Ranges of Low-Energy Gallium Atoms in Copper and Zinc*

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The ranges of 0.07–1.0-MeV gallium atoms in copper and zinc have been measured by means of thick-target recoil experiments. Monoenergetic gallium recoils were generated by the $Zn^{64}(p,\gamma)$, $Zn^{64}(d,\gamma)$, and $Cu^{63}(\alpha,\gamma)$ reactions. The results can be expressed by an empirical range-energy relation of the form $R(\mu g/cm^2)=0.193\,E(keV)$ for $E\leq 1.0$ MeV. The results of the present experiment and of other studies in this mass range are compared with the theoretical range-energy relation of Lindhard, Scharff, and Schiott, and very good agreement is found for values of the reduced energy ranging from 0.4 to 5.0. The low-energy results are also compared with the calculation of Oen, Holmes, and Robinson. In its simplest form, this calculation predicts range values that are significantly larger than the experimental results.

I. INTRODUCTION

THE investigation of the recoil properties of residual nuclei has proved to be a useful tool in the study of nuclear reactions. One of the simplest techniques employed in these studies is the determination of the recoil loss from targets thicker than the range of the recoil products. The interpretation of these data requires a knowledge of the range-energy relationship for the recoil atoms in the target material. In recent years there have been a number of experimental and theoretical studies of the ranges of monoenergetic atoms with moderately low (≤ 1 MeV) kinetic energies. Davies and his collaborators[1] have measured the ranges of rare-gas and alkali atoms in aluminum and tungsten. These authors have determined the effect of a number of factors on the measured ranges. Powers and Whaling[2] report results of range determinations for a number of low-energy projectiles in solids. Lindhard and Scharff[3] have calculated a universal range-energy relation for low-energy atoms based on a Thomas-Fermi interatomic potential. More recently, this calculation has been modified by Lindhard *et al.*[4] to take account of the important contribution of electronic stopping. An alternative theoretical treatment has recently been developed by Oen *et al.*[5] who use a Monte Carlo technique for calculating the ranges of low-energy atoms on the assumption of an exponentially screened Coulomb potential for the scattering process.

In order to apply these theoretical relations to an analysis of thick-target recoil data, it would first be desirable to compare them with range-energy data obtained from thick-target studies. The reason for this is related to the fact that the latter differ in principle both from the theoretical models and the above-mentioned range-energy experiments in that the escaping atoms move through both the target and catcher media before coming to rest. This gives rise to possible scattering effects at the interface and these are not considered in the calculations. A number of investigators[6–8] have, in fact, shown that measurable scattering effects at an interface are obtained in the case of recoiling fission fragments.

Several range-energy studies, using the thick-target technique, have been reported. The ranges of recoils arising from (γ,n) reactions have been measured by Van Lint *et al.*[9] Bryde, Lassen, and Poulsen[10] measured the ranges of Ga^{66} recoils formed in (α,n) reactions. Winsberg and Alexander[11] determined the ranges of somewhat more energetic Tb recoils produced in heavy-ion induced reactions. In the present study we present range measurements of monoenergetic recoils produced in thick-target irradiations. Monoenergetic recoils can be produced by means of either radiative capture reactions or of reactions involving particle emission at energies barely above the threshold. We have chosen the first of these methods and present results for the $Cu^{63}(\alpha,\gamma)$, $Zn^{64}(p,\gamma)$, and $Zn^{64}(d,\gamma)$ reactions, all leading to the formation of gallium atoms with known energies. Strictly speaking, of course, the gallium atoms will not be monoenergetic because of recoil due to γ-ray emission. However, the recoil energy due to this process is in all cases less than 2% of that due to the capture of the projectile, and may be neglected.

II. EXPERIMENTAL PROCEDURE

In this experiment targets were irradiated with the deflected proton, deuteron, and He^4-ion beams of the

* Supported in part by the U. S. Atomic Energy Commission.
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Brookhaven 60-in. cyclotron. The target foils were placed in an evacuated chamber attached to a Faraday cup.[12] Bombardments were performed for periods of 1–300 min, with ion currents of approximately 0.05–0.5 μA. The targets for the (p,γ) and (d,γ) reaction studies consisted of zinc foils[13] enriched to 98.5 at.% in Zn^{64}. These foils had a uniform thickness of 1.7 mg/cm^2. The targets for the (α,γ) experiments consisted of copper evaporated to a thickness of 1.5 mg/cm^2 onto 0.00025-in-thick aluminum. During bombardment, the target foils were placed adjacent to 0.001-in-thick aluminum catcher foils of high purity (99.99%). In some cases, 0.00025-in.-thick Mylar foils were used as catchers. The foils had a larger cross-sectional area than that of the beam in all cases, so that there was no recoil loss due to edge effects. Prior to bombardment, the various foils were carefully rinsed with acetone and water.

