that used by one of the authors to investigate hydrogen-palladium systems.[2] The sample was a dispersion of sodium in mineral oil as described in the accompanying letter.[3]

Within experimental error, T_1 appears to be inversely proportional to the absolute temperature, in agreement with the theory of Heitler and Teller[4] regarding nuclear relaxation by interaction with the conduction electrons. From Korringa's theory[5] and Knight's measurement[6] of the frequency shift between Na^{23} resonances in the metal and in a salt, one calculates that T_1 due to conduction electrons should equal 11.7 milliseconds at room temperature, in excellent agreement with the measured value of 9.2 milliseconds. A 20 percent increase in the shift, such as Gutowsky proposes in the accompanying letter,[3] would lower the theoretical T_1 to a value even closer to the experimental result.

The T_2' data are shown in Fig. 1. Over the entire temperature range covered, T_2' is temperature dependent and is larger than the rigid lattice value by an order of magnitude. These results are in agreement with those of Gutowsky[3] which indicate that the line-width is narrower than the rigid lattice value for all temperatures above $-100°C$. The spin echo results show that T_2' increases markedly with temperature from the lowest temperature at which spin echoes were observed ($-58°C$) to about $-25°C$, where T_2' becomes of the order of T_1. For higher temperatures, T_2' goes as $1/T$ within experimental error and is of the order of T_1, indicating that spin-lattice relaxation determines the line-width in the high temperature range.

Using a simple theory, the observed low temperature behavior of T_2' can be explained as the combined effect of spin-lattice line broadening and nuclear dipolar broadening. T_2' is assumed to be given by the equation

$$1/T_2' = (1/T_2) + 1/T_2^a, \tag{1}$$

where T_2 is the phase-memory time determined by dipolar interactions alone, and T_2^a is that determined by spin-lattice interactions alone. The expression provides a better fit to the data than does the addition of second moments.

The large values observed for T_2' indicate that there is a motion of the sodium nuclei. Taking the motion to be self-diffusion of the nuclei, one may calculate the line narrowing on the basis of the theory of Bloembergen, Purcell, and Pound.[7] The calculation assumes the metal to be a liquid in which the atoms come no closer than a distance r, and predicts an exponential temperature dependence of T_2 according to the law

$$\frac{1}{T_2} = \frac{4}{5}\frac{\gamma^4\hbar^2 I(I+1)Ne^{E/RT}}{rD_0}, \tag{2}$$

where γ is the nuclear gyromagnetic ratio, I is the nuclear spin, N the number of atoms per unit volume, and the diffusion constant, D, has been written in the customary form $D = D_0 e^{-E/RT}$. For numerical work r was taken to be the rigid-lattice nearest-neighbor distance 3.7A. The liquid theory should give the temperature dependence of T_2 rather well, but be less reliable in giving the actual magnitude of T_2.

To compare Eqs. (1) and (2) with experiment, T_2^a was taken to be a constant (10.8 milliseconds), since T_2^a is a much more slowly varying function of temperature than T_2. The work of Nachtrieb[8] has been utilized in the comparison. He has measured the coefficient of self-diffusion for sodium by means of radioactive tracers and finds $D = 0.320e^{-10650/RT}$ cm^2/sec. Extrapolating his measurements to $-56°C$ gives $D = 0.74 \times 10^{-11}$ cm^2/sec. The nuclear resonance data at this temperature, where the T_2^a correction is small, yield $D = 1.3 \times 10^{-11}$ cm^2/sec. The order of magnitude agreement is considered satisfactory, since the theory is somewhat crude.

To compare the temperature dependence of the nuclear resonance data with Nachtrieb's results, a theoretical T_2' curve was constructed. Equations (1) and (2) and the constant T_2^a were used to calculate a value of T_2 at $-56°C$ from the data. This value of T_2, together with T_2^a and Nachtrieb's value of the activation energy, determined the theoretical T_2' curve shown in Fig. 1. Curves corresponding to values of activation energy 20 percent higher and lower are also shown. The agreement of both the temperature dependence and the order of magnitude of D with Nachtrieb's results confirms the hypothesis of diffusion narrowing. Similar work is currently in progress on the Li^7 relaxation times.

