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SIMILARITY OF CROSS SECTIONS FOR PERIPHERAL COLLISIONS AT 20 MEV/A AND 2.1 GeV/A*

M. Buenerd[†], C. K. Gelbke, B. G. Harvey, D. L. Hendrie, J. Mahoney, A. Menchaca-Rocha[‡], C. Olmer and D. K. Scott

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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Abstract:

Peripheral collisions between ^{16}O and ^{208}Pb are investigated at a laboratory energy of 315 MeV. The relative cross sections are remarkably similar to published cross sections measured at 33.6 GeV laboratory energy. They are compared with statistical models involving di-nuclear systems and projectile fragmentation.

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The measurement of cross sections for particles produced by heavy ions of relativistic energies at forward scattering angles[1,2] has evoked substantial theoretical study.[3-7] At these energies the relative velocities of the colliding nuclei considerably exceed the Fermi velocities of the nucleons in the target and projectile. Consequently the interactions between the two nuclei occur on time scales short compared with the time required for nuclear relaxation. However, the rather small momentum transfers and the distribution of the particle yields observed in these peripheral reactions have suggested that the comparatively slow statistical decay of the primary reaction products is important for a quantitative understanding of the experimental findings.[3-7] The abrasion-ablation model[7] is an example of such a two-step process in which the initial abrasion of nucleons from projectile and target is followed by the statistical decay of the highly excited remnants. In contrast, diffusion and equilibration phenomena of the target-projectile complex[8-10] are observed in heavy-ion reactions at energies only a few (1-3) MeV/A above the Coulomb barrier. Here the relative ion velocities are smaller than the Fermi velocity and the interaction times are long enough to permit at least partial equilibration of the di-nuclear system. Intermediate energies of a few tens of MeV/A, where the relative velocities of the interacting nuclei are comparable to the Fermi velocity, might be expected to provide results bridging the two energy regions and with characteristics of both types of reactions. We here report the surprising similarity of particle yields for peripheral collisions of ^{16}O on ^{208}Pb at laboratory energies of 20 MeV/A ($\frac{v}{c} \approx 0.2$) and 2.1 GeV/A[2] ($\frac{v}{c} \approx 0.95$), possibly indicating a similarity of the reaction mechanism at these energies compared to the suggested mechanism at energies closer to the Coulomb barrier.

A ^{208}Pb target of 0.7 mg/cm^2 thickness was bombarded by $^{16}O^{6+}$ -ions of 315 MeV energy from the 88-Inch Cyclotron of the Lawrence Berkeley Laboratory. The reaction products were identified with a triple ΔE-ΔE-E solid state detector telescope using detectors of 40 μm, 80 μm and 2000 μm thickness, respectively. Absolute cross sections were obtained from the integrated beam current, the target thickness and the solid angle of the detector telescope. The associated uncertainties are estimated to be less than 15%.

At forward scattering angles ($\Theta_{cm} \lesssim 20^o$), the energy spectra for all outgoing particles with $3 \leq Z \leq 8$ and $A < 16$ exhibit broad peaks (FWHM $\approx$ 50-100 MeV) centered at energies per nucleon slightly less than that of the incident ^{16}O beam. This observation indicates that all these particles are produced by a similar quasielastic process. (No significant yield of particles with $Z > 8$ was observed). The centroids of these energy distributions move systematically to lower energies as the scattering angle is increased beyond $\Theta_{cm} \approx 20^{o}$. Integration over the quasielastic peaks yields angular distributions which are strongly forward peaked and exhibit a steep exponential fall-off with increasing scattering angle. The dependence of energy spectra and cross sections on scattering angle will be presented in detail in a subsequent paper. Here we discuss the quasielastic yields for the various isotopes integrated over all scattering angles.

