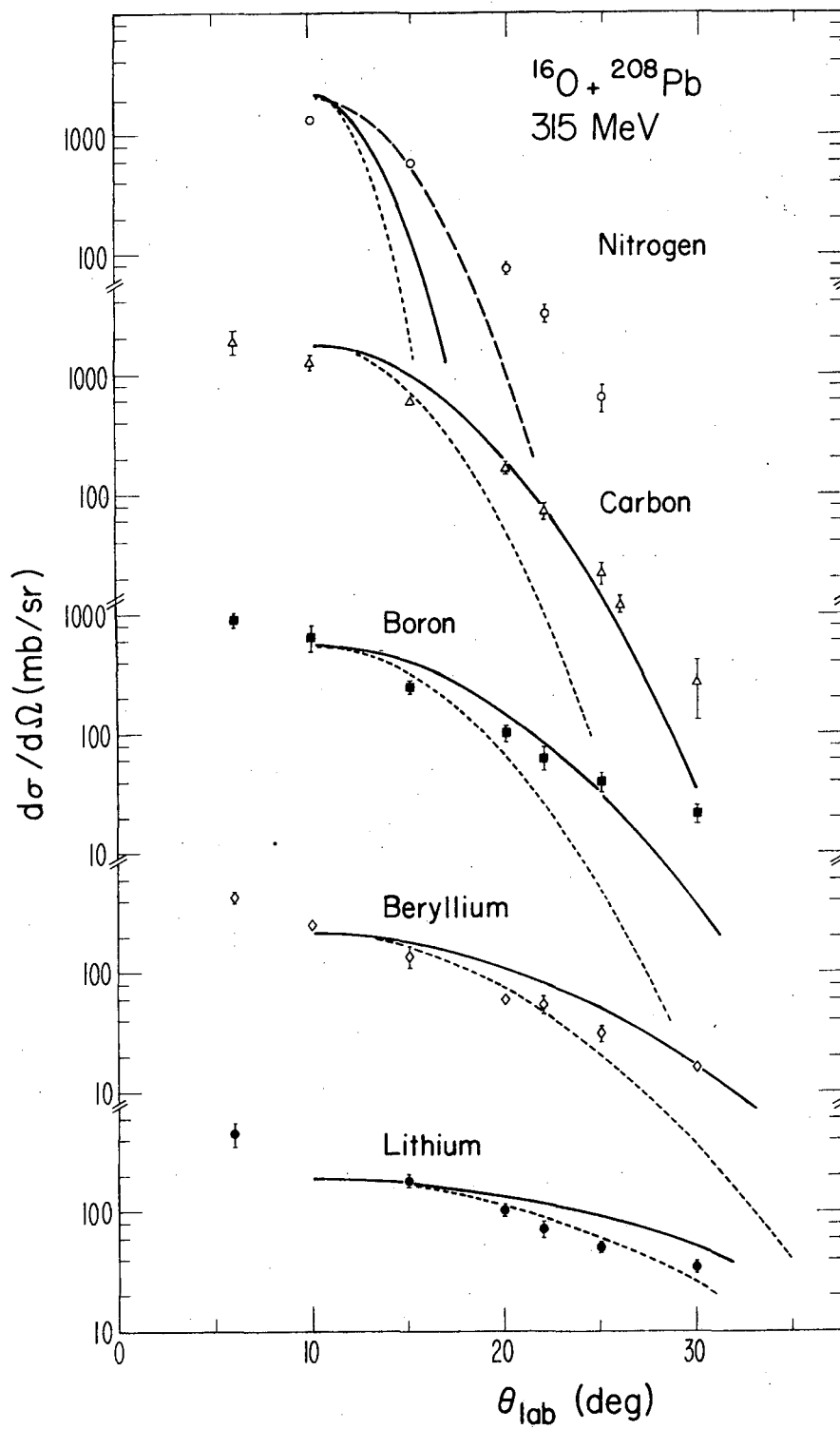


Fig. 2

This report was done with support from the United States Energy Research and Development Administration. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the United States Energy Research and Development Administration.

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