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Gamma Rays from Proton Bombardment of Li^6†

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A NaI(Tl) scintillation spectrometer, limited to 1.5-Mev gamma rays, detected 430±20 kev radiation when separated Li^6 was bombarded with monochromatic protons from 180 kev to 415 kev. Spectrometer efficiency was measured using an Au^{198} source of beta-gamma coincidences. The thick target yield was $(7\pm4)\times10^{-13}$ gamma per proton at 180 kev and $(170\pm35)\times10^{-13}$ at 415 kev. The 430-kev gamma ray was interpreted as part of the cascade decay of the broad 6.35-Mev state of Be^7. Assuming s-wave capture, the experimental yield has been fitted with a Breit-Wigner resonance curve. At 415 kev, a cross section of 0.7 ± 0.2 μb is obtained for the decay of the capture state through the 430-kev state. This gives $(2J+1)\Gamma_\gamma$ a value of 1.0 ± 0.3 ev for this cascade process. The spectrometer, when unlimited, detected gamma rays corresponding to transitions from the capture level to the ground and 430-kev states. The number of transitions from the capture state to the 430-kev state of Be^7 is 35±5 percent of the total radiative decays. Transitions through the 4.65-Mev state of Be^7 occur in less than 4 percent of the total radiative decays.

INTRODUCTION

THE level structure of the nucleus Be^7 has been studied in a number of nuclear reactions.[1] These investigations have located the four excited states shown in Fig. 1. The evidence for the spin and parity assignments indicated in Fig. 1 is discussed in the review article by Ajzenberg and Lauritsen.[1] These assignments are consistent with the interpretation that each of the Be^7 levels is mirror to a state of approximately the same energy in Li^7.

An energetically possible alternative to particle emission from Be^7 as formed in the proton bombardment of Li^6 is de-excitation to lower states by electromagnetic radiation. The first search[2] for the $Li^6(p,\gamma)Be^7$ reaction had a negative result, from which an upper limit of 2.5×10^{-10} gamma per proton was deduced for 950-kev protons incident on a thick target. However, it has recently been reported[3] that a complicated pattern of direct and cascade gamma rays has been observed for bombarding energies from 400 kev to 2.2 Mev.

In the present experiment, the absolute, thick target yield curve for gamma radiation from the $Li^6(p,\gamma)Be^7$ reaction was measured for bombarding energies between 180 kev and 415 kev. The relative intensities of the gamma rays leading from the capture state to the ground state directly and in cascade through the first excited state were also studied. These measurements were made in the hope of clarifying the nature of the gamma-ray transitions.

EXPERIMENTAL METHOD

A 500-kev Cockcroft-Walton voltage multiplier was used to accelerate protons to well-defined energies between 180 kev and 415 kev. Proton energies were measured in terms of the current needed for an electromagnet to deflect the beam 90° and, through a slit system, into the target chamber. Resonances at 163 kev in the $B^{11}(p,\gamma)C^{12}$ reaction, at 224 kev and 340 kev in the $F^{19}(p,\alpha\gamma)O^{16}$ reaction, and at 440 kev in the $Li^7(p,\gamma)Be^8$ reaction, were used to calibrate the magnet current against proton energy. The reproducibility of the resonance points indicated that proton energies were known to ±5 kev over the range of this experiment.

Thick targets of elemental, separated[4] Li^6 (93 percent Li^6, 7 percent Li^7) were evaporated *in situ* on a $\frac{1}{8}$-in. thick aluminum plate. The accumulation of carbon on the target surface was reduced to a negligible amount by the installation of a dry ice and acetone cold trap immediately in front of the target chamber. The cleanliness of the target was attested by the absence of any ten minute period annihilation radiation from N^{13}, which would have resulted from the $C^{12}(p,\gamma)N^{13}$ reaction, and by the constancy of the $Li^6(p,\gamma)Be^7$ yield during lengthy bombardments at a fixed incident energy.

The target chamber served as a Faraday cage, and the cold trap, biased at 300 volts below ground, served as a secondary electron repeller. Charge measurements were made with a condenser-discharge type of current integrator. Beam currents of about 5 μa were used.

