the gravitational red shift of a photon. At a height of 20 meters this would produce a shift in the energy of the gamma rays which would be 1% of the width. With a one-curie source of Co^{57}, this effect would be measured with 10% accuracy, in 20 hours of counting. An experiment to measure this is also under way in collaboration with Dr. Cranshaw and awaits the successful preparation of a source of sufficient intensity.[3]

*John Simon Guggenheim Fellow on leave from Argonne National Laboratory, Lemont, Illinois.

[1]R. L. Mossbauer, Z. Naturforsch. 14a, 211 (1959). Craig, Dash, McGuire, Nagle, and Reiswig, Phys. Rev. Letters 3, 221 (1959).

[2]Lee, Meyer-Schutzmeister, Schiffer, and Vincent, Phys. Rev. Letters 3, 223 (1959).

[3]After the conception of this last experiment it came to our attention that this application of recoilless resonance absorption has also been proposed by D. H. Wilkinson and by A. Boyle and S. Devons several months before us. It has also been suggested more recently by R. V. Pound and G. A. Rebka, Jr., Phys. Rev. Letters 3, 439 (1959).

NUCLEAR FRAGMENTS PRODUCED IN THE HEAVY ION BOMBARDMENT OF ALUMINUM*

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(Received November 13, 1959)

We have observed reaction products ranging from lithium to fluorine produced by bombarding aluminum with 160-Mev oxygen ions. The data were taken by means of a plotting oscilloscope which recorded the energy and rate of energy loss of each particle. The energy detector was a CsI scintillator and the dE/dx detector was a short proportional counter. A photographic record of 2000 particles is shown in Fig. 1. Each spot represents a detected particle. Its location on the photograph is determined by its energy and its rate of energy loss. Each curved line represents particles of the same Z, since dE/dx is approximately proportional to MZ^2/E. This simple relationship is modified by the dependence of the pulse-height response of CsI on the type and energy of particle[1] as well as by the dependence of the effective charge of the particle on energy. In principle each curve could be further separated into isotopes. The lack of separation may be due to insufficient detector resolution but also may be due in these photographs to the ratios of yields of different isotopes, i.e., an isotope in large yield may obscure small yields of adjacent isotopes.

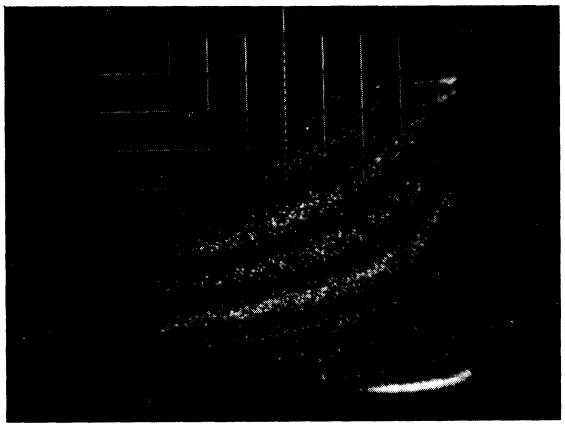

FIG. 1. Photographic record of nuclear fragments emitted at 15° in the bombardment of Al by 160-Mev oxygen ions. E increases to the left and dE/dx increases upward. The three most prominent lines in the center are due to oxygen, nitrogen, and carbon fragments; the solid line at the bottom is due to helium; also visible but less conspicuous are lines due to lithium, beryllium, boron, and fluorine and a few heavier fragments.

The energy spectrum and angular distribution in the laboratory for each element can be determined by counting and measuring the CsI pulse-height coordinates of spots on photographs. Photographs to be counted are limited to about 200 particles to reduce the possibility of overlapping spots.

Preliminary results obtained from 10 photographs at each angle of observation are shown in Figs. 2 and 3. Figure 2 shows the total number of particles emitted of each element (independent of energy) as a function of laboratory angle. Figure 3 shows the energy spectra of emitted carbon fragments in the center-of-mass system at various center-of-mass angles. The center-of-mass transformation was made assuming that the carbon fragments were of mass 12.

