

EXPERIMENTAL EVIDENCE FOR THE INCREASE OF HEAVY ION RANGES BY CHANNELING  
IN CRYSTALLINE STRUCTURE

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(Received 25 March 1963)

Recent experiments at Chalk River on the effect of low-temperature neutron irradiation of aluminum suggested the presence of a focusing event in the atomic collisions.<sup>1</sup> However, in aluminum, the normal focuson and focusing replacement collisions, in which momentum is transferred along preferred directions in the lattice, are not expected because of the small ratio of ion size to interatomic distance.<sup>2</sup> Therefore, a different type of focusing event is probably occurring. Concurrent with these experiments, computer calculations at Oak Ridge<sup>3</sup> and the General Electric Company<sup>4</sup> predicted a tunnel focusing or channeling event in which an atom with high energy can readily move down the channel between atoms aligned in the close-packed directions. This channeling could influence the measured ranges of high-energy atoms in crystalline lattices. In fact, earlier experimental studies at Chalk River<sup>5,6</sup> and at Stockholm<sup>7</sup> on the range of bombarding ions in polycrystalline aluminum showed that some of the incident ions penetrated several times the mean range to form an exponential tail in the range curve. This tail was not expected from Monte Carlo calculations on an amorphous structure, and has been interpreted by Robinson and Oen<sup>8</sup> as evidence for atoms traveling a long distance down channels.

In order to investigate the effect of a crystalline structure on the range distribution, two different types of experiments were performed. In both cases the target was bombarded with a 40-keV ion beam of pure Kr<sup>85</sup> (integrated current  $4 \times 10^{14}$  ions/cm<sup>2</sup>) in the Chalk River electromagnetic isotope separator. The range of the ions was measured using the same electrolytic stripping technique as in the previous work.<sup>5</sup>

In the first type of experiment, the range of 40-keV Kr<sup>85</sup> in amorphous Al<sub>2</sub>O<sub>3</sub> was measured by bombarding a series of sixteen aluminum targets, each possessing an anodic oxide layer of different thickness. By measuring the radioactivity of Kr<sup>85</sup> in the target before and after stripping off the oxide layer, the fraction of ions penetrating given thicknesses of oxide was obtained. The range distribution of 40-keV

Kr<sup>85</sup> in polycrystalline aluminum was measured also; the result agrees with that obtained at Stockholm.<sup>7</sup> The measured integral range distribution in Al<sub>2</sub>O<sub>3</sub>, shown in Fig. 1(a), has the shape predicted by a Monte Carlo analysis for a random structure and does not have the exponential tail found in the metal. This marked difference in behavior between the amorphous oxide and the polycrystalline metal strongly suggests that the exponential tail observed in the metal is due to its crystalline nature.

In the second type of experiment, the range distributions in a single crystal of aluminum were measured as a function of the crystallographic orientation with respect to the incident beam. A crystal with a flat face 28° from the <110>, <100>, and <111> directions was cut from

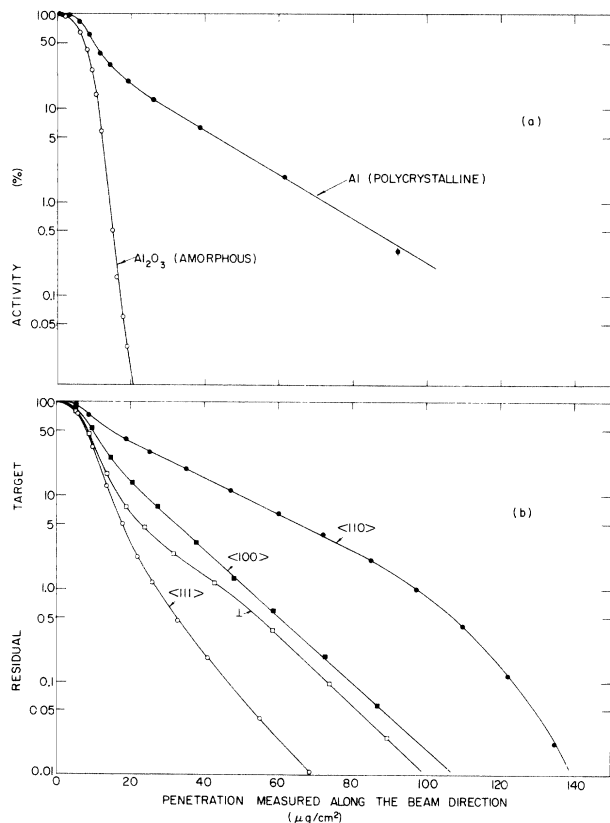


FIG. 1. Experimental range curves showing the residual target activity (percentage of ions not yet stopped) plotted against the penetration distance.