Gamma rays ranging in energy from 430 kev to $(5.60\text{ Mev}+6E_p/7)$ are possible when Li^6 is struck by protons whose energy in the laboratory system is E_p. The energetic photons due to decays from the capture state to the ground and first excited states of Be^7 were studied at a bombarding energy of 300 kev, but they were not well resolved. They were also obscured, for incident energies above 340 kev, by the 6.13-Mev gamma rays from the $F^{19}(p,\alpha\gamma)O^{16}$ reaction in fluorine contamination on the slit system at the target end of

† Supported in part by the U. S. Atomic Energy Commission.

[1] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952). See also forthcoming supplement in the *Reviews of Modern Physics*. We wish to thank Professor Lauritsen for a preprint of the supplement.

[2] S. C. Curran and J. E. Strothers, Proc. Roy. Soc. (London) **A172**, 72 (1939).

[3] Erdman, Warren, James, and Alexander, Phys. Rev. **96**, 858(A) (1954).

[4] The enriched Li^6 was kindly supplied by the Oak Ridge National Laboratory.

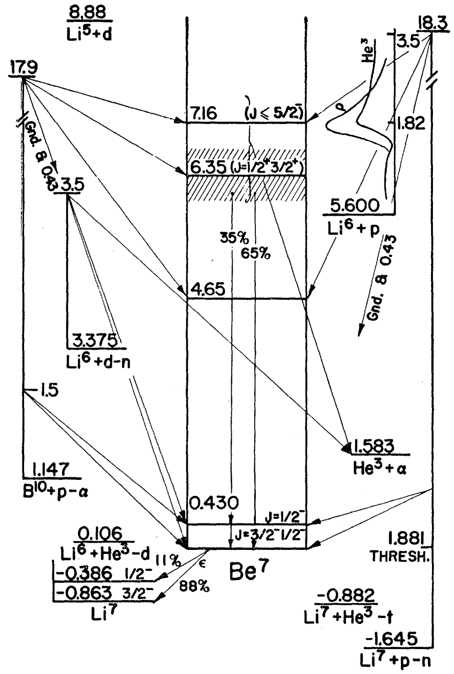

FIG. 1. Energy level diagram of Be^7 [after Ajzenberg and Lauritsen (see reference 1)].

the accelerator. The 430-kev cascade gamma rays appeared in the presence of pile-up x-rays from the accelerator, degraded photons, and annihilation radiation due principally to pair formation in materials near the detector. Comparing the factors involved, it was clear that more precise studies were possible with the 430-kev gamma rays than with the higher-energy gamma rays.

Gamma radiation was detected with a NaI(Tl) crystal $1\frac{1}{2}$ in. in diameter and 2 in. long, mounted on an RCA5819 photomultiplier tube. The photomultiplier output was fed into a limiter of Elmore's design[5] adjusted so that all radiation above 1.5 Mev gave the same size output pulse. An Atomic Instruments Company Model 204B linear amplifier followed the limiter and delivered pulses to a ten-channel pulse-height analyzer of Johnstone's design.[6] Below the limiting region, the detecting system was found to be linear within the accuracy of measurement. Sources of Au^{198} (411-kev gamma rays), Na^{22} (annihilation radiation), Cs^{137} (667-kev gamma rays) and Co^{60} (1.17-Mev and 1.33-Mev gamma rays) were used to calibrate the energy scale of the detector to ± 20 kev.

The absolute efficiency of the detector was measured by counting coincidences between the Au^{198} betas and the subsequent 411-kev gamma rays. A source of Au^{198} was painted on a thin anthracene crystal which, optically coupled to an RCA5819 photomultiplier tube, was used to detect the betas. The NaI(Tl) crystal was placed the same distance from the source as it was from the lithium target, and the aluminum target-backing plate was placed between the source and crystal. Only the total absorption peak of the 411-kev gamma ray in the NaI(Tl) crystal was counted. After correcting for geometry, the absolute efficiency of the present crystal was found to be the same as that reported by Hornyak and Coor[7] for a somewhat smaller crystal. Hence Hornyak and Coor's empirical relation for the energy dependence of their crystal's detection efficiency was used to correct the measured efficiency of our crystal at 411 kev for the 430-kev gamma radiation studied in this experiment. The correction was a 9 percent reduction. The uncertainty in the absolute efficiency is estimated at 10 percent.

