Fast Meson Interactions in Nuclear Emulsions. II. π^+ Mesons*

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π^+ mesons produced in the exterior proton beam of the Berkeley cyclotron are bent by an auxiliary magnet and detected in Ilford G5 emulsions. These mesons are studied in the same way as were the π^- mesons in Part I of this experiment. Extra care is taken to eliminate protons from the data and a special technique is developed to make more efficient small angle scattering measurements. The average initial energy, 45.5 Mev, is slightly higher than that of the π^- mesons, and the spread in energy is greater. Less than 18 percent of observed track is less than 30 Mev and 98 percent of it is over 22 Mev.

No disappearances are found over the 902 cm of track. Fewer are expected than were found in Part I, since the average number of charged prongs is greater for π^+ induced stars than for π^-. No inelastic scatters are found among the 5 scatters greater than 30°. Though the star frequency is the same as in the previous experiment, the frequency for scatters is significantly lower, a fact which is not explained by the slightly higher energy. A statistical upper bound on the cross section for π^+ scattering on hydrogen is obtained as 2.3×10^{-28} cm^2.

INTRODUCTION

THE earliest laboratory experiments[1,2] on meson scattering and absorption were designed for emulsion instrumentation and were performed on π^- mesons. The scatterer, which was the emulsion, would serve as a detector so that the paths of the mesons in matter could be examined in detail. These experiments obviated the problems of geometry encountered elsewhere[3] when emulsions were used as detectors only. They admitted the technical difficulties of microscope scanning in preference to the problems of electronic counting. However, their disadvantage was obvious: Only the hydrogen scattering could be analyzed independently, while the rest of the observed interaction was due to a family of elements which made up the emulsion. The information potentially available in particular events, such as the energy loss of the meson in scattering, the prong distribution from absorption, and the frequency of charge exchange during disappearances, was partially obscured by an ignorance of the elements involved.

These experiments could, however, serve as a beginning for accurate relative measurements on π^- and π^+ meson interactions, the material of the scatterer being held constant. The earliest experiments were made on π^- mesons because it was technically simpler to do so. Fortunately, by August, 1950, Richman *et al.* provided a copious source of π^+ mesons[4] by making use of the reaction

$$p+p\rightarrow d+\pi^+,$$

which occurred when the 340-Mev protons of the external cyclotron beam impinged upon polyethylene, $(CH_2)_n$. The mesons produced are monoenergetic. If their mass is 275.1 electron masses, the unique energy is 70 Mev. With a π^+ beam at hand, the present experiment was undertaken, first, to provide estimates on the π^+ meson scattering and absorption cross section and, second, to provide information about the relative interaction properties of high energy positive and negative mesons. It was designed to parallel its forerunner[5] on π^- mesons as closely as possible.

Three experiments[3,6,7] on the π^+ interactions in pure materials have now been reported. But aside from the Cornell evidence that π^+ and π^- do not interact differently, the best empirical evidence available with which to compare our relative measurements is found in the Columbia emulsion work[8–11] on π^- and π^+ mesons. From the theoretical point of view it is not clear at this time whether positive and negative mesons are essentially different particles in terms of meson forces. It is not known at what energy the Coulomb-nuclear interference can be neglected. Nor is it safe to say that the incident meson energy at the nucleus determines the scattering properties rather than the energy at a nucleon. The meson may ineract with the nucleus as a whole or may scatter within the nucleus. Hence, a large part of the interpretation of our experiment must be done in the future.

EXPERIMENTAL ARRANGEMENT

Our object in setting up the experiment was to get a high flux of approximately 45-Mev π^+ mesons entering normal to the edge of photographic plates, with a minimum number of background protons and other

