element is about 50 percent larger than here estimated (as could perhaps happen for example by superposition of spin and orbital effects), since this should be the large term and the observed lifetime[15] is 0.75×10^{-13} sec. For electric quadrupole radiation, we assume that the charge is, in effect, associated with the protons, in keeping with Siegert's theorem extended to higher electric multipoles,[21] and then have as a similar rough estimate of the lifetime

$$\tau > [(2/\hbar)(\omega/c)^5 e^2 (r_{\shortparallel} r_{\perp})_{mn}{}^2]^{-1} \approx [(137)^6/2\times10^{23}]\ \text{sec} = 4\times10^{-11}\ \text{sec}.$$

(For heavy nuclei, the magnetic moments μ are about the same because of the suppressing effect of shell structure, and the electric quadrupole reciprocal lifetime grows relative to magnetic dipole by a factor $\omega^2 A^{4/3}$, making the two about equal for $\hbar\omega = 5mc^2$, $A = 100$, in keeping with the customary classification of degrees of forbiddenness.) For this rather soft radiation from a light nucleus one thus expects the electric quadrupole radiation to be something like 200 times weaker than the magnetic dipole radiation, implying $b/a \leqslant 1/15$. The numerical coefficient 4.5 in the expression for A is, however, so large that the rather small value $b/a \approx 1/5$ would make it possible for A to be zero (as was pointed out by Adams). Thus, an electric quadrupole matrix element three times larger than this rough upper limit[21a] would make it possible for A to vanish fortuitously. For $I = 5/2$, this would require either a failure of Siegert's theorem to hold to this accuracy, or a concerted action of more than one proton in spite of the stability of the s-shell, or a considerably larger nucleus than estimated, as might be associated with the weak stability of Li^7 relative to $\alpha + T$, or a combination of these effects and a surprising lack of cancellation in the matrix element, but in any case with the simultaneous circumstance that $\sin\delta$ have the right sign, this seems much less likely than that one matrix element in the intensity ratio should be small because of cancellation by a factor 6.

The observed approximate lack of alpha-gamma angular correlation, together with the expectation of predominantly magnetic dipole radiation and the isotropy of the $Li^7(p,p')$ gammas, thus seem to demonstrate[22] that $I = \frac{1}{2}$ considerably more conclusively than does the thermal intensity ratio suggest that $I = 5/2$, and thus practically forces one to ascribe the anomalous intensity ratio to chance misbehavior of a matrix element. This conclusion is happily in keeping with theoretical expectations based on nuclear models, that $I = \frac{1}{2}$ with odd parity.

Gratitude is expressed to Professor E. Fermi and Dr. E. N. Adams, II, of the University of Chicago and to Professor S. Devons of Imperial College, London, for discussion of these and related topics.

[21] A. Seigert, Phys. Rev. **52**, 727, (1937), and recent discussions of R. G. Sachs.

[21a] *Note added in proof:* An empirical tendency of electric multipole matrix elements to be much smaller than such a roughly estimated upper limit, especially when compared with magnetic multipoles to which meson exchange currents may contribute, has been pointed out by M. Goldhaber, Bull. Am. Phys. Soc. **26**, No. 1, M4 (title only) (1951).

[22] There is another possibility not represented in Fig. 1 which would give no angular correlation (Reference 7) and require the unexpected behavior to provide only a factor 17 instead of 34, namely, $5/2^+$ for both the compound state and the 480-Kev state; but this parity for Li^7 seems too unlikely, on the basis of models and the observed isolation of the two low states, to merit further consideration.

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Variation with Energy of Nuclear Collision Cross Sections for High Energy Neutrons

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Nuclear total cross sections for high energy neutrons have been measured for approximately known neutron energies in the range 90 to 270 Mev. It is observed that cross sections in every case drop rather rapidly between 100 and 180 Mev to a level which continues with little further variation up to the highest neutron energies available in the experiment. Comparisons are made with nuclear attenuation data for cosmic rays.

I. INTRODUCTION

Nuclear collision cross sections for high energy neutrons have been measured at three different energy regions for neutrons produced by the University of California 184-inch cyclotron. Stripping of 90-, and 190-Mev deuterons by beryllium targets produced neutrons[1,2] of mean energies 40 and 90 Mev, respectively. Measurements[3,4] utilizing the $C^{12}(n,2n)C^{11}$ reaction for detection provided total nuclear cross sections at estimated mean neutron detection energies of 42 and

* This paper is based on material submitted to the University of California in partial satisfaction of the requirements for the Ph.D. degree.