ABSOLUTE THICK TARGET YIELD

The limited pulse-height distribution obtained at an incident proton energy of 215 kev is shown in Fig. 2. A single gamma ray of energy 430 ± 20 kev appears in the range up to 1.5 Mev. The arrow at a pulse height corresponding to 1.13 Mev indicates where the total absorption peak of a gamma ray from the capture state to the 4.65-Mev state should show up. The 430-kev gamma ray was taken to be the lower element of the cascade decay of the capture state through the first excited state of Be^7. The yield of the cascade gamma ray was measured at six different energies using a freshly evaporated target which showed no signs of deterioration or carbon accumulation during the bombardment. The uppermost curve in Fig. 3 shows the pulse-height distribution for the 430-kev gamma ray obtained at a proton energy of 365 kev. Background was approximated over the width of each total absorption peak by a straight line, as illustrated in Fig. 3,

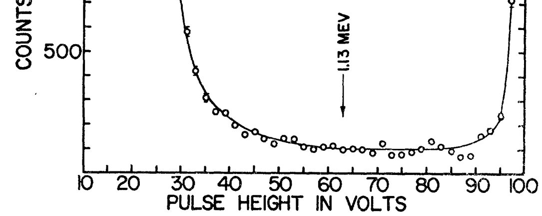

FIG. 2. Limited, single-crystal spectrometer, pulse-height analysis of gamma rays from capture by Li^6 of protons having energy of 215 kev. Arrows indicate where the total absorption peaks of gamma rays of the energies specified should appear.

[5] W. C. Elmore, Rev. Sci. Instr. **20**, 963 (1949).
[6] W. C. Johnstone, Nucleonics **11**, No. 1, 36 (1953).
[7] W. F. Hornyak and T. Coor, Phys. Rev. **92**, 675 (1953).

drawn roughly tangent to the high-energy tail of the pulse-height distribution and giving the same peak-to-valley ratio as measured with the Au^{198} source. The area, shown shaded in Fig. 3, under the total absorption peak in the net curve was then measured. The six areas so obtained, together with the detection efficiency, the charge collected, and the isotopic content of the target, gave the absolute thick target yield points shown in Fig. 4. Statistical and subtraction uncertainties are indicated by vertical lines. There is an additional 10 percent uncertainty in the absolute yield from the detection efficiency measurement.

The thick target yield, Y, is related to the cross section, σ, by

$$Y=\int_0^E \frac{\sigma}{\epsilon}dE,$$

where E is the bombarding energy in the center-of-mass system and ϵ is the stopping power[8] of the target. Over the energy range of this experiment, the $Li^6(p,\gamma)Be^7$ excitation function is resonant in nature, being influenced primarily by the broad level at 6.35 Mev[1] in Be^7. Assuming single-level Breit-Wigner resonance theory to be adequate, the above expression can be numerically integrated. For a total width at resonance of 1.5 Mev and s-wave proton capture, both obtained from the

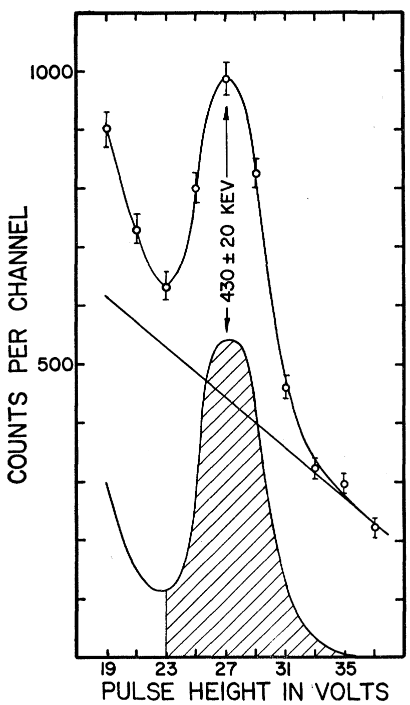

FIG. 3. Total absorption peak of the $Li^6(p,\gamma)Be^7$ 430-kev cascade gamma ray at a proton bombarding energy of 365 kev. Top curve shows the raw data. The slanting straight line is the background correction. Bottom curve shows the net data. The absolute efficiency of the detector was measured for gamma-ray pulses in the shaded region.