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[1] H. Bradner and B. Rankin, Phys. Rev. **80**, 916 (1950).
[2] Bernardini, Booth, Lederman, and Tinlot, Phys. Rev. **80**, 924 (1950).
[3] M. Skinner and C. Richman, Phys. Rev. **83**, 219 (1951).
[4] Cartwright, Richman, Whitehead, and Wilson, **78**, 823 (1950), also **81**, 652 (1951), also Richman, Skinner, Merrit, and Youtz, University of California Radiation Laboratory Report No. 922 (1950).
[5] H. Bradner and B. Rankin, Part I of this paper, Phys. Rev. **87**, 547 (1952).
[6] A. M. Shapiro, Phys. Rev. **83**, 874 (1951).
[7] Anderson, Fermi, Long, and Nagle, Phys. Rev., to be published.
[8] Bernardini, Booth, Lederman, and Tinlot, Phys. Rev. **82**, 105 (1951).
[9] Bernardini, Booth, and Lederman, Phys. Rev. **83**, 1074 (1951).
[10] Bernardini, Booth, and Lederman, Phys. Rev. **83**, 1277 (1951).
[11] G. Bernardini and F. Levy, Phys. Rev. **84**, 610 (1951).

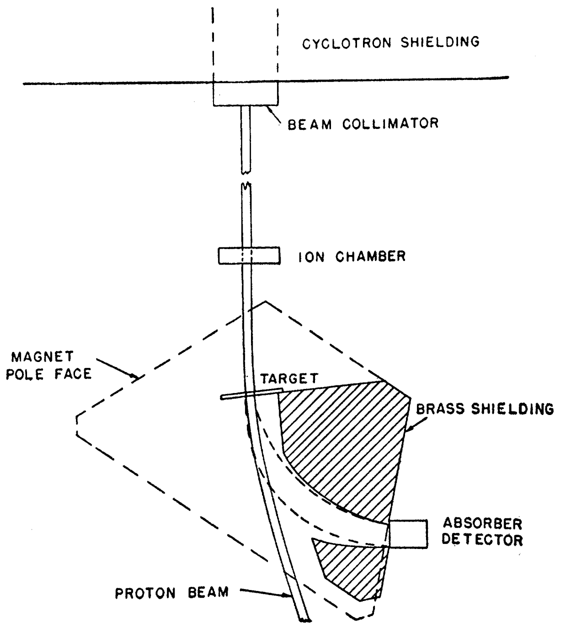

FIG. 1. Diagram of the equipment. The 68-Mev mesons, created in a $\frac{1}{4}$-inch polyethylene target, are bent by an auxiliary magnet and enter two sets of photographic plates at the point marked "absorber detector."

heavy particles. The mesons should be found easily under the microscope and yet not be confused with one another. We would follow them individually in the direction of flight noting where they were deflected through an angle greater than 30° or abruptly stopped in the emulsion. We arranged the experiment also to yield a supply of 68-Mev mesons which could be followed later.

Figure 1 is a diagram of the equipment in the "cave" just outside the cyclotron shielding. The 68-Mev mesons, created in a $\frac{1}{4}$-inch polyethylene target, are bent by an auxiliary magnet and enter two sets of photographic plates at the point marked "absorber detector." Each set of plates is pressed tightly together and wrapped as a group in black paper. One group stands in front of the other, acting as a partial absorber, and a $\frac{1}{2}\times\frac{1}{2}$ inch 2S aluminum bar is placed between them. A $\frac{1}{2}$-inch thick aluminum plate above and a 1-inch thick aluminum plate below the three pieces helps to define a parallel meson beam and at the same time shields out extraneous particles that would enter the surfaces of the emulsions. With about 600 mesons per second leaving a $2\times2\frac{1}{2}$ inch channel exit, a suitable exposure is obtained in 15 minutes.

The distribution of meson energies at the leading edge of the front plate should correspond to the beam distribution[12] with a half-width of 5 Mev. The distribution at the leading edge of the back plates should center about 45 Mev assuming the total path in the front plates to be in glass and all other conditions as calculated. However, upon passing through the absorbers, the lower half of the distribution will be stretched by about a factor of two, while the upper half will remain essentially unaltered. Actually, the mean of the energy distribution for mesons entering the back plates was found by the more direct methods of grain counting to be 49 Mev. The discrepancy is attributed to slight errors in the estimates of beam energy.

The plates were all 400μ, G5, Ilford emulsions. They were developed in the same way as the plates exposed to π^- mesons.[13]

MICROSCOPE TECHNIQUES

Throughout most of the experiment, random samples of the grain density and small angle scattering were taken on the selected particles. A sampling procedure was desirable, for it allowed us to choose the particles rapidly by sight and still have a check on their mass and velocity. Moreover, during the later part of the experiment we improved on our usual scattering method[13] and facilitated our sampling procedure by making a special "reflection goniometer"[14] for the microscope. The device is especially suited for making small angle measurements rapidly and accurately under the microscope.