† This work was performed under the auspices of the AEC.

[1] Helmholz, McMillan, and Sewell, Phys. Rev. **72**, 1003 (1947).
[2] R. Serber, Phys. Rev. **72**, 1008 (1947).
[3] R. Hildebrand and C. Leith, in preparation for publication.
[4] Cook, McMillan, Peterson, and Sewell, Phys. Rev. **75**, 7 (1949).

84 Mev, respectively. Bismuth fission, which has a threshold at about 50 Mev, was used for detection of the 90-Mev neutrons; and both inelastic and total cross sections of nuclei were measured[5] at an estimated mean detection energy of 95 Mev.

The bombardment of a 2-inch Be target with 350-Mev protons produces high energy neutrons with a broad energy distribution possessing a maximum at about 270 Mev. Total cross sections were measured for various nuclei using both bismuth fission[6] detection and a scintillation counter recoil proton telescope[7] possessing an equivalent neutron threshold of 250 Mev. The two methods gave values which agreed well with each other.

However, the model of the transparent nucleus developed by Fernbach, Serber, and Taylor,[8] which described the inelastic and total cross-section measurements adequately in the region of 90 Mev, could not fit the 270-Mev data if expected values independent of the atomic number were employed for the two parameters of their theory. The two parameters are k_1, the change in propagation vector of the neutron upon entering nuclear matter; and K, the absorption coefficient for the neutron wave in nuclear matter.

Indeed, the 270-Mev data would require that an impinging neutron experience no change in potential on entering a nucleus, if this theory were to be retained.

As the energy interval between the 95- and 270-Mev measurements was wide, it was felt necessary to investigate the variation of neutron total cross sections of a representative number of nuclei within this energy region.

II. PARTICLE ENERGIES AND EFFECTIVE DETECTION ENERGIES

In connection with various experimental programs with the 184-inch cyclotron the energy distribution of the neutrons knocked out of a 2-inch Be target by the

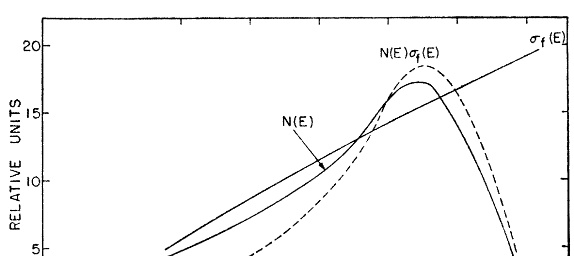

FIG. 1. Estimation of detection efficiency *vs* neutron energy in the case of 350-Mev protons. $N(E)$ is the neutron energy spectrum from a two-inch Be target bombarded by 350-Mev protons. $\sigma_f(E)$ is the approximate excitation function for Bi fission by neutrons. The dashed curve is then the detection efficiency *vs* energy.

350-Mev protons has been measured by Cladis and Hadley, by Fox, *et al.*,[7] and by Kelly, Wiegand, and Segrè. All three measurements show a broad distribution peaked around 270 Mev, a composite result of which is shown in Fig. 1 as $N(E)$.

In order to obtain information concerning the variation with neutron energy of the bismuth fission counter, the ratio of Bi fission to the $C^{12}(n,2n)C^{11}$ reaction was studied for neutrons with mean energies at 90 Mev, at 270 Mev, and for several intermediate values. This ratio increased uniformly by a factor of 3.56 ± 0.11 as the mean neutron energy changed from 90 to 270 Mev. According to theoretical calculations by Baumhoff at this laboratory, the $(n,2n)$ reaction yield in carbon should decrease slowly over this region to a value of about 0.8 of the 90-Mev yield. Similar theoretical calculations for the (p,pn) reaction[9] in carbon have proved to be quite valid. It may be presumed therefore that the efficiency of the Bi fission reaction increases uniformly by a factor of about three in the neutron energy interval in question.

The selection of neutrons with different mean energies was accomplished by the use of a $\frac{1}{2}$-inch Be target at various radii in the cyclotron, with appropriate adjustments of the counters for each target position. It is necessary then to estimate the neutron spectra produced by the various proton energies employed. The following data are pertinent:

(1) The neutron spectra from $\frac{1}{2}$-inch and 2-inch Be targets are very nearly identical at these energies, because of multiple passages of the circulating beam through the targets.