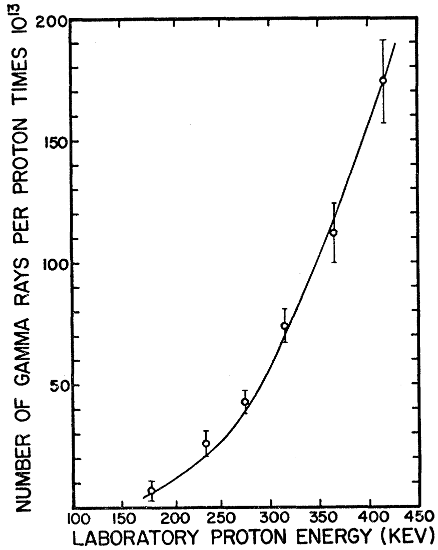

FIG. 4. Thick target yield curve for the $Li^6(p,\gamma)Be^7$ 430-kev cascade gamma ray. Points are experimental. The curve was calculated from Breit-Wigner resonance theory.

$Li^6(p,\alpha)He^3$ experiment,[9] the theoretical thick target yield of 430-kev cascade gamma rays was computed. It was assumed that the gamma width varied as the cube of the gamma-ray energy. The curve, shown in Fig. 4, was normalized to the data at an incident proton energy of 415 kev. The agreement of the calculated curve and the data makes unnecessary the use of Thomas' more complete expression for the energy dependence of the gamma width.[10] To within an uncertainty of 30 percent, a cross section of 0.7 μb at a bombarding energy of 415 kev results for the cascade process. As discussed below, direct transitions to the ground state are expected to have a somewhat larger probability. The total radiative capture cross section is estimated as 2 ± 1 μb for an incident energy of 400 kev, in comparison with the 10^{-30} cm^2 obtained by Erdman *et al.*[3] at the same energy. For reasons given below, the present estimate does not include any contributions from decays through the second excited state of Be^7.

The cross section at an energy E is given by the relation

$$\sigma=\pi\lambda\!\!\!^{-2}\omega\frac{\Gamma_p\Gamma_\gamma}{(E-E_r)^2+\frac{1}{4}\Gamma^2},$$

where $2\pi\lambda\!\!\!^{-}$ is the deBroglie wavelength of the proton, ω is a statistical weight factor equal to $(2J+1)/6$, J is the spin of the compound nucleus, E_r is the resonance energy, Γ is the total width of the state, Γ_p is the proton width, and Γ_γ is the radiative width, where all quantities refer to the center-of-mass system. The quantity $(2J+1)\Gamma_\gamma$ is 1.0 ± 0.3 ev for cascade decay at an excitation of 5.95 Mev in Be^7. Weisskopf[11] has given

[8] Warters, Fowler, and Lauritsen, Phys. Rev. **91**, 917 (1953).

[9] S. Bashkin and H. T. Richards, Phys. Rev. **84**, 1124 (1951).
[10] R. G. Thomas, Phys. Rev. **88**, 1109 (1952).
[11] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).

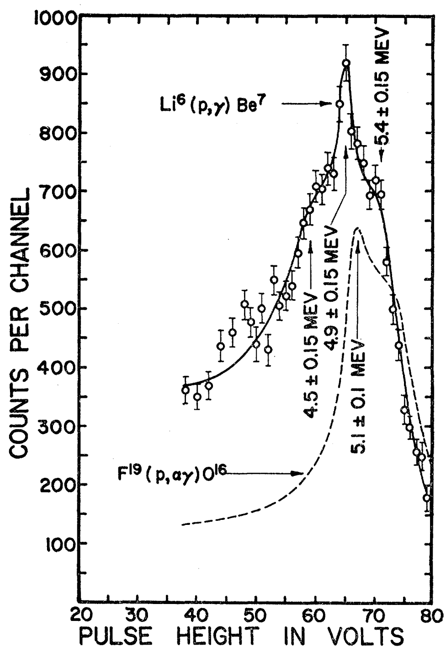

FIG. 5. Single-crystal spectrometer pulse-height analysis (solid curve) of high-energy gamma rays from capture by Li^6 of protons having energy of 300 kev. Dashed curve shows one- and two-escape peaks of 6.13-Mev gamma from $F^{19}(p,\alpha\gamma)O^{16}$ reaction.

formulas for calculating radiation widths of various multipole orders and types. The calculated values are expected to be too large by perhaps as much as 10^3, although a survey of the light elements[12] suggests somewhat better agreement. An electric dipole calculation for the high-energy component of the cascade decay in Be^7 gives 60 ev for the radiative width.