The instrument is simple. It is essentially three concentric cylinders, two of which are free to rotate, one containing the eye piece and reticle and the other a thin strip of glass tilted at 45°. The inside cylinder clamps to the microscope barrel. The arrangement allows a row of point light sources outside the microscope to appear in the field of view. Upon rotating both cylinders through some angle, the light sources, if correctly placed, will appear to rotate with twice the angular velocity about a center fixed at half the focal distance away. In other words, a scale can be made to pass over the field of view which might otherwise be swept by a 25-cm lever arm attached to the eyepiece. It is easily read to 1/20 of a degree. That is better by a factor of 2 then is required if the direction of a 100μ segment length is defined up to $\frac{1}{2}$ a grain diameter, or $\frac{1}{6}\mu$. A comparison can also be made with our previous small angle scattering method. We then measured tangents under 450$\times$ by the lateral displacement of a track over, say, a 100μ cell length. The advantage of the present method can be shown to be:[14]

$$\text{advantage} = \text{focal length}/(\text{power}\times\text{cell length}) = 5.5.$$

By measuring the angle between two adjacent 100μ segments, we are not dependent upon the stage.

ENERGY SELECTION AND PROTON DISCRIMINATION

All observations were made more than 5 mm in from the leading edge of the back plate. A track had to extend further than 500μ beyond the 5-mm starting point, if

[12] W. F. Cartwright, thesis, University of California Radiation Laboratory Report No. 1278 (1951).

[13] See Part I (reference 5).

[14] Bayard Rankin, Rev. Sci. Instr. (to be published).

it was to be considered. It was accepted for study solely on the basis of its behavior in the first 500μ. If it had the visual characteristics of a 40-Mev meson whose direction was within 10° of the beam, it was then followed until it left the emulsion or traveled 10 mm. We relaxed the angular discrimination rule of the π^- experiment because the energies in the π^+ beam were not strongly dependent upon angle. The 500μ distance was chosen as the minimum distance in which a meson could be identified, if it were actually measured. The distance allotted for selection was not extended even in special cases.

We introduced a 10 percent sampling technique which would check our selection efficiency; the absorbers skewed the energy distribution, reducing a 62-Mev meson to 28 Mev at 5 mm into the back plate. Also a dangerous directional spray of high energy protons entered the plates despite the quantities of brass shielding. We masked a table of random numbers,[15] allowing only one digit to show, and moved the mask after each particle had been chosen. Whenever the number 7 appeared, the particle was measured for grain density and small angle scatter over a 1000μ distance starting at 5 mm into the plate.

A relation of the form $G=KI/I_0$ had been established for π^- mesons of energy 30 to 60 Mev. To evaluate the constant K, for the π^+ plates, we compared grain counts of 500μ long segments of four π^+ mesons and eight π^- mesons at 2100μ residual range. The relation becomes $G/100\mu=19I/I_0$ for the π^+ plates. The relation taken together with $E_\pi=f(\lambda I/I_0)$, an adaptation of Aron's curve[16] for energy loss of a proton in aluminum, allowed us to convert the average grain density of our sample to an estimate of the average energy. In the last equation $E_\pi=(m_\pi/m_p)E_p$, and λ, a constant, converts specific ionization in emulsion to energy loss in Mev/mg-cm^{-2} in aluminum. We obtained 45.5 Mev as the average energy for accepted mesons at 5 mm into the back plate.

Figure 2 is a plot of 50 sample points after converting grain density to specific ionization. The errors shown exemplify the standard deviations for any point. It is clear that the majority of the meson population have specific ionization in the range 1.39–1.85. The corresponding energy range is 34–56 Mev. Half of the mesons, those with initial energies above 45.5 Mev, will still have energies above 30 Mev after traveling 10 mm.[17] The lower energy mesons, say those of 34 Mev, will reach 30 Mev after 4 mm and 22 Mev after 10 mm of travel in emulsion. However, in the π^- experiment where the selection rules were the same, 64 percent of the 35.5-Mev mesons left a 400μ emulsion in less than 4.5 mm. It is then overly safe to say that less than 18 percent of the observed track was less than 30 Mev and 98 percent of it was over 22 Mev.