Table 1 gives a comparison of the cross sections at laboratory energies of 315 MeV (this experiment) and of 33.6 GeV (taken from Ref. 2). Also included are the total reaction cross sections measured[11] at 33.6 GeV and estimated from an optical model analysis of the elastic scattering at 315 MeV. A comparison of the relative cross sections at the two energies is made in Fig. 1. Several points should be noted:

1) The relative cross sections for the production of different isotopes at 20 MeV/A and 2.1 GeV/A are generally of the same magnitude although differences do exist, especially for the lighter particles. There is a general trend towards larger cross sections for the production of more neutron deficient isotopes at the higher energy. Note, however, that the relative element yields are identical within the experimental errors. This is a most unexpected result, since similar experiments at energies only a few MeV/A above the barrier give entirely different distributions of reaction products.[8,12]

2) Assuming that the total reaction cross section σ_R is given by the sum of the cross sections for central collisions σ_C and for quasielastic (i.e., peripheral) collisions σ_P, one obtains $\sigma_C \approx 2100$ mb at 315 MeV and $\sigma_C \approx 2200$ mb at 33.6 GeV. Hence the cross section for central collisions does not change significantly between 20 MeV/A and 2.1 GeV/A, and agrees with the high energy limit for the

estimated fusion cross section[13] $\sigma_F = [1.0(A_1^{1/3} + A_2^{1/3})]^2 \text{ fm}^2 = 2240$ mb.

For the interpretation of peripheral reactions induced by heavy ions, different assumptions have been made at low energies ($E/A \lesssim 3$ MeV/A above the Coulomb barrier) and at high energies ($E/A \gtrsim 1$ GeV/A). At low energies the reaction is assumed to proceed through the formation of a very short lived di-nuclear system accompanied by transfer or diffusion of nucleons.[8-10,14,15,16] It has been shown that the cross sections for the production of isotopes follow the relation[8]

$$\sigma = f(Z) \cdot \exp\ (Q_{gg}/T) \tag{1}$$

where f(Z) depends only on the nuclear charge of the reaction products, Q_{gg} is the ground state Q-value of the corresponding transfer reaction and T is a constant. Such a dependence derives from a statistical model of a partially equilibrated di-nuclear system and the parameter T is interpreted as an effective temperature.[8,14,15] Equation (1) has, however, also been obtained by the molecular wave function method[16] which does not use the concept of temperature. At higher energies, on the other hand, the ablation mechanism has been shown to result in a comparable expression for the particle yields[6,17]

$$\sigma(N,Z) = C \sum_i \exp\ (Q_i/T). \tag{2}$$

Here C is a constant, the Q_i are threshold Q-values for the various projectile fragmentations and T corresponds to the effective temperature of the excited projectile. The sum includes all possible break-up channels producing the experimentally observed fragment.

In Fig. 2 the experimental cross sections are compared with the predictions of Eq. (1) by plotting the logarithms of the particle yields vs. Q_{gg}. According to Eq. (1), the points for different isotopes of a given element should lie on a straight line and the lines for different elements should have the same slope (displaced by ΔV_C, the difference between entrance and exit channel Coulomb barriers[8,14]). It is evident in Fig. 2 that these predicted trends are poorly reproduced[18] by the data at 20 MeV/A compared to the quality of agreement obtained at lower energies.[8,12] Equation (1) is not expected to be relevant for the 2.1 GeV/A data, and a similar plot shows that the slopes of lines through isotopes not only vary (as in Fig. 2) but even change sign. On the other hand, Eq. (2) reproduces the observed particle yields both at 20 MeV/A and at 2.1 GeV/A[6] to a remarkable degree of accuracy as shown in Fig. 3 where the ratios $C(N,Z) \equiv \sigma_{exp}(N,Z)/(\sum_i \exp(Q_i/T))$ are plotted for all particles lighter than the projectile. (If Eq. (2) holds these ratios should be constant.) Note that Eq. (2) fails for the reaction $^{16}O + {}^{232}Th$ at 137 MeV (i.e. 3 MeV/A above the Coulomb barrier) where the ratios $C(N,Z)$ vary by several orders of magnitude for any temperature between 1 and 10 MeV.