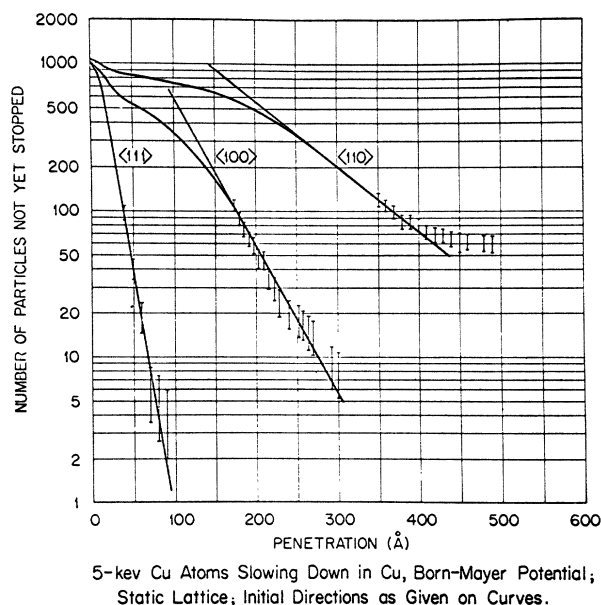


FIG. 2. Calculated range curves<sup>8</sup> with statistical error shown by the vertical bars.

a melt-grown crystal of 99.99% purity using a sparkatron, and electropolished to within  $2^\circ$  of the desired orientation. Bombardments and range determinations were made in the usual way.<sup>5,6</sup> Figure 1(b) shows the integral range distribution curves for the crystal at normal incidence (beam  $7^\circ$  from  $\langle 211 \rangle$ ) and for the same crystal tilted  $28^\circ$  in order to align the  $\langle 110 \rangle$ , the  $\langle 100 \rangle$ , or the  $\langle 111 \rangle$  direction with the beam of krypton ions. The penetration is given in the direction parallel to the incident beam. The results show that both the slope and the intensity of the penetrating tail are very much affected by the orientation of the crystal. A simple lattice model

predicts that the directions of preferred penetration should increase in the order  $\langle 111 \rangle$ ,  $\langle 211 \rangle$ ,  $\langle 100 \rangle$ ,  $\langle 110 \rangle$ , and the experimental results [Fig. 1(b)] are consistent with this prediction.

Recently, Robinson and Oen<sup>8</sup> have developed a computer program for determining range distributions in a crystalline solid. Figure 2 shows their calculated integral range distributions for 5-keV copper ions incident upon the various principal planes of copper which, like aluminum, has a face-centered cubic lattice. The statistical uncertainty in the calculation is shown by the vertical bars along the curves. In these calculations the exponential tail is due to those ions that had become focused down channels between lines of close-packed atoms. The striking qualitative resemblance between experiment and calculation strongly supports the existence of a channeling process, although a quantitative comparison is not yet possible due to the difference in energy, target material, and incident ions.

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<sup>7</sup>I. Bergström, J. A. Davies, B. Domeij, and J. Uhler (to be published).

<sup>8</sup>M. T. Robinson and O. S. Oen (to be published).

### TRIPLET EXCITONS AND DELAYED FLUORESCENCE IN ANTHRACENE CRYSTALS

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(Received 25 March 1963)

Laser-induced fluorescence in powdered anthracene and several other organic materials was recently reported.<sup>1</sup> The fluorescence was attributed to double photon excitation from the singlet ground state to the first-excited singlet state. While studying this fluorescence in anthracene single crystals, we detected delayed fluorescence after the laser pulse ended. We

explain the rate of decay of this fluorescence and other experimental observations by assuming that the singlet state giving rise to the fluorescence is produced not by a double photon process as concluded by Peticolas, Goldsborough, and Rieckhoff,<sup>1</sup> but via bimolecular annihilation of triplet excitons generated directly by the ruby laser light. The lifetime and the bimolecular