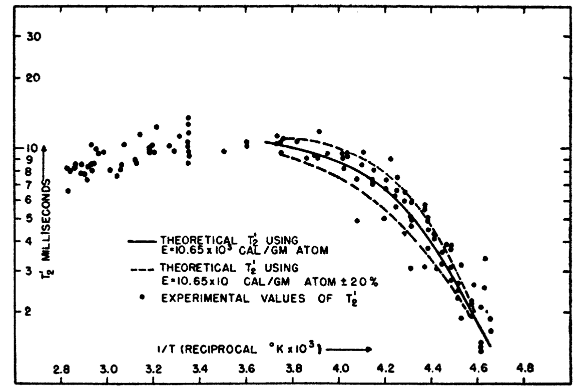

FIG. 1. Temperature dependence of T_2' for metallic Na^{23}.

The authors are indebted to Dr. Nachtrieb for sending them his experimental results in advance of publication. Much of the electronic equipment was built by Mr. L. S. Kypta.

* This work was supported in part by the ONR.

[1] E. L. Hahn, Phys. Rev. 80, 580 (1950).
[2] R. E. Norberg, thesis, University of Illinois (1951), unpublished.
[3] H. S. Gutowsky, Phys. Rev. 83, 1073 (1951).
[4] W. Heitler and E. Teller, Proc. Roy. Soc. (London) A155, 629 (1936).
[5] J. Korringa, Physica 16, 601 (1950).
[6] W. D. Knight, Phys. Rev. 76, 1259 (1949).
[7] Bloembergen, Purcell, and Pound, Phys. Rev. 73, 679 (1948).
[8] N. Nachtrieb, private communication.

Nuclear Absorption of Negative Pi-Mesons at Different Energies

G. Bernardini, E. T. Booth, and L. Lederman
Physics Department, Columbia University, New York, New York
(Received July 9, 1951)

ILFORD G-5, 400-, and 600-micron nuclear emulsions were exposed to the 70- and 105-Mev external π^- meson beams of the Nevis cyclotron, and the analysis of the interaction with emulsion nuclei was continued.[1,2] To extend the energy range, additional plates were exposed to the 70-Mev beam behind 8″ of lithium plus ½″ of carbon. The energy of the mesons crossing these plates was 30–50 Mev, as determined by plural scattering and grain density

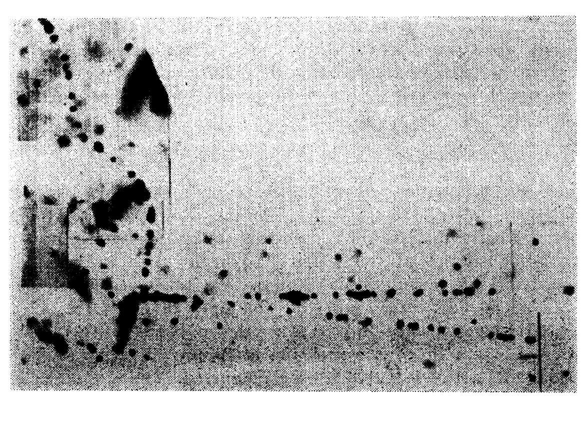

FIG. 1. Backward elastic scattering ($E = 105$ Mev, $\Theta = 173°$) with recoil and slow electron at the vertex (observed by Mrs. N. Bernardini).

TABLE I. Energy dependence of nuclear events.