(2) The neutron spectrum from a Be target bombarded by 180-Mev protons has been observed by Fox and Wouters[10] to have its maximum in the vicinity of 110 Mev.

(3) The neutron spectrum from a 2-inch Be target bombarded by 350-Mev protons has its maximum at about 270 Mev.

(4) The ratio of Bi fission cross section to the $C^{12}(n,2n)C^{11}$ cross section for neutrons from 165-Mev protons was equal to that for the neutrons of 90-Mev mean energy from the stripping of 190-Mev deuterons.

In the light of these observations it will be assumed that the mean energy of the neutron spectrum falls 70 Mev lower than the energy of the bombarding protons for a $\frac{1}{2}$-inch Be target.

The comparison of Bi fission with the $C^{12}(n,2n)C^{11}$ reaction was accomplished by exposing a fission counter and a polystyrene foil simultaneously in the proper location relative to the proton target. Measurements were made at 40-Mev intervals of proton energy ranging from 150 to 350 Mev. Sufficient absorbing material was placed before the detectors to stop protons scattered out through the tank wall from the target.

The effective neutron detection energy is estimated by plotting the product of the neutron energy distribution and the Bi fission cross section *vs* energy. In Fig. 1 this is illustrated for the case of neutrons from the 350-Mev protons. The effective detection energy is not

[5] J. DeJuren and N. Knable, Phys. Rev. **77**, 606 (1950).
[6] J. DeJuren, Phys. Rev. **80**, 27 (1950).
[7] Fox, Leith, Wouters, and MacKenzie, Phys. Rev. **80**, 23 (1950).
[8] Fernbach, Serber, and Taylor, Phys. Rev. **75**, 1352 (1949).
[9] W. Heckrotte and P. Wolff, Phys. Rev. **73**, 264 (1948).
[10] R. Fox and L. Wouters (private communication).

significantly different from the mean energy of the neutrons.

III. EXPERIMENTAL ARRANGEMENT

The neutrons produced by the bombardment of the 2-inch Be target by 345-Mev protons have a wide angular distribution with a half-width at half-maximum of 25° (as measured with bismuth fission). Since only two collimators are present in the concrete shielding, corresponding to proton energies of 180 and 350 Mev, the detector must be placed inside the shielding for intermediate energies (Fig. 2). Most of the neutron flux passes through an inch of steel tank wall as well as other tank fixtures, so that the elastically scattered flux from these could constitute a background of perhaps 10 to 20 percent of the undeviated flux in the absence of any collimation. To reduce the detector background the chamber was placed behind a 7-foot thick concrete block with an adjustable collimating arrangement through its central region admitting a neutron beam slightly less than 2 inches in diameter. As the target position was varied from 81 inches to 54 inches to obtain the desired proton energy settings, the collimating apparatus was swiveled into alignment for the various target positions. The detector was placed six feet to the rear of the concrete block, and the attenuating materials were aligned immediately in front of the block on a wooden holder as shown in Fig. 2. The distance from absorbers to detector was about 13 feet, so the geometry was "good" with only small angular scattering corrections necessary.

To monitor the neutron beam a bismuth fission chamber was placed to one side of the concrete block where the contribution of neutrons scattered from the absorbers to its counting rate was negligible. Background was determined by placing approximately seven mean free paths of absorbers on the holder. For most measurements the background was of the order of 5 percent of the detector counting rate with no absorbers present. The geometry was tested by comparison of the attenuation of the 270-Mev neutrons using the above geometry with the previous[6] setup in which the detector was placed outside the 10-foot concrete shielding in the collimated neutron beam. With the detector outside the shielding the background was completely negligible and the angular scattering correction smaller by a factor of two than in the present case.

To test the new geometry the length of copper absorber was increased by 3-inch steps to 12 inches, and the resulting attenuation when corrected for background was found to be linear as a function of absorber length when plotted on semilogarithmic paper.