The relative particle yields at 2.1 GeV energy have also been interpreted in terms of a direct fragmentation of the projectile into its cluster sub-structures.[19] Therefore the statistical decay aspect of the reaction mechanism still requires experimental verification from a measurement of the relative probabilities of the different fragmentation channels occuring in the sum of Eq. (2).

In conclusion we have shown that there is a remarkable similarity of the inclusive particle yields for peripheral reactions between ^{16}O and ^{208}Pb at 20 MeV/A and 2.1 GeV/A laboratory energies. The failure of isotope production cross section systematics associated with the formation of a di-nuclear system which are established for energies a few MeV/A above the Coulomb barrier[8] indicates that the link between high and low energy phenomena in peripheral collisions of heavy ions can be made in the energy range of a few tens of MeV/A where the ion velocities are comparable to the Fermi velocity.

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

†Permanent address: Institut des Sciences Nucléaires, Cedex 257, 38044 Grenoble, France.

‡Permanent address: Instituto de Fisica, U.N.A.M., Mexico

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TABLE CAPTION

Integrated cross sections for peripheral interactions of ^{16}O on ^{208}Pb at 315 MeV (this experiment) and 33.6 GeV (Ref. 2). The total peripheral cross section and the total reaction cross section are also shown.

Table 1.

Particle	σ(315 MeV)[mb]		σ(33.6 GeV)[mb]	
^{19}F	20±2		-	
^{15}O	38±19		138±22	
^{15}N	211±53		202±26	
^{14}N	140±42	378±57	71.2±22.5	290±35
^{13}N	27^{+5}_{-14}		17±3.1	
^{14}C	43^{+7}_{-22}		12.3±2.2	
^{13}C	127^{+19}_{-32}		45.4±8.3	
^{12}C	198±30	396±59	126±25	228±27
^{11}C	28^{+4}_{-14}		36.9±5.7	
^{10}C	-		7.2±1.4	
^{13}B	-		.699±.436	
^{12}B	23^{+8}_{-12}	187±23	3.98±.75	93±13
^{11}B	114^{+40}_{-17}		52.8±5.9	
^{10}B	50±18		35.2±11.3	
^{10}Be	39^{+19}_{-10}		6.8±1.14	
^{9}Be	54^{+27}_{-8}	108±12	15.3±2.1	65±7
^{7}Be	15^{+8}_{-3}		43.±6.9	

(continued)

Table 1. (continued)

Particle	σ(315 MeV[mb]		σ(33.6 GeV[mb]	
^{9}Li	$5.0^{+1.8}_{-2.5}$		-	
^{8}Li	16^{+6}_{-8}		-	
^{7}Li	93^{+33}_{-19}	168±18	39.7±4.3	96±14
^{6}Li	54^{+19}_{-16}		56±13.4	
σ_P	1295±194		910±53	
σ_R	3400		3100	

FIGURE CAPTIONS

Fig. 1. Ratios of cross sections measured for the reactions $^{16}O + {}^{208}Pb$ at 315 MeV and 33.6 GeV laboratory energies.

Fig. 2. Dependence of isotope yields on the ground state Q-values (Eq. 1) of the corresponding multinucleon transfer reactions induced by $^{16}O + {}^{208}Pb$ at 315 MeV laboratory energy. Isotopes lying on approximately straight lines have been connected.

Fig. 3. Plot of ratios $C(N,Z) = \sigma_{exp}(N,Z)[\sum_i \exp(Q_i/T)]^{-1}$ (Eq. 2) for particles observed in the reaction $^{16}O + {}^{208}Pb$ at (a) 315 MeV and (b) 33.6 GeV (Ref. 2) laboratory energies. The effective temperatures T = 7.3 MeV and T = 6.2 MeV have been used at the energies of 315 MeV and 33.6 GeV, respectively.