Figure 2 of this experiment and Fig. 4 of its forerunner on π^- mesons can be used to demonstrate that practically no protons were admitted into the data. A special control against protons was carried out for 191 cm of track, however, after we had noticed a peculiar lack of nuclear scatters. At the same time the average accepted meson energy was controlled by grain count and was lowered to 36 Mev. There was a fast method to use. We made only two 100μ grain counts and two scattering measurements on each track, achieving our purpose by spreading these measurements over 1.6 mm. We chose tracks which would almost certainly stay in the emulsion for 1.6 mm beyond the 500μ mark. One grain count at the 500μ mark, one grain count and one scatter count at the 1300μ mark, and one scatter count at the 2100μ mark served to throw out 99 percent of all protons and keep 70 percent of the mesons. Moreover, a track was dropped as soon as one of the measurements fell outside a specified tolerance limit. This minimized the possibility of dropping a track after following it for 2 mm. If an event occurred before we finished those measurements, or if the track went out, we would take grain count and scattering measurements over the first 500μ. We assured ourselves of the validity of this procedure by applying it to two hundred 340-Mev proton tracks. The proton tracks were obtained by Frank L. Adelman by exposing plates to the external beam of the

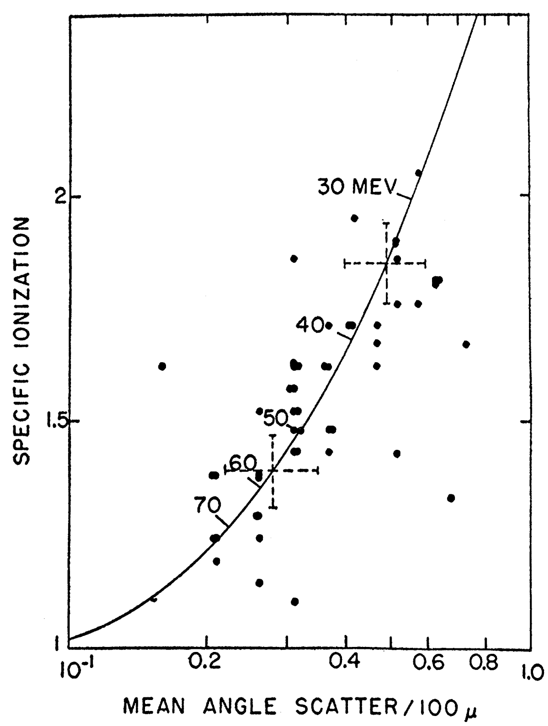

FIG. 2. A plot of 50 sample points after converting grain density to specific ionization. The heavy curve is that of Y. Goldschmidt-Clermont. The statistical errors exemplify the standard deviations for any point.

[15] M. G. Kendall and B. B. Smith, *Tables of Random Sampling Numbers* (Cambridge University Press, Cambridge, 1939).

[16] Aron, Huffman, and Williams, University of California Radiation Laboratory Report No. 121 (1949).

[17] Bradner, Smith, Barkas, and Bishop, Phys. Rev. **77**, 462 (1950).

TABLE I. Large angle scatters.

Angle (degrees) Horizontal projection	Total	Distance in plate (mm)	Grain density/100μ[a] Before	After	Average scattering angle before event (degrees/micron)	Specific ionization corresponding to average grain density before event
29	33	6.6	36.2±2.0	37.3±2.4	0.26/110	1.90
35	35	14.0	23.2±1.5	23.5±1.5	0.16/110	1.22
30	41	2.7	31.7±1.4	36.1±4.8	0.31/158	1.66
52	52	7.6	35.0±1.8	37.7±1.8	0.42/110	1.83
134	128	6.4	32.5±1.7	38.0±3.2	0.31/110	1.70
			Stars			
Number of prongs						
1		8.3	30.3±1.7		0.26/110	1.59
2		6.2	29.3±1.7		0.26/110	1.53
3		11.8	35.1±1.8		0.42/110	1.84
3		12.5	27.9±1.6		0.21/110	1.46
3		10.9	23.9±1.5		0.37/110	1.25
3[b,c]		8.5	41.2±1.6		0.73/158	2.16
3[b]		7.7	31.2±1.7		0.31/110	1.63
4		6.2	32.2±1.7		0.42/110	1.69
4		2.3	33.2±1.5		...	1.74
4		5.5	32.5±1.7		0.52/110	1.70
6[d]		4.7	30.9±1.4		0.42/158	1.62