If N_0 is the number of neutrons per second reaching the detector with no absorber present and N is the number when absorber of length L is present, then

$$(N-b)/(N_0-b)=e^{-n\sigma_t L}, \qquad (1)$$

where b is the background counting rate when an absorber that absorbs essentially all the neutrons is placed in position, n is the number of nuclei per cubic centimeter, and σ_t is the total nuclear cross section. A value of $1.14\pm0.02\times10^{-24}$ cm^2 was obtained with the present arrangement, as compared with the result outside the shielding of $1.15\pm0.02\times10^{-24}$ cm^2 for the copper total cross section.[6] Linear semilog plots were obtained at other probe positions to check the geometry. Most of the measurements were made with between one and two mean free paths of absorber present in order to obtain optimum statistics for a minimum time of cyclotron operation.

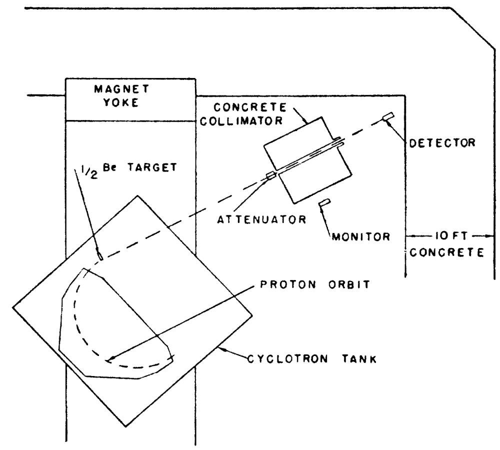

FIG. 2. Plan view of experimental arrangement.

IV. ATTENUATOR MATERIALS

The metals used in the experiments were usually machined cylinders, three or four inches in diameter with negligible chemical impurities. Densities were obtained from measurements of the physical volumes with micrometer and vernier calipers and accurate weights of the cylinders.

The total cross section of hydrogen was measured using pentane-carbon differences. A brass cylindrical holder 48 inches long with $\frac{1}{32}$-inch thick walls and bases held the pentane. An array of seven machined, 3-inch diameter graphite cylinders, with total mass per unit area equal to that of the carbon in the 48-inch length of pentane, plus a $\frac{1}{16}$-inch thick brass disk, were alternately used with the pentane to attenuate the neutron beam. The decrease in the detector counting rate when the graphite was replaced by pentane is from the attenuation of the neutrons due to the hydrogen alone. Since only 0.3 to 0.4 mean free path of hydrogen is present (depending on the neutron energy), repeated cycles were made at a given probe setting to obtain good statistics. The percent statistical error of the cross-section measurement is equal to the percent statistical error in counting divided by the number of mean free paths of hydrogen present. Short blank cycles were taken with an empty holder to obtain the carbon cross section.

TABLE I. Total cross sections of nuclei for high energy neutrons measured with bismuth fission chambers.

Proton energy (Mev)	Target	Estimated neutron energy (Mev)	Element	σ_t (barns)
310	0.5″ Be	240	Al	0.576 ±0.012
			Cu	1.15 ±0.02
			Pb	2.88 ±0.05
290	0.5″ Be	220	H	0.0410±0.0041
				0.0410±0.0029
				0.041 ±0.0024 (av)
			C	0.288 ±0.10
				0.283 ±0.08
				0.285 ±0.06 (av)
			Al	0.576 ±0.021
			Cu	1.15 ±0.035
			Pb	2.99 ±0.14
270	2″ Be	190	C	0.291 ±0.009
			Al	0.540 ±0.028
			Cu	1.15 ±0.04
			Sn	1.90 ±0.07
			Pb	2.85 ±0.10
			U	3.28 ±0.13
250	0.5″ Be	180	Al	0.575 ±0.013
			Cu	1.25 ±0.03
			Pb	3.06 ±0.06
230	0.5″ Be	160	H	0.0548±0.0060
				0.0504±0.0029
				0.0512±0.0026 (av)
			C	0.298 ±0.012
				0.295 ±0.0075
				0.296 ±0.006 (av)
225	2″ Be	145	Cu	1.31 ±0.04
	0.5″ Be	155	Cu	1.30 ±0.04
185	0.5″ Be	115	Cu	1.52 ±0.06
180–190[a]	0.5″ Be	110–120	Al	0.733 ±0.012
			Cu	1.49 ±0.02
			Pb	3.71 ±0.06

[a] Probe position not accurately known.

