amount to -0.25. Thus we see that the GMB calculation greatly underestimates the magnitude of the correlation energy for the larger values of coupling constant, or in terms of density, for the larger values of r_s. The error grows as the density is decreased and amounts to at least 40% for $r_s = 3$. Although this is a rigorous lower limit on the error in Eq. (1) and has been established here without employing any special model or theory, it should be noted that Nozières and Pines[3] reach qualitatively this same conclusion concerning the GMB formula on the basis of a detailed calculation using the Bohm-Pines formalism.

In conclusion, we wish to emphasize that the limitation found here on the range of validity of Eq. (1) is in no way inconsistent with the claims of GMB and in no way detracts from the fundamental theoretical interest of their work as a weak-coupling calculation. We also wish to acknowledge a stimulating discussion with Dr. Michael Cohen which led to this investigation.

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*Investigation carried out by the author as consultant to the Rand Corporation, while on summer leave from the University of Maryland.

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MEASUREMENT OF THE RANGE OF RECOIL ATOMS

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An important problem[1] in the interpretation of radiation-damage and sputtering phenomena is the evaluation of the range of an atom which moves through a lattice after having received an initial energy of 10 to 100 kev. A novel experimental technique has been applied to the problem of determining the ranges of atoms in the kev region. Atoms with initial energies in this region are produced by irradiating suitable targets with high-energy bremsstrahlung, and the products of photonuclear reactions, such as photoneutron (γ, n) transmutations, are observed. The bremsstrahlung used in this work were generated by a 24-Mev Allis-Chalmers betatron. The photon spectrum is continuous from 0 to 24 Mev; the energy spectra of evaporated neutrons from copper[2] and lead[3] are centered at about 1.5 Mev, with a full width at half maximum of about 2 Mev. Since (1) the energy thresholds for the photoneutron reactions of the majority of the elements reported in Table I are well below 24 Mev and near the copper and lead photoneutron thresholds and (2) all the photonuclear absorption cross sections of elements in Table I closely resemble the giant-resonance cross-section curve of copper and lead, it is anticipated that the spectra of evaporated neutrons for all the targets studied here are centered at about 1.5 Mev, with corresponding half-widths of 2 Mev.

The nucleus receives a negligible amount of momentum from the incoming gamma ray. However, the nucleus (atom) recoils from neutron emission with an energy E_R, given by the formula $E_R = E_N(M_N/M_A)$, where E_N is the neutron energy and M_N and M_A are the masses of the neutron and atom, respectively. As a result of photoneutron emission, the nuclei of the recoiling atoms are usually unstable to beta (positron) decay and, therefore, are amenable to detection by standard scintillation and beta-counting methods.

The ranges were determined for carbon (C^{11} in polystyrene, CH), fluorine (F^{18} in Teflon, CF_2), chlorine (Cl^{34} in Saran, CHCl), and the metals titanium, iron, zinc, copper, molybdenum, silver, and gold in their respective metallic lattices. The method used was somewhat similar to the stacked-foil technique commonly used in charged-particle excitation-function studies. Thin elemental or plastic target foils about 0.001 in. thick were interleaved between 0.0008-in. thick aluminum catchers (Alcoa 1199-0, 99.986% pure). Before use, the metallic foils were cleaned with organic solvents and etched with appropriate acids; plastic foils were detergent-cleaned. In order to evaluate the background activities present in the aluminum catchers, an equal number of aluminum foils without targets were simultaneously irradiated. About 2000 roentgens per minute of 23-Mev bremsstrahlung were incident on the sandwiched targets.

Immediately after irradiation, the sandwich was disassembled and the radioactivities of the

target foils, aluminum catcher foils, and aluminum background-monitoring foils were measured by scintillation-counting the annihilation radiation (0.51 Mev) of the positrons with the single exception of gold (Au^{196}), which was detected via its 354-kev gamma ray. The recoiling atoms which are close to the target-foil surface are caught in the aluminum foils. If the range of the recoil atoms is small compared with the foil thickness, then the range, R, is related to the fraction N_C/N_f of atoms which recoil out of the target foil and to the foil thickness, x, by $R = 2(N_C/N_f)x$, where N_C and N_f are the numbers of atoms that recoil into the catcher and that are retained in the target foil, respectively.