Energy (in Mev)	Σl (in cm)	Stars	Stops	Elast. scatt. (>30°)	Inelast. scatt.
30– 50	2145±21	49 (15)	8	8 (17)	2 (6)
70– 80	1438±14	44 (11)	4	4 (4)	7 (8)
60– 90	1000±50	19 (7)	4	3 (6)	6 (8)
100–110	2761±28	76 (16)	18	15 (20)	22 (32)

measurements. It was possible to obtain plates covered by such a uniform and well-collimated flux that scanning "along the track" (with 90×, 80×, and 43× oil objectives) was as rapid as the conventional area scanning, and was employed exclusively in this work.

The actual numbers of the nuclear interactions observed in the total path of meson track followed, Σl, are given in Table I. In this classification we define "elastic scattering" as an event in which the incident and scattered pi-meson differ in energy by less than 15 percent. Occasionally, these may be accompanied by a short black prong or slow electron (10–100 kev) at the vertex. "Inelastic scatterings" are defined as events in which the scattered meson demonstrates, by grain density and plural scattering measurements, an energy loss >15 percent of the energy of the incident meson. When the outgoing track is shorter than 700 microns, only its grain density can be determined and the distinction between mesons and protons is not completely certain. The figures enclosed by brackets in columns 5 and 6 include these doubtful scatterings. In the third line, the data obtained in the old (60–90 Mev) meson beam[1] are also reported. The bracketed figures in column 3 give the number of stars having a proton prong of at least 30 Mev.

The angular distribution of the elastic scatterings <30° strongly suggests that most of these can be considered as shadow and coulomb scattering or $\pi-\mu$-decays. Since the results are quite insensitive to the choice of this cut-off angle, we assume that the remaining events are true interactions of pi-mesons with the nuclear matter in the emulsion. Table II gives the total number Σn

TABLE II. Corrected mean free path.

Energy (Mev)	$I(e)$ (percent)	$I(\mu)$ (percent)	$\Sigma'(l)$ (cm)	Σn	λ_{geom} (cm)	λ_{obs} (cm)
30– 50	(3±2)	(8±4)	1910±100	80	15.6	24.0±3.0
70– 80	(10±2)	(9±3)	1165± 55	60 }	19.1	19.4±2.6
60– 90*	(10±5)	(10±5)	800±100	37 }		21.5±4.2
100–110	2	(5±3)	2610±100	146	20.4	18.0±1.3

* Old meson beam.

of these and the corresponding total mean free paths. In the $I(e)$ and $I(\mu)$ columns, the relative fractions of the electrons and μ mesons of the different beams are given. These fractions were estimated principally by counter experiments.[3] Further and consistent data were provided by cloud chamber runs[4] and by analysis of track characteristics. The $\Sigma' l$ column gives the corrected path length of π^- meson observed. The geometrical mean free path, λ_{geom}, is taken to be

$$\lambda_{geom}=1/\Sigma_i N_i\pi\hbar^2[(A^{\frac{1}{3}}/\mu c)+(1/p)]^2,$$

where the summation is over the emulsion constituents. This includes the finite extent of the pi-meson wave packet. At high energy, $\lambda_{obs}\cong\lambda_{geom}$; at low energy there is a transparency of ~30 percent. Since probably less than 25 percent of the collisions involve the light elements, this transparency is believed to originate in an energy dependence of the character of the interactions. Table III gives the absolute cross sections in barns for the various types of interactions as a function of energy. In this table, the bracketed figures of Table I were employed. The stoppings are included with stars because of the information in the π^+ interactions (to be published), which strongly indicate that these are stars containing only neutron prongs.

TABLE III. Cross sections, in barns.*

Energy	Stars and stops	Elast. scatt. 30°	Inelast. scatt.	Total
30– 50	0.62	0.19	0.06	0.87
60– 90	0.76	0.10	0.19	1.05
100–110	0.75	0.16	0.25	1.16

* Obtained from $\sigma=(21/\lambda)$ barns.

The definite increase with energy of the relative frequency of catastrophic processes (absorption and inelastic scattering) with respect to the elastic scatterings can partially explain the discrepancy between the results, here presented, and those of Bradner and Rankin.[5] However, in the energy interval (30–50 Mev) corresponding to the Berkeley experiment, the relative star frequency found by us is still twice that given by the Berkeley authors.