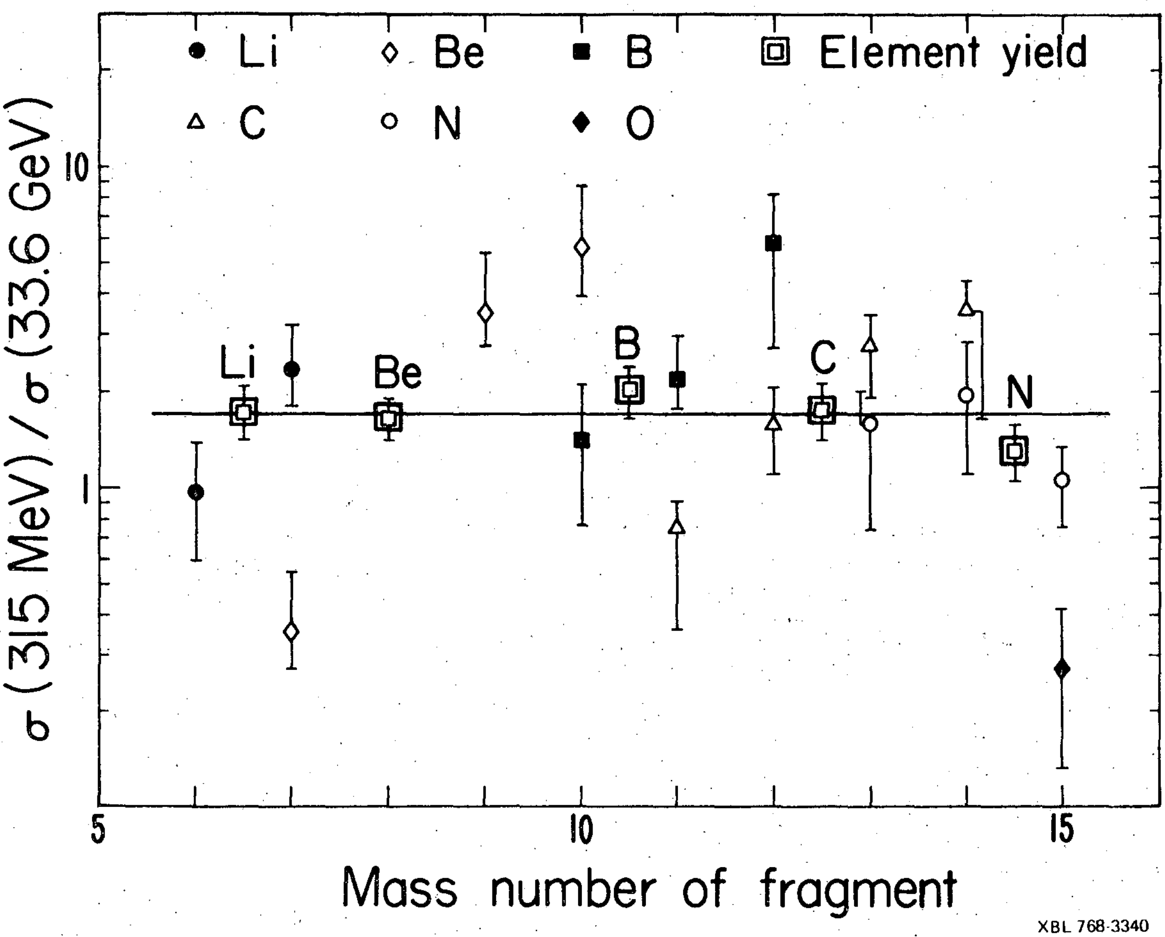