The target stack consisted of the target and catcher foils, of additional aluminum or Mylar foils that served to determine the activation blank, and of aluminum foils that served to degrade the energy of the incident particles to the desired values. The bombarding energy at a particular position in the target stack was determined by means of a range-energy relation based on the data for protons of Bichsel *et al.*[14] The initial energy was usually determined by means of range measurements. In view of the fact that the incident beam was being continually degraded in energy throughout the target stack, it was impossible to measure the activation blank at the bombarding energy corresponding to the position of the catcher foils. Instead, the correction was determined by interspersing a number of blank foils throughout the target stack and interpolating to the desired energies. In no case was the activation correction larger than 5%. In some instances, a check was made of recoil emission in the backward direction. Although conservation of momentum forbids this type of emission, large-angle scattering processes could lead to it. No evidence for backward emission was, in fact, found.

After irradiation the target stack was disassembled for assay of the activity of the target, forward catcher, and activation blank foils. In some instances gallium was radiochemically separated[15] from the catcher and blank foils as extraneous activities were found to interfere. The activity of 15-min Ga^{65} formed in the Zn^{64} (p,γ) reaction was assayed with end-window beta-proportional counters. Self-absorption studies indicated that the counter efficiency for Ga^{65} was the same, within experimental error, for both the target and catcher samples. The activity of 9.5-h Ga^{66}, resulting from the $Zn^{64}(d,\gamma)$ reaction, was determined in the same manner as that of Ga^{65}. In this case too, the counter efficiency was the same for all samples. A 3-in.×3-in. NaI(Tl) detector connected to a 100-channel pulse-height analyzer was used to measure the γ rays of 78-h Ga^{67} produced by the $Cu^{63}(\alpha,\gamma)$ reaction.

The experimental average ranges in the target material are given by the expression

$$R=FW, \tag{1}$$

where F is the fraction of the total activity of a given nuclide found in the forward recoil catcher and W is the target thickness. The type of range obtained in this experiment has been variously referred to as the average projected range[4] and the average penetration.[5] The above expression assumes that the recoil production rate is constant throughout the target. It has been pointed out[16] that this assumption is often not valid for reactions with steep excitation functions, particularly if the energy degradation in the target is appreciable. The information on the degradation of the various projectiles is summarized in Table I, and it is seen that

TABLE I. Experimental ranges of gallium atoms.

Reaction	Bombarding energy MeV	c	Recoil energy keV	FW μg/cm^2	R μg/cm^2
$Zn^{64}(p,\gamma)Ga^{65}$	4.9–5.0	0.1	75±2	6.7	7.0±2.4
	6.5–6.6	0.1	100±2	16.4	17.2±3.8
	8.1–8.2	0.0	125±2	25.0	25.0±3.2
	9.0–9.1	0.0	138±2	39.0	39.0±3.5
$Zn^{64}(d,\gamma)Ga^{66}$	4.0–4.3	0.0	121±3	27.7	27.7±2.8
	6.4–6.6	0.0	192±4	34.6	34.6±2.8
$Cu^{63}(\alpha,\gamma)Ga^{67}$	10.8–11.3	0.1	645±8	124	130±14
	13.2–13.6	0.0	788±10	166	166±13
	14.8–15.1	0.0	884±11	175	175±13
	16.1–16.5	0.0	961±13	185	185±14

the energy loss in the target foils varies from 0.1 to 0.5 MeV. If a linear variation of cross section over an energy range corresponding to the target thickness is assumed, i.e., if the relative cross section for a given reaction varies with target thickness as

$$\sigma=1+(ct/W), \tag{2}$$

where $t=0$ at the target-catcher interface, then one obtains the values of the constant c listed in Table I. These values were obtained by interpolation from the measured excitation functions. It is seen that σ is constant in all cases except those for the (p,γ) and (α,γ) reactions at the lowest energies, where a 10% variation is noted. It can be shown that the range of recoils initially moving in the forward direction is given by

$$R=FW(1+\tfrac{1}{2}c), \tag{3}$$

if the variation of σ with t given in Eq. (2) is assumed. It is also assumed that range is proportional to energy and that $F\ll 1$.

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[13] Obtained from Oak Ridge National Laboratory.
[14] H. Bichsel, R. F. Mozley, and W. A. Aron, Phys. Rev. **105**, 1788 (1957).
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[16] N. T. Porile, Phys. Rev. **127**, 224 (1962).

