the amplitudes of the fine-structure peaks to decrease with increasing excitation energy.

Figure 3 shows the angular distribution of the GR for these nuclei at 172.5 MeV incident energy. These experimental data show a structure which can be described in distorted-wave Born-approximation (DWBA) calculations with $L=2$. Similar results have been obtained at 145 MeV. This supports the predominant isoscalar quadrupole nature of the strong excitation in the GR region. On the basis of calculations similar to those of Ref. 4, the isoscalar $E2$ EWSR limit is estimated to be depleted in both cases to about 40–70%. The observed increase of the GR cross section with incident α energy at the same momentum transfer is in agreement with DWBA predictions made with extrapolated optical-model parameters.

Finally, the question remains as to why so little $E2$ strength in the GQR region of light nuclei was seen in capture reactions.[2] Possibly, in addition to the configurations involved in the $E2$ excitation in capture reactions, other configurations carrying $E2$ strength can be excited in (α, α') scattering.

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Similarity of Cross Sections for Peripheral Collisions at 20 MeV/A and 2.1 GeV/A*

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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 dinuclear systems and projectile fragmentation.

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 dinuclear 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 report here the surprising similarity of particle yields for peripheral collisions of ^{16}O on ^{208}Pb at laboratory energies of 20 MeV/A ($v/c \approx 0.2$) and 2.1 GeV/A^2 ($v/c \approx 0.95$), possibly indicating a similarity of the reaction mechanism at these energies.

TABLE I. 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.

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	71.2 ± 22.5
^{13}N	27^{+5}_{-14}	17 ± 3.1
Total N	378 ± 57	290 ± 35
^{14}C	43^{+7}_{-22}	12.3 ± 2.2
^{13}C	127^{+19}_{-32}	45.4 ± 8.3
^{12}C	198 ± 30	126 ± 25
^{11}C	28^{+4}_{-14}	36.9 ± 5.7
^{10}C	...	7.2 ± 1.4
Total C	396 ± 59	228 ± 27
^{13}B	...	0.699 ± 0.436
^{12}B	23^{+8}_{-12}	3.98 ± 0.75
^{11}B	114^{+40}_{-17}	52.8 ± 5.9
^{10}B	50 ± 18	35.2 ± 11.3
Total B	187 ± 23	93 ± 13
^{10}Be	39^{+19}_{-10}	6.8 ± 1.14
^{9}Be	54^{+27}_{-8}	15.3 ± 2.1
^{7}Be	15^{+8}_{-3}	43 ± 6.9
Total Be	108 ± 12	65 ± 7
^{9}Li	$5.0^{+1.8}_{-2.5}$	...
^{8}Li	16^{+6}_{-8}	...
^{7}Li	93^{+33}_{-19}	39.7 ± 4.3
^{6}Li	54^{+19}_{-16}	56 ± 13.4
Total Li	168 ± 18	96 ± 14
σ_P	1295 ± 194	910 ± 53
σ_R	3400	3100

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-in. 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-, 80-, and 3000-μm thickness, respectively. Absolute cross sections were obtained by measuring 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 ($\theta_{c.m.} \lesssim 20°$), the energy spectra for all outgoing particles with $3 \leqslant Z \leqslant 8$ and $A < 16$ exhibit broad peaks (full width at half-maximum $\approx 50-100$ 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 $\theta_{c.m.} \approx 20°$. 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 I gives a comparison of the cross sections at laboratory energies of 315 MeV (given by 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:

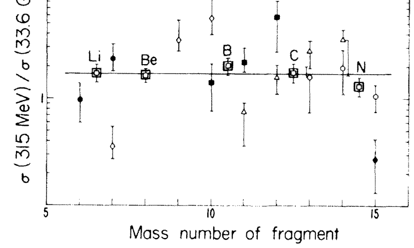

FIG. 1. Ratios of cross sections measured for the reactions ^{16}O + ^{208}Pb at 315-MeV and 33.6-GeV laboratory energies.

(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 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] $\sigma_F = [1.0(A_1^{1/3} + A_2^{1/3})]^2$ 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 dinuclear system accompanied by transfer or diffusion of nucleons.[8-10,14-16] It has been shown that the cross sections for the production of isotopes follow the relation[8]

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

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 is derived from a statistical model of a partially equilibrated dinuclear system; and the parameter T in 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.

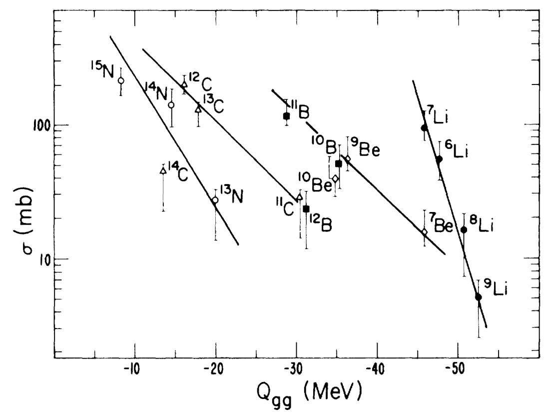

FIG. 2. Dependence of isotope yields on the ground-state Q values [Eq. (1)] of the corresponding multinucleon transfer reactions induced by ^{16}O + ^{208}Pb at 315-MeV laboratory energy. Isotopes lying on approximately straight lines have been connected.

In Fig. 2, the experimental cross sections are compared with the predictions of Eq. (1) by plotting the logarithms of the particle yields versus 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-channel 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 $C(N, Z) \equiv \sigma_{\text{exp}}(N, Z)/[\sum_i \exp(Q_i/T)]$ are plotted for all particles lighter than the projectile.[19] [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 substructures.[20] Therefore, the statistical-de-

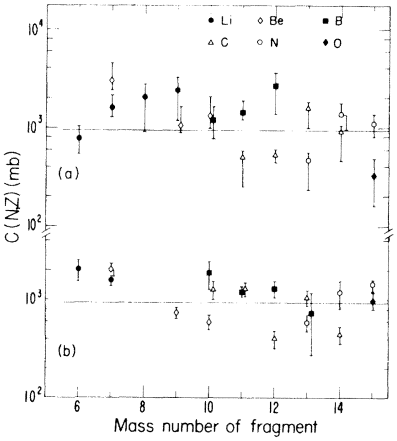

FIG. 3. Plot of ratios $C(N,Z)=\sigma_{\exp}(N,Z)/[\sum_i \exp(Q_i/T)]$ [Eq. (2)] for particles observed in the reaction ^{16}O +^{208}Pb at (a) 315-MeV (present work) and (b) 33.6-GeV (Ref. 2) laboratory energies. The effecitve temperatures $T=7.3$ and $T=6.2$ MeV have been used at the energies of 315 MeV and 33.6 GeV, respectively (Ref. 19).

cay 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 dinuclear system which are established for energies a few MeV/A above the Coulomb barrier[8] indicates that the link between high-energy and low-energy phenomena in peripheral collisions of heavy ions occurs at energies less than a few tens of MeV/A.

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