Table I gives the total cross section for the production of each element obtained by numerical integration of the yield as a function of the labor-

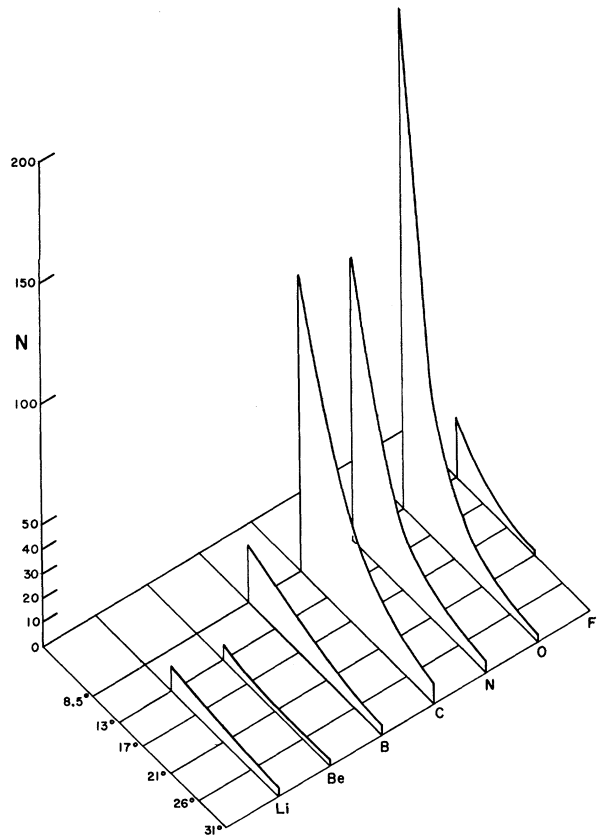

FIG. 2. Total numbers of particles per unit solid angle versus laboratory angle of observation.

atory angle. The cross sections for Li and Be are minimum values since the angular distributions are rather flat and larger angles may make appreciable contributions. Relative cross sections for B, C, N, and F are estimated to be accurate to ± 20% while the errors on the absolute cross sections are estimated to be about ± 50%. The value for the oxygen cross section depends on how the separation of elastic from inelastic events is made.

Table I. Total cross sections in millibarns for production of nuclear fragments in the bombardment of Al by 160-Mev oxygen ions.

Element	σ (mb)
Fluorine	30
Oxygen (inelastic)	150-300
Nitrogen	170
Carbon	210
Boron	60
Beryllium	>20
Lithium	>30

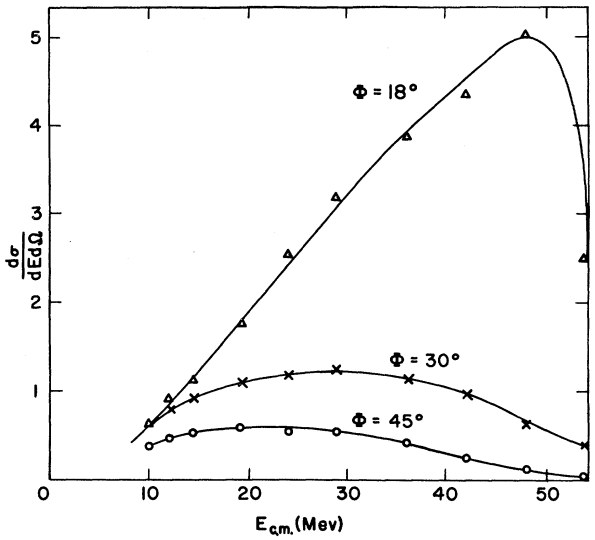

FIG. 3. Differential cross section in millibarns per Mev per steradian for carbon fragments in the center-of-mass system.

Fragments produced in the bombardment of a polyethylene target by 160-Mev oxygen ions have also been observed by visual inspection of pictures similar to Fig. 1. Qualitatively the spectra and relative numbers of particles in this reaction are very similar to those of the oxygen on aluminum reaction except for an obvious difference in elastic scattering at the smallest angles of observation.

We interpret these results in the following way:

1. The relatively flat angular distribution of Li products as well as their low cross section (an order of magnitude less than that of α particles observed, but not shown here) suggest their production by evaporation from a compound nucleus.[2] A similar argument applies, but less strongly, to the Be products.

2. The very large cross sections for the heavier fragments definitely rule out evaporation processes even without considering their angular distributions.

3. Comparison with radiochemical data[3] shows that the radiochemically observable products form only a small fraction of the total yield for fragments lighter than the projectile. The thick-target C^{11} cross section is about 1% of our observed carbon fragment cross section at 160 Mev. Similarly the N^{13} cross section is 2 or 3% of our observed nitrogen fragment cross section. This indicates that the more stable isotopes are produced with much greater cross section than

the previously observed radioactive products.

4. The angular distributions of carbon fragments are strongly peaked at forward angles in the center-of-mass system. This is particularly true for those fragments whose velocity approaches that of the incident oxygen ion. These observations suggest that "impact disintegration" or "stripping" of the projectile plays a large part in the production of fragments lighter than the projectile. This is also supported by studies of stars produced in nuclear emulsions by energetic carbon[4] and nitrogen[5] ions.