RELATIVE INTENSITIES

The relative intensities of the gamma rays leading from the capture state to the ground and first excited states can be predicted[11] rather crudely on the basis of the spins and parities of these states. The commonly accepted assignments[1] of $1/2^-$ or $3/2^-$ for the Be^7 ground state and $1/2^-$ for the 430-kev state mean that the cascade transition cannot predominate over the direct decay, no matter what the spin of the third excited state may be. If that state has even parity and a spin of 1/2 or 3/2, as implied in the assumption of *s*-wave proton capture, the two gamma rays should have comparable intensities. Erdman *et al.*[3] have found that an appreciable fraction of the decays proceed through the first excited state. This is substantiated by two measurements made in the present experiment.

The first of these measurements was a single-crystal pulse-height analysis of the high-energy gamma-ray spectrum, obtained at a bombarding energy of 300 kev. For this work, the spectrometer was calibrated with the 2.62-Mev gamma ray from *ThC''* and the 6.13-Mev gamma ray from the $F^{19}(p,\alpha\gamma)O^{16}$ reaction. As shown in Fig. 5, the one- and two-annihilation photon escape peaks of the ground state-gamma ray from the $Li^6(p,\gamma)Be^7$ reaction are clearly seen in the pulse-height distribution, along with the two-escape peak of the more energetic component of the cascade. The one-escape peak of the latter is submerged in the two-escape yield of the direct gamma ray. The pulse-height analysis of the spectrum obtained in the same crystal with the single 6.13-Mev gamma ray from $F^{19}(p,\alpha\gamma)O^{16}$ is included for comparison. From Fig. 5, it is deduced that the direct transition is about two times as intense as the cascade transition.

The second measurement establishes a poorer, but still significant, upper limit to the ratio of the number of direct to cascade transitions. If there were appreciably more ground-state transitions than cascade transitions, the number of Be^7 nuclei formed should be correspondingly greater than the measured number of 430-kev gamma rays. However, Be^7 decays to Li^7 by *K*-capture, with 11 percent[13] of the Li^7 nuclei being formed in the first excited state. This state de-excites by emitting a 480-kev gamma ray. Hence the ratio of the number of 430-kev gamma rays counted in a lengthy bombardment to the number of delayed 480-kev gamma rays should be a measure of the relative intensities of the cascade and direct transitions.

This measurement was made with a 4 μa-hour bombardment at a proton energy of 365 kev, the limitations on the bombardment being the stability of the target under the beam and the rate of growth of carbon on the target surface. The accelerator was turned off at the end of the bombardment and the target was counted for one hour, during which time the decay rate rate of the Be^7 (half-life 53 days[14]) was constant. No delayed 480-kev gamma rays were seen. From the efficiency, background, resolution, and statistics, it is estimated that the cascade transition occurs at least 1 percent as often as the direct transition. The spin assignments discussed above are consistent with these measurements.

Gamma decay by cascade through the second excited state is not expected to compete with the transitions discussed above since no spin assignment to this level can overcome the discouragement resulting from the reduced energy available.[11] The arrow at 1.13 Mev in Fig. 2 indicates where the total absorption peak of the gamma ray from the capture level to the 4.65-Mev level should appear for an incident energy of 215 kev. If we assume that the efficiency of detection in the total absorption peak varies inversely as the 1.31 power of the gamma-ray energy,[7] the results shown in Fig. 2 allow a limit to be placed on the number of transitions from the capture level to the second excited state. At a bombarding energy of 215 kev the number of transi-

[12] D. H. Wilkinson, Phil. Mag. 44, 450 (1953).

[13] R. M. Williamson and H. T. Richards, Phys. Rev. **76**, 614 (1949).

[14] E. Segrè and C. E. Wiegand, Phys. Rev. **75**, 39 (1949).

tions through the second excited state is less than 10 percent of those through the first excited state, as expected.