The ranges, obtained by the formula $2(N_C/N_f)x$, are the vector sums of the tortuous paths traveled by the recoiling atoms. Theoretical ranges, calculated by assuming billiard-ball collisions, were made according to Seitz and Koehler,[1] and, in general, the theoretical ranges were many times higher than those observed. Nielsen,[4] following the lines of Bohr,[5] obtains the following theoretical expression for the range:

$$R = 0.6 \frac{(Z_1^{2/3} + Z_2^{2/3})^{1/2}}{Z_1 Z_2} \frac{A_1 + A_2}{A_1} \times A_2 E_1 (\mu g/cm^2) ,$$

where Z_1, A_1 and Z_2, A_2 are the atomic numbers and masses for the incoming particles and the target atoms, respectively, and E_1 is the energy of the incoming particle in kev. In calculating the theoretical ranges for the nonmetals (C^{11}, F^{18}, and Cl^{34}) in their respective plastic matrices, Z_2 and A_2 have been averaged stoichiometrically over the target-foil atoms, excluding the hydrogen atoms. Agreement between observed and theoretical range values is rather good (within a factor of two for most ranges).

The fraction of metal atoms that recoil out of 0.001-in. foils varies exponentially with $1/A$ (which is proportional to the recoil energy); fluorine, chlorine, and carbon in the plastic

Table I. Fraction (N_C/N_f) of activated atoms recoiling out of 0.001-in. foils and calculated ranges of the recoil atoms. (23-Mev bremsstrahlung incident on foils.)

Recoiling atom	Most probable recoil energy [a] (kev)	$(N_C/N_f) \times 10^4$ [b]	Observed range in A (10^{-8}cm)	Observed range in $\mu g/cm^2$ [c]	Theoretical range in $\mu g/cm^2$ [d]
C^{11}	130	216 ± 20	11 000 [e,f]	117	214 [g]
F^{18}	85	182 ± 18	9200 [e,h]	200	105
Cl^{34}	45	104 ± 10	5300 [e,h]	90	31 [g]
Ti^{45}	33	6.1 ± 0.8	310	14	25
Fe^{53}	30	11.0 ± 1.7	560	44	20
Zn^{63}	25	2.7 ± 0.3	137	9.8	15
Cu^{62}	25 ± 16	3.1 ± 0.2	163	14.5	16
Cu^{64}	25 ± 16	3.2 ± 0.2	157	14.0	16
Mo^{91}	16	1.4 ± 0.4	71	7.3	8.1
Ag^{106}	14	1.4 ± 0.3	71	7.5	6.7
Au^{196}	9	0.55 ± 0.06	28	5.4	3.2

[a] Estimated by assuming that the evaporated-neutron spectra were similar in shape to those observed for copper and lead. The average recoil energy is assumed to be 1.6 times the most probable recoil energy.

[b] Errors are two standard deviations of counting statistics only.

[c] Obtained from the previous column by the formula $R\rho$, where R is the range and ρ is the density of the target foil.

[d] Theoretical ranges calculated according to K. O. Nielsen [reference 4, p. 73, Eq. (13)].

[e] Range of C^{11} is in polystyrene (CH); for Cl^{34}, in Saran ($CHCl$); and for F^{18}, in Teflon (CF_2). Other ranges are in their respective metallic lattices.

[f] Range of C^{11} (for same recoil energy) in polyethylene (CH_2) and in cellulose acetate ($C_{1.0}H_{1.3}O_{0.7}$) are 10 600 ± 1100 A and 11 900 ± 1800 A, respectively.

[g] With the exception of the hydrogen atoms, it was assumed that the target atoms shared equally in stopping the recoiling atoms. Hydrogen atoms were neglected in the calculations.