V. RESULTS

The data obtained are given in Table I. Pertinent results from the previous studies[5,6] at 95 and 270-Mev are given in Table II. Copper, tin, lead, and uranium have small diffraction scattering corrections (<1 percent) incorporated into their cross-section values. The variations of the cross sections with energy are shown in graphical form for carbon, aluminum, copper, and lead in Fig. 3. The variation of the hydrogen cross section is illustrated in Fig. 4. Data from previous studies[3–6] are included in these curves, and in Fig. 3, published results at[11] 14 Mev and[12] 25 Mev have been also plotted. The errors given are the statistical fluctuations from counting alone expressed in standard deviations.

TABLE II. Total cross sections for 95- and 270-Mev neutrons measured previously with bismuth fission chambers.[a]

Element	σ_t(95 Mev) $\times 10^{24}$ cm²	σ_t(270 Mev) $\times 10^{24}$ cm²
Hydrogen	0.073±0.0015	0.038±0.0015
Carbon	0.498±0.003	0.288±0.003
Aluminum	0.993±0.011	0.555±0.008
Copper	2.00 ±0.02	1.15 ±0.02
Lead	4.48 ±0.03	2.84 ±0.03

[a] References 5 and 6.

VI. DISCUSSION OF RESULTS

Carbon, aluminum, copper, and lead all exhibit little variation in their total cross-section values from about 180-Mev to 270-Mev mean neutron energy, as Fig. 3 indicates. The neutron energy distribution detected by the fission chambers is rather broad for the measurements undertaken and the resulting cross sections may

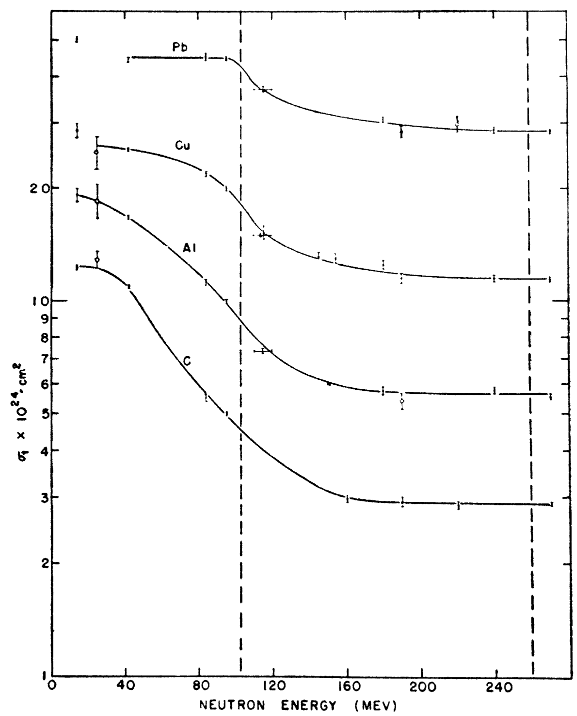

FIG. 3. Total cross sections *vs* neutron energy. The region between dashed lines contains the data from the present experiment. On either side of this region are data from earlier experiments by the same authors and by others mentioned in text.

not correspond exactly to the true cross section at the mean detected energy of the unattenuated distribution. If the detected energy distribution is given by $f(E)$, where $f(E)$ is normalized so that

$$\int_{E_{\min}}^{E_{\max}} f(E)dE = 1,$$

the measured value of the cross section is from Eq. (1):

$$nL\sigma_m = \ln\left(\frac{N_0 - b}{N - b}\right) = -\ln \int_{E_{\min}}^{E_{\max}} f(E)e^{-n\sigma_t(E)L}dE,$$

[11] Amaldi, Bocciarelli, Cacciapuoti, and Trabachi, Nuovo cimento **3**, 203 (1946).
[12] R. Sherr, Phys. Rev. **68**, 240 (1945).