The results on intensity measurements may be summarized by saying that 35±5 percent of the gamma decays of the capture state proceed by cascade through the first excited state and 65±5 percent by direct transition to the ground state. Less than 4 percent of the gamma decays of the capture state proceed by cascade through the second excited state.

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Angular Distributions of Deuteron-Induced Reactions in Lithium*

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Angular distributions of (d,t), (d,He^3), (d,p), and (d,d') reactions have been obtained using a natural lithium target. Butler type calculations for $l=1$ transfer fit all of the above data except for the (d,d') reactions. A Q-value of 0.974±0.015 Mev has been assigned to the first excited level in Li^8. The He^5 ground state was observed with the two reactions $Li^7(d,\alpha)He^5$ and $Li^6(d,He^3)He^5$ for which the Q values were 14.26±0.09 Mev and 0.91±0.09 Mev, respectively.

I. INTRODUCTION

A STUDY of the angular distributions of some of the reaction particles resulting from the bombardment of Li^6 and Li^7 with 14.4-Mev deuterons has been made here. The observed angular distributions of the (d,t), (d,He^3), (d,p), and (d,d') reactions are shown. Butler-type calculations[1–3] are used, where possible, to determine the angular momentum transfer and parity change of the reaction. Information about the He^5 ground state is obtained from the two reactions $Li^7(d,\alpha)He^5$ and $Li^6(d,He^3)He^5$.

II. APPARATUS

The scattering project at the University of Pittsburgh[4] uses an incident beam of 14.4-Mev deuterons. The angular spread of the incident beam and of the outgoing particles accepted by the particle analyzer were each 1.8°. A new scattering chamber was installed which could rotate 60° under vacuum. The particle analyzer could be made to cover a continuous range of 120° by changing ports on the scattering chamber. The detector was a CsI crystal cemented to a Type 6292 Dumont photomultiplier tube. The pulse-height resolution was between 4 percent and 6 percent for all charged particles observed. Various aluminum foils could be rotated in front of the crystal to aid in identifying the particles by their pulse height and their energy loss in the foils. Foils also separated pulses of different particles so that they could be resolved and counted simultaneously with a six-channel pulse-height analyzer.

III. TARGET PREPARATION

The target was prepared by evaporating natural lithium, which contains 92.5 percent Li^7 and 7.5 percent Li^6, on a thin silver foil (0.01 mg/cm^2) in the scattering chamber. Two targets, No. 1 and No. 2, were used during the experiment. The absolute thickness of the targets was measured with a Beckman spectrophotometer, yielding values of 0.16 mg/cm^2 for target No. 1 and 0.10 mg/cm^2 for target No. 2. The relative thicknesses as obtained from the magnet spectrometer were in the ratio of 2.1/1.

IV. RESULTS

A. Magnetic Analysis

Table I lists the energy levels observed whose assignments have been uniquely determined by the variation in recoil energy of the outgoing particles with angle except for the $(d,\alpha)He^5$ and $(d,He^3)He^5$ reactions. Data for these two reactions were taken at only one angle; however, the Q-values were such that the detected particles could not have come from any of

TABLE I. List of energy levels and reactions observed. (g.s.≡ground state.)

Reaction	Levels (Mev)
$Li^7(d,t)Li^6$	g.s., 2.187
$Li^7(d,d')Li^7$	g.s.,[a] 0.478, 4.61
$Li^7(d,p)$ Li^8	g.s., 0.97, 2.28[a]
$Li^7(d,He^3)He^6$	g.s., 1.71
$Li^7(d,\alpha)He^5$	g.s.[a]
$Li^6(d,p)Li^7$	g.s., 0.478, 6.56[a]
$LI^6(d,He^3)He^5$	g.s.[a]

[a] Levels observed but angular distribution data not taken.

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† Now at Westinghouse Atomic Power Division Laboratory.
[1] H. C. Newns, Proc. Phys. Soc. (London) **A65**, 916 (1952).
[2] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1951).
[3] R. Huby and H. C. Newns, Phil. Mag. **42**, 1442 (1952).
[4] Bender, Reilley, Allen, Ely, Arthur, and Hausman, Rev. Sci. Instr. **23**, 542 (1952).