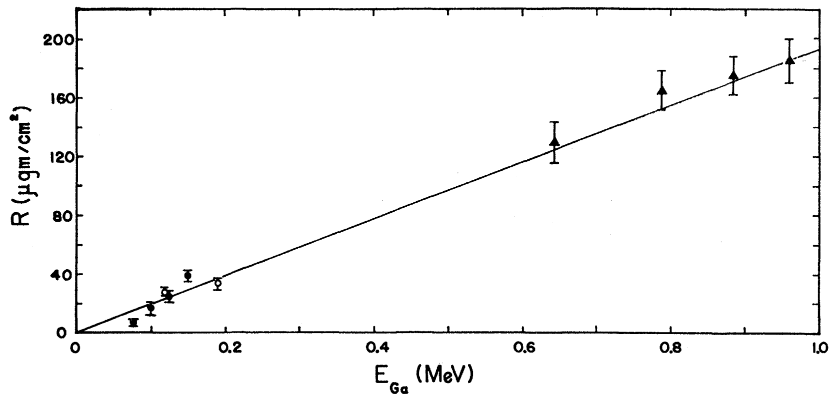

Fig. 1. Range-energy relation for gallium atoms in zinc or copper. ●—(p,γ) recoil ranges; ○—(d,γ) recoil ranges; ▲—(α,γ) recoil ranges.

III. RESULTS AND DISCUSSION

The results of the range measurements are summarized in Table I. The recoil energy was obtained from the projectile energy assuming conservation of momentum. This computation was based on the bombarding energy at the downstream end of the target in view of the fact that the ejected recoil atoms originate in a layer of negligible thickness at this location. The error associated with the recoil energy is based on the estimated uncertainty in beam energy and on the estimated energy straggling. The effect of recoil due to γ-ray emission has been neglected in the equations for the recoil range but has been included in the estimated uncertainty of the recoil energy. The recoil energy due to γ-ray emission is at most 1–2% of that due to the capture of deuterons and protons and less than 0.3% of that due to capture of an α particle. The experimental values of FW have been converted to ranges by means of Eq. (3). The errors of the ranges are based on the uncertainty in the activation correction, the error in the correction for cross-section variation, the statistical error in the activity measurements, and on the uncertainty in thickness and uniformity of the target foils.

The range-energy data are plotted in Fig. 1. It is seen that the ranges show an approximately linear dependence on recoil energy. The empirical relation $R(\mu\text{g/cm}^2)=0.193\,E$ (keV) gives a good fit to the data over the energy range of 0.1–1.0 MeV, as shown in Fig. 1.

The results of this study may be compared with the universal range-energy relation obtained by Lindhard, Scharff, and Schiott.[4] The results of these authors are given in terms of the dependence of the reduced range ρ on the reduced energy ϵ and a family of ρ-ϵ curves characterized by the value of the electronic stopping parameter k is obtained. Lindhard's calculated range refers to the total path length of the recoil atoms, whereas the experimental range corresponds to the projection along the initial direction of motion. We have converted the experimental ranges to total path lengths in the manner suggested by Lindhard *et al.*[4] This amounts to increasing the ranges by factors of 1.2–1.4.

The experimental results are shown on a $\rho-\epsilon$ plot in Fig. 2. We include the results of two other thick-target studies in the mass region of interest. Bryde *et al.*[10] measured the ranges of Ga^{66} atoms produced in the $Cu^{63}(\alpha,n)$ reaction. We have reduced their range values by 2–5% in order to account for the effect of recoil due to neutron evaporation.[17] Van Lint *et al.*[9] measured the ranges of Cu^{62} atoms formed in the $Cu^{63}(\gamma,n)$ reaction. These authors calculated the recoil energies on the assumption that neutrons were emitted with kinetic energies corresponding to an evaporation spectrum. Some representative data from this study are shown in Fig. 2. In all instances, the experimental ranges were