[h] Preliminary experiments on recoil ranges of F^{20} and Cl^{38} - produced by (n,γ) reactions and having recoil energies of <0.5 kev-in Teflon and Saran, respectively, indicate anomalously large ranges of several thousand angstroms.

matrices increase slowly with $1/A$. By performing recoil experiments with photoproton, photodeuteron, and photoalpha transmutations, it will be possible to see the effect on N_c/N_f by varying the recoil energy only.

It should be noted that the N_c/N_f fractions for Cu^{62} and Cu^{64} agree well within experimental error. Since the photoneutron thresholds for Cu^{62} and Cu^{64} are nearly equal (10.7 and 10.0 Mev, respectively) and the corresponding photoneutron cross sections are roughly superimposable after normalization by a constant factor, the kinetic energies of the evaporated neutrons are expected to be identical. By measuring the average evaporated photoneutron energy, using the simple recoil technique outlined in this paper, it is possible to compare the nuclear temperatures of pairs of excited nuclei. The comparison should be restricted to a narrow range of atomic numbers because of the variation in recoil range with electronic structure.

We wish to acknowledge helpful discussions with Dr. Victor A. J. van Lint of General Atomic and the generous cooperation of Dr. Waldo K. Lyon and Mr. R. B. Doherty of the U. S. Navy Electronics Laboratory, San Diego, California, in the performance of these irradiations.

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THERMAL EFFECTS OF THE MARTENSITIC TRANSFORMATION IN LITHIUM

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Some measurements on sodium showing the influence of the martensitic transformation[1,2] on the specific heat have been reported in a previous letter.[3] The similar transformation in lithium metal[4,5] has now been investigated using the same technique and apparatus. On cooling below about 80°K the body centered cubic lattice begins to change to hexagonal close packed with stacking faults. The extent of the transformation depends on the purity and previous thermal history of the specimen and also on the temperature to which it is cooled. Figure 1 shows the specific heat of b.c.c. lithium as a continuous line and the anomalous specific heat found after cooling to 55°K (from room temperature) as a dotted line. (The experimental points have been omitted for clarity.) The anomaly occurs in the temperature range where that part of the sample which had been transformed on cooling reverts from h.c.p. to b.c.c. lattice. The excess energy absorbed on heating through this region is about 7 cal/g atom. The temperature range observed for reversion agrees well with the x-ray observations of Barrett and Trautz.[5]

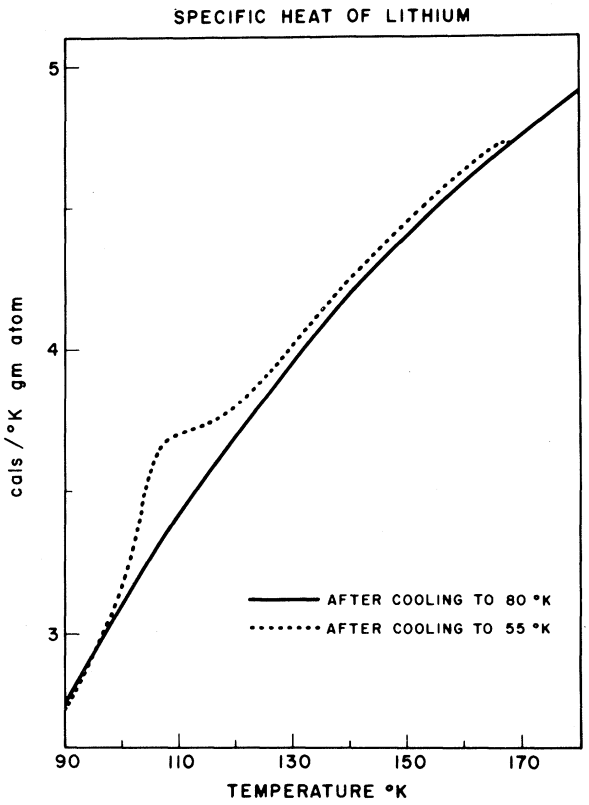

FIG. 1. The specific heat of lithium.

Below the temperature region of the reversion anomaly the specific heat of lithium remains dependent upon the thermal history of the sample. Differences of the order of 1% have been observed and, by observation of the heat content of