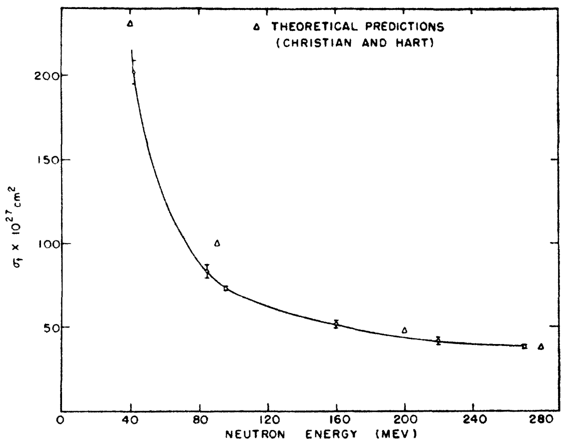

FIG. 4. Total n–p cross section *vs* neutron energy. Triangles represent theoretical predictions of Christian and Hart (reference 13).

or

$$\sigma_m = \frac{-1}{nL} \ln \int_{E_{\min}}^{E_{\max}} f(E) e^{-n\sigma_t(E)L} dE. \qquad (2)$$

If σ_m is examined for the energy intervals where measurements were made, the following statements may be made for the four nuclei above:

(1) For mean energies of 240 Mev or above, the variation of $\sigma_t(E)$ over the distribution is slight and σ_m agrees with $\sigma(\bar{E})$ at the mean energy

$$\bar{E} = \int_{E_{\min}}^{E_{\max}} Ef(E) dE.$$

(2) As the mean energy of the distribution is lowered to 160 Mev, $\sigma_t(E)$ begins to increase on the low energy side of the distribution from its level value, and the measured value σ_m will be higher than $\sigma(\bar{E})$.

In general the broad neutron distribution tends to round off the shape of the curves of Fig. 3. The plateaus are possibly slightly flatter and longer in extent than shown.

No attempt has been made to correct the present data for the spread in the neutron energies, since the detected neutron distribution is hardly known with sufficient accuracy. A measurement of cross sections for a small neutron energy interval centered about 140 Mev would define the cross-section variations in this region more precisely. Faster electronic circuits under development in connection with scintillation counters may make this measurement feasible.

The theoretical predictions of Christian and Hart[13] for a Yukawa potential with tensor interaction are also shown in Fig. 4. Experimentally, the cross section deviates more markedly from an $1/E$ variation than it does theoretically.

[13] R. Christian and E. Hart, Phys. Rev. **77**, 441 (1950).

VII. COMPARISON WITH CROSS SECTIONS OBSERVED IN COSMIC-RAY ATTENUATION

Estimates of the attenuation in the atmosphere of the components of cosmic radiation giving rise to penetrating showers, bursts in thin-walled chambers, nuclear stars, and slow neutrons have been given by Rossi.[14,15] It is shown that these events are almost certainly due to the high energy nucleon components of the cosmic radiation, consisting of both primary nucleons and energetic secondary nucleons formed in the atmosphere.

A summary of the data in references 14 and 15 is given in Table III. The attenuation lengths listed apply to integrated intensities, i.e., intensities measured without close angular or energy definition.

In some previous measurements by DeJuren[6] of poor geometry attenuation of the 270-Mev neutrons, it was found that the cross sections for inelastic collision were at least one-half the total collision cross sections. For 90-Mev neutrons the inelastic cross section is slightly less[5,16] than $\frac{1}{2}\sigma_t$.

TABLE III. Attenuation lengths for reduction of integrated intensity by factor of $1/e$.

Type of event	Attenuation length in atmosphere	Attenuation length in Pb
Penetrating showers	110–125 g/cm^2	
Bursts	120–140 g/cm^2	250–450 g/cm^2
Stars	135–150 g/cm^2	<250 g/cm^2
Slow neutrons	160–190 g/cm^2	

If, for comparison with the cosmic-ray data, absorption cross sections of one-half the total cross sections measured for 270-Mev neutrons[6] are used, the calculated attenuation lengths are 138 g/cm^2 in air, and 250 g/cm^2 in Pb. Rossi[15] quotes an attenuation length for "neutral N-rays" (supposedly high energy neutrons) in air of 130 g/cm^2.

It appears that cross sections for high energy neutron absorption fall rather abruptly to a broad, slowly-varying or flat region at approximately the minimum level demonstrated in cosmic rays, and that this flat region is entered at energies as low as approximately 200 Mev.

[14] B. Rossi, Revs. Modern Phys. **20**, 537 (1948).
[15] B. Rossi, ONR Technical Report No. 26 (Massachusetts Institute of Technology) April 4, 1949; AEC Index No. NP-891.
[16] Bratenahl, Fernbach, Hildebrand, Leith, and Moyer, Phys. Rev. **77**, 597 (1950).