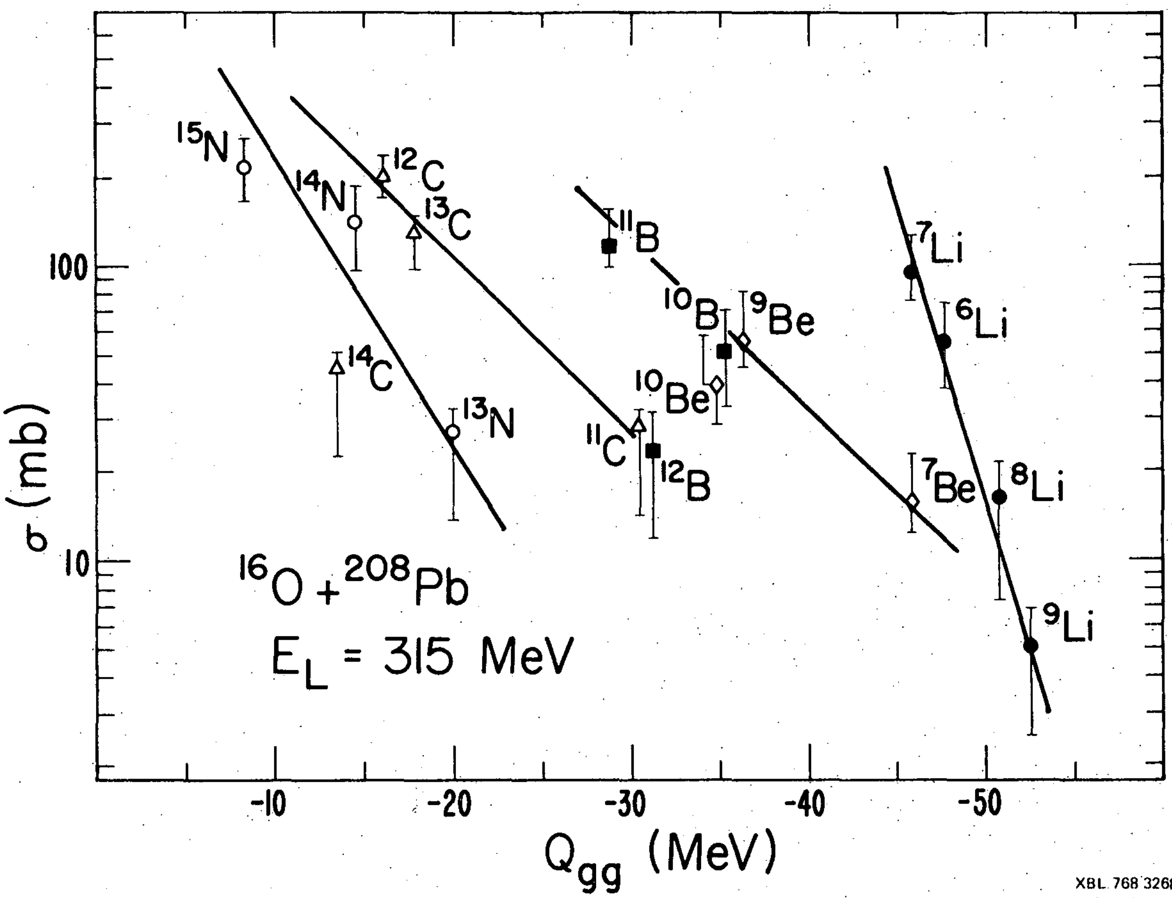