5. The fluorine fragment cross section, although much lower than that for C, N, and O, is still rather large compared to observed cross sections for nucleon transfer processes.[6] The fluorine fragments are also of conspicuously lower energy than the C, N, and O fragments. Thus it is suggested that the fluorines may be produced by breakup of target nuclei although an appreciable part of the cross section may still be due to nucleon transfer to the projectile.

6. The qualitative lack of dependence of the products of high yield on the nature of the target indicates that processes involving breakup or stripping of the projectile predominate in these observations.

7. The observed cross section for fragmentation represents a large fraction of the geometric cross section for this reaction. This may be related to the high angular momentum involved in heavy-ion reactions[8] (the rms angular momentum in this reaction is about $30\hbar$). Calculations using the liquid drop model of the nucleus indicate that the compound nucleus may not be formed in collisions involving such high angular momentum.[7]

More detailed studies of specific reaction products will be made. It is hoped that the isotopes of some of the products may be separated using this experimental technique.

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*This work has been supported by the U. S. Atomic Energy Commission.

†National Science Foundation Undergraduate Summer Research Grant.

[1]Quinton, Anderson, and Knox, Phys. Rev. 115, 886 (1959).

[2]J. Hudis and J. M. Miller, Phys. Rev. 112, 1322 (1958).

[3]R. Kaufmann and R. Wolfgang, Phys. Rev. Letters 3, 232 (1959).

[4]J. F. Miller, University of California Radiation Laboratory Report UCRL-1902, 1952 (unpublished).

[5]Parfanovich, Rabin, and Semchinova, J. Exptl. Theoret. Phys. 31, 188 (1956) [translation: Soviet Phys. JETP 4, 99 (1957)].

[6]Volkov, Pasiuk, and Flerov, J. Exptl. Theoret. Phys. 33, 595 (1957) [translation: Soviet Phys. JETP 33, 459 (1958)]; Fisher, Zucker, and Gropp, Phys. Rev. 113, 542 (1959); Karnaukhov, Ter-Akop'yan, and Khalizev, J. Exptl. Theoret. Phys. 36, 748 (1959) [translation: Soviet Phys. JETP 36, 525 (1959)]; J. A. McIntyre (private communication).

[7]R. Beringer and W. J. Knox (private communication).

DISTRIBUTION OF PARTIAL RADIATIVE WIDTHS IN Cu^{59} FOLLOWING PROTON CAPTURE IN Ni^{58}

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(Received November 16, 1959)

In view of recent interest[1,2] in the distribution of partial radiative widths, it seems appropriate to publish some preliminary results from analysis of radiative capture of protons in Ni^{58}. In a previous Letter,[3] a distribution of total radiative widths was given; in addition, using two 5-in. diam×6-in. long NaI detectors, we have obtained information on partial radiative widths by taking spectra of the γ radiation at 0° and 90° to the proton beam. Measurements have been made on 48 of the larger, better separated, resonances.

If the intense components of the spectra are predominantly dipole, the ratio of yields at 0° and 90° gives a strong indication of the spin of the resonant state in Cu^{59}. The estimated radiative widths for emission of radiation of energy 5 Mev are: $E1$, 2 ev; $M1$, 0.04 ev; $E2$, 7×10^{-4} ev; $M2$, 1.5×10^{-5} ev. These estimates are derived from Blatt and Weisskopf,[4] taking 60 kev as an estimate of the mean spacing of levels in Cu^{59} of given J at the excitation energy concerned[5] and 5 Mev for the "single-particle spacing" D_0. Since we are dealing with resonances for which the total radiative widths fluc-

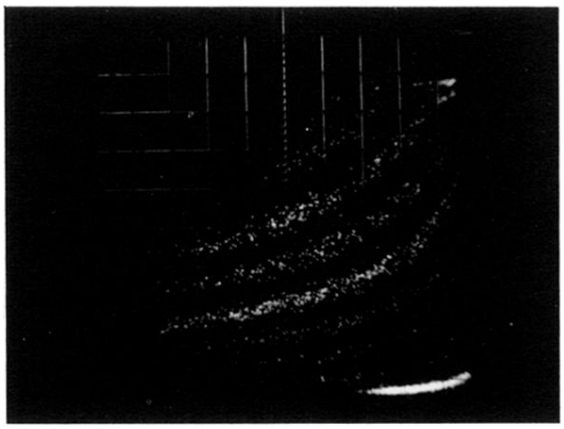

FIG. 1. Photographic record of nuclear fragments emitted at 15° in the bombardment of Al by 160-Mev oxygen ions. E increases to the left and dE/dx increases upward. The three most prominent lines in the center are due to oxygen, nitrogen, and carbon fragments; the solid line at the bottom is due to helium; also visible but less conspicuous are lines due to lithium, beryllium, boron, and fluorine and a few heavier fragments.