[a] The errors are standard deviations.
[b] Accompanied by a recoil.
[c] Abnormally low energy.
[d] One prong makes a hammer track.

cyclotron. After it became evident that this special procedure gave no different results, the simpler sampling technique was recalled.

μ-meson contamination was considered negligible since less than 9 percent[4] of the π^+ mesons would decay before reaching the plates and only a fraction of the decay products would be detected. Fast electrons could not have been followed by mistake because their ionization was too low. The plates were lightly developed so that minimum ionizing electrons, such as β-particles from the π–μ–β decay process, whose average energy is about 35 Mev,[18] were soon lost in the background. The same thing would have happened to higher energy electrons also since electron ionization is an extremely weak function of energy above 1 Mev.

RESULTS

The processes that can take place as a π^+ meson passes through matter are absorption by a nucleus, scattering by a nucleus or nucleon, charge exchange scattering by a neutron, and radiative absorption of the meson by a neutron. The probability for the last process to occur in emulsion must be small, as inferred by the inverse process[19]

$$\gamma+p\rightarrow\pi^++n.$$

Chedester *et al.*[20] predict about 10^{-28} cm^2 for the radiative absorption cross section, assuming that the following reactions occur with the same probability:

$$\pi^++n\rightarrow\gamma+p,\quad \pi^-+p\rightarrow\gamma+n.$$

Wilson and Perry[21] have recently shown that the cross section for charge exchange scattering is the order of 10^{-27} cm^2 or less and so is small also. Consequently, we should observe only absorption and scattering.

Some interesting properties of π^+ absorption seem to make the probability of emitting only neutrons much smaller than in the π^- case.[5,9] We found, in fact, no disappearances. The scatters and absorptions were analyzed according to the criteria set up in the previous experiment. However, no inelastic scatters were found in this experiment. We have measured all scatters greater than 30° but again use only what is found above 90° for a cross section. In computing an interaction cross section, we assume an equal number of scatters above and below 90°.

Tables I to III include all the data on the nuclear events. The data for the two scanning procedures is shown separately and together.

Table II includes star prong measurements that were made on a separate area scan expressly to augment the π^+ capture data and display the interesting prong distribution. Since area scanning is especially suited for picking up stars, in this case we followed the tracks of the captured mesons only to make scattering and grain count measurement. 1000μ measurements were sufficient to eliminate proton induced stars. A plot of our measurements had about the same spread as the plot in Fig. 2. It revealed no dependence of prong number on meson energy. Since the total number of stars was few, we made no attempt to estimate energies of the emitted particles.

It was possible to obtain an upper bound on the cross section for the scattering of π^+ mesons on hydrogen simply by analyzing the one two-prong star which was found. It was clear that the prongs were not the products of a meson-proton collision, because they were not in the same plane with the incident track. Since proton collisions will be distributed in any specified segment of meson path according to a Poisson distribution, we found no Poisson event in our total path length L. Any mean free path which would make this event more than 50 percent probable must be more than 1.43 L. Or, using the Ilford published data[22] on the hydrogen content of emulsion, the corresponding cross section must be less than 2.3×10^{-26} cm^2.

CONCLUSIONS

The prong distribution of the stars given in Table II is of special interest when taken in comparison with the

TABLE II. Star prong distribution.