Li
Be
B
Element yield
C
N
O
10
1
σ (315 MeV) / σ (33.6 GeV)
Li
Be
B
C
N
5
10
15
Mass number of fragment
XBL 768-3340

Fig. 1



^{15}N
^{14}N
^{12}C
^{13}C
^{14}C
^{13}N
^{11}B
^{10}B
^{9}Be
^{10}Be
^{11}C
^{12}B
^{7}Li
^{6}Li
^{7}Be
^{8}Li
^{9}Li
100
10
σ (mb)
^{16}O + ^{208}Pb
E_L = 315 MeV
-10
-20
-30
-40
-50
Q_{gg} (MeV)
XBL 768 3268

Fig. 2

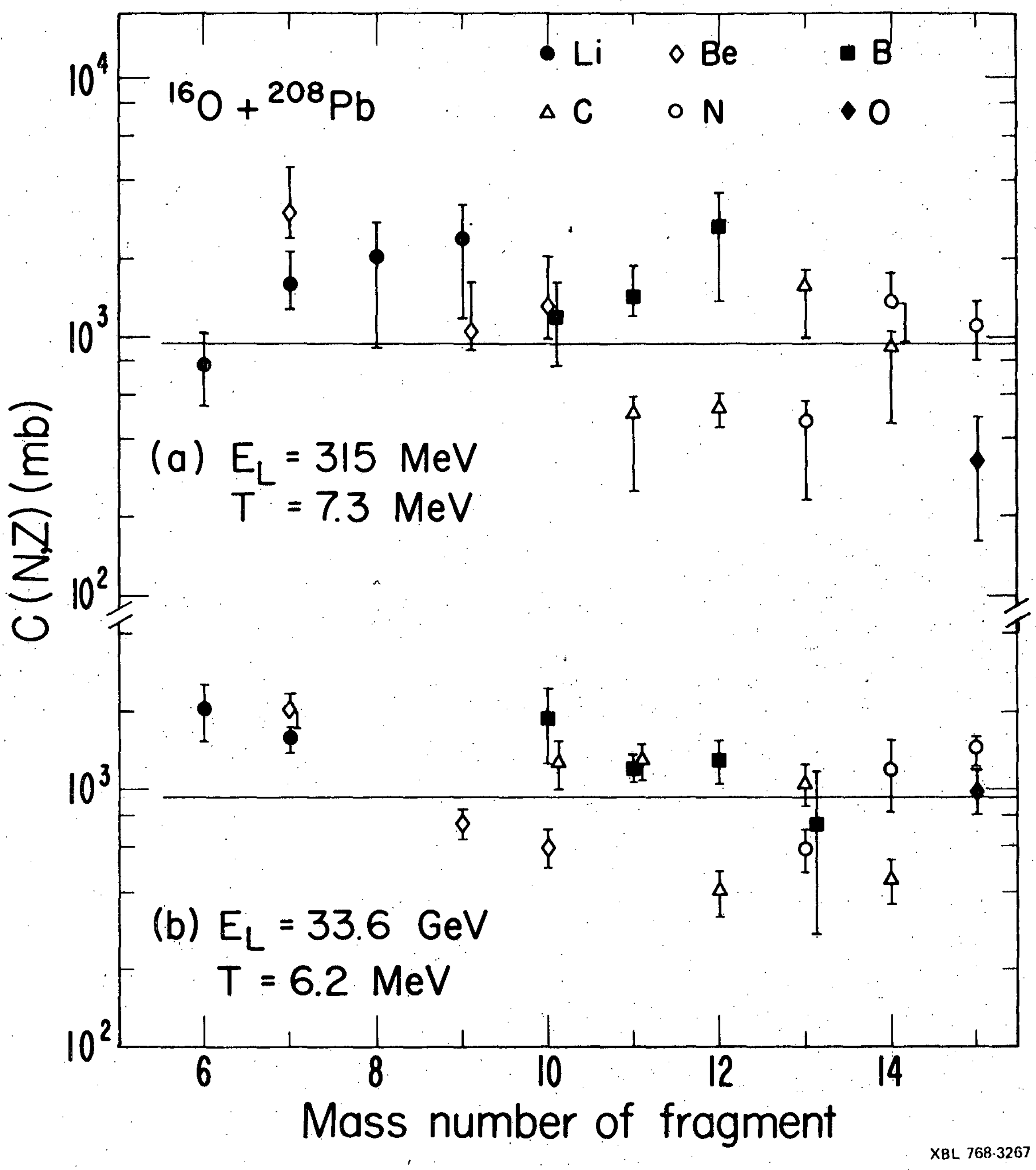

Li
Be
B
C
N
O
$^{16}O + ^{208}Pb$
(a) E_L = 315 MeV
T = 7.3 MeV
(b) E_L = 33.6 GeV
T = 6.2 MeV
C(N,Z) (mb)
Mass number of fragment
XBL 768-3267

Fig. 3

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720