The general features of the stars do not change with the π^- energy, and it is evident that a large fraction of the absorbed energy is carried away by neutral particles (neutrons). However, a clearer analysis of the pion absorption mechanics will be possible through the comparison of these results with data now being assembled on the π^+ interactions.

We should like to acknowledge the invaluable assistance of Mr. Harrison Edwards, Mr. J. Spiro, and the Nevis staff, and to express appreciation to Mrs. N. Bernardini, Mrs. D. Lee, and Miss E. Wimmer for the scrupulous care taken in the scanning. Mrs. J. Bielk did excellent work in processing of the plates.

[1] Bernardini, Booth, Lederman, and Tinlot, Phys. Rev. 80, 924 (1950).
[2] Bernardini, Booth, Lederman, and Tinlot, Phys. Rev. 82, 105 (1951).
[3] The authors wish to thank Professors A. Sachs and J. Steinberger, and Dr. P. Isaacs for informing them of their results. See also Chedester, Isaacs, Sachs, and Steinberger, Phys. Rev. 82, 958 (1951).
[4] Lederman, Booth, Byfield, and Kessler, 83, 685 (1951).
[5] H. Bradner and B. Rankin, Phys. Rev. 80, 916 (1950).

Probable Emission of a Beryllium-8 Nucleus in the Fast Neutron Fission of Thorium-232

E. W. TITTERTON
Research School of Physical Sciences, Australian National University, Canberra, Australia
(Received July 9, 1951)

IN the course of recent photographic plate experiments on the fast neutron fission of thorium-232 using 2.5-Mev D−D neutrons,[1] an event was observed in which two light particle tracks emanate from the point of fission in addition to the two heavy fragments. The event is very similar to that observed earlier by Goward, Titterton, and Wilkins[2] in the course of experiments on the photofission of uranium. The explanation suggested in the photofission case was that the event represented ternary fission with the emission of a Be^8 nucleus. If the same explanation is applied to the present event, the α-particles are found to have energies of 10.0 and 9.6 Mev, respectively, and are inclined at 9° each other. Calculation shows that the energy release in the to disintegration of such a Be^8 nucleus into the two α-particles is 120±10 kev. This is somewhat higher than the measured value for the instability of the ground state of Be^8 given by Hemmendinger[3] as 103±10 kev, by Tollestrup, Fowler, and Lauritsen[4] as 89±5 kev, and more recently by Carlson[6] as 72±5 kev. Nevertheless, it seems reasonable to interpret the event as representing the fast neutron ternary fission of a thorium-232 nucleus, the third fragment being a Be^8 nucleus in its ground state emitted with an energy of 19.6±0.5 Mev at an angle of 62° to the fission fragment of smaller charge.

That such events are very rare is indicated by the fact that the two discussed above are the only ones observed in investigations including examination of 600,000 slow neutron events in-

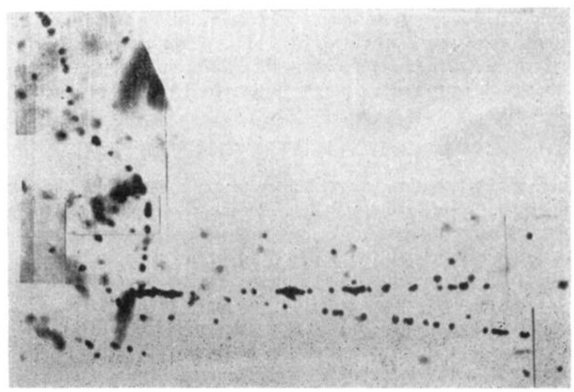

FIG. 1. Backward elastic scattering (E = 105 Mev, Θ = 173°) with recoil and slow electron at the vertex (observed by Mrs. N. Bernardini).