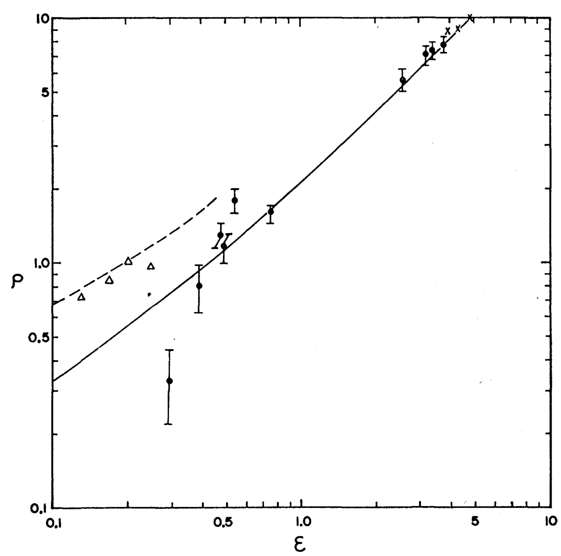

Fig. 2. Comparison of experimental range-energy values for gallium and copper atoms with calculations. ●-present results; X—data of Bryde *et al.* (Ref. 10) for Ga^{66} in copper; Δ—data of Van Lint *et al.* (Ref. 9) for Cu^{62} in copper. Solid curve—calculation of Lindhard *et al.* (Ref. 4) for $k=0.16$. Dashed curve—calculation of Oen *et al.* (Ref. 5) for Bohr's screening radius value. The experimental data have been converted to total path lengths. The ρ-ϵ coordinates are defined by Lindhard *et al.* (Ref. 4).

[17] N. T. Porile, A. M. Poskanzer, and M. Rho, Phys. Rev. **128**, 242 (1962).

first converted to total path lengths. The theoretical curve of Lindhard *et al.*[4] has been computed for $k=0.16$, a value that is appropriate to all the data under consideration. It is seen that both the present results and those of Bryde *et al.*[10] are in very good agreement with the theoretical curve over the entire energy range covered in these studies. This agreement substantiates the belief that Lindhard's theory may be validly applied to the analysis of thick-target recoil data up to moderately high recoil energies.

The data of Van Lint *et al.*[9] lie well above the theoretical curve. Although these results do not quite overlap in recoil energy with the present data, it appears that the two sets of results are mutually inconsistent. This is probably related to the fact that it is difficult to obtain an accurate estimate of the recoil energy from a (γ,n) reaction induced by bremsstrahlung.

The low-energy data may also be compared with the Monte Carlo calculation of Oen *et al.*[5] of the ranges of low-energy atoms in solids. Their results for the total path length of Cu atoms slowing down in Cu have been transformed to $\rho-\epsilon$ coordinates and are shown by the dashed line in Fig. 2. This curve, based on Bohr's value for the screening length, predicts range values that are significantly larger than the present results. The calculated curve can be brought into better agreement with experiment by increasing the screening length, as suggested by Oen *et al.*[5]

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Effective *g* Factor of Electrons and Holes in Bismuth

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Shubnikov–de Haas type oscillations have been studied in bismuth in magnetic fields up to 88 kG. Oscillations are observed which have been attributed to the hole band in bismuth. A machine calculation of the density of states and of the Fermi level as a function of magnetic field is used to fit the data. The calculation is based on the nonparabolic (two-band) model of the electron band, and includes the possibility of spin splitting for both electrons and holes. It correctly predicts the observed change in Fermi energy with magnetic field. We find that the hole Landau levels are indeed split by spin. The spin splitting is almost twice the Landau level spacing along the trigonal axis and is extremely small perpendicular to the trigonal axis. Spin splitting is also observed for electrons. We find that the spin splitting is about one-third the orbital splitting in the heaviest mass direction and about 10% larger than the orbital splitting in the light mass direction. Our observations imply that there are important states both above and below the hole band. This is in direct contradiction to the Abrikosov and Falkovskii model which considers only one set of states (either above the hole band or below) with which the hole band interacts.

I. INTRODUCTION

It is well known that the transverse energy of electron or hole states in a magnetic field will be quantized, the allowed energies being called Landau levels and the spacing between levels being proportional to the field strength H. Since the electron has a spin degree of freedom, each Landau level has a twofold degeneracy arising from spin. Associated with the spin is a magnetic moment whose energy E_m in the magnetic field is also proportional to the field strength. This energy is often written $E_m=\frac{1}{2}g\beta_0 H$, β_0 being the Bohr magneton and g being denoted the effective g factor. This energy may add to or subtract from the energy of the Landau level, thus splitting each level into a pair of levels. The density of states at the Fermi level in a magnetic field is determined to a large extent by the spacing and splitting of the Landau levels. This paper reports on oscillations in the magnetoresistance of bismuth which result from a change in scattering time as the density of states at the Fermi level is changed by the magnetic field. Previously unobserved oscillations are seen at high field which are attributed to spin splitting of the hole band. With the magnetic field parallel to the binary axis, oscillations from the heavy electron mass are observed and the spin splitting is found to be different than the Landau spacing.

The magnitude of the g factor depends on details of the band structure. For free electrons, $g=2$. The g factor for electrons in bismuth was calculated by Cohen and Blount[1] to be $g=2m_0/m_c$, m_c being the cyclotron effective mass. This value of g factor yields a spin

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