Prong number	1	2	3	4	5	6
Number of events	1	5	12	5	5	3

[18] R. Sagane and W. L. Gardner, University of California Radiation Laboratory Report No. 1261 (1951).
[19] Bishop, Steinberger, and Cook, Phys. Rev. 80, 291 (1950).
[20] Chedester, Isaacs, Sachs, and Steinberger, Phys. Rev. 82, 958 (1951).
[21] R. Wilson and J. P. Perry, Phys. Rev. 84, 163 (1951).
[22] The data is distributed with the Ilford emulsions.

corresponding distribution of the π^- experiment. The average number of prongs is significantly higher in the present case. This is qualitatively explained by assuming a primary nucleon-meson interaction in the absorption process. The reaction yields an energetic proton in the case of π^+ absorption and an energetic neutron in the other case. Charged particle emission is favored in π^+ absorption even without secondary collisions in the nucleus, while, if an α-particle model is justified, multiple charged particle emission is extremely likely. More data on π^+ meson capture, such as is being gathered at Columbia,[11] will be very valuable.

The cross section for the scattering of π^+ mesons on hydrogen as measured by Anderson *et al.*, imply a low cross section at 45 Mev. Yet even the upper bound for the cross section found in this experiment is low enough to show that multiple collisions within the nucleus are unlikely for π^+ mesons, as is also the case for π^- mesons.[20,23] It is reasonable then that no inelastic scatters were found.[5,10]

In contrast to Part I of this experiment on π^- mesons, few nuclear scatters were found. Though the statistical errors are large, it is striking that the estimated mean free path for scattering is significantly higher in the present experiment, a fact which is not reasonably explained by the slightly higher energy. The relative measurements are in qualitative agreement, however, with the Columbia emulsion investigations.[9–11]

TABLE III. Summary of results.

	Proton control technique	Usual scanning procedure	Either[a] technique
Total path length scanned (cm)	191	711	902
Number of disappearances in flight	0	0	0
Number of stars	1	10	11
Number of scatters greater than 30°	0	5	5
Number of scatters greater than 90°	0	1	1
Mean free path for stars (cm)			82+17
Mean free path for total nuclear interaction (cm) (assuming symmetry about 90°)			69±13
Mean free path corresponding to nuclear area (cm) (for emulsion)			23

[a] The errors are probable errors.

We wish to thank Dr. Chaim Richman and Dr. Miriam Cartwright for their help in exposing the plates. Mrs. Edith Goodwin scanned the plates with the extreme care that is necessary for an accurate experiment.

[23] H. A. Bethe and R. R. Wilson, Phys. Rev. 83, 690 (1951).

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Search for Betatron Induced, Low Z, Activities of Short Half-Life

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B^8 has been observed as a 0.61±0.11 sec positron emitter produced by the following reactions: $B^{10}(\gamma,2n)B^8$, $B^{11}(\gamma,3n)B^8$, and $C^{12}(\gamma,p3n)B^8$. Li^9 has been observed as a 0.19±0.05 sec beta minus emitter produced by the reaction, $B^{11}(\gamma,2p)Li^9$. Irradiation of elements from $Z=3$ to $Z=9$ with a 0–50 Mev gamma-ray spectrum failed to induce any other short-lived activities. In spite of this, B^{13}, C^9, and O^{13} are not ruled out as short-lived activities. Li^4 is not produced in observable amounts through the reaction $Li^6(\gamma,2n)Li^4$ if it has a half-life between 0.1 sec and 1 min; it is probably particle unstable.

I. INTRODUCTION

An investigation was undertaken to survey the field of short-lived radioactivities among the elements with $Z<12$ with particular emphasis on elements with $Z<8$. It seemed highly probable that any new radioactive isotopes found in this region would be short-lived because most of the isotopes which had not been observed would lie considerably away from the stability region of equal neutrons and protons. Equipment was set up specifically to observe activities of short half-life, i.e., in the region from 0.1 sec to several hours. Then an attempt was made to observe as many betatron-produced short-lived activities as possible.

Since B^8 and Li^9 had been observed only recently, confirmation of their existence from a betatron irradiation seemed significant. B^8 has been observed as a delayed alpha-emitter by Alvarez.[1] He found that it decays by a 13.7-Mev positron with a 0.65-sec half-life to the same excited state of Be^8 as does Li^8; the B^8 was produced by the following nuclear reactions: $B^{10}(p,H^3)B^8$, $Be^9(p,2n)B^8$ and $C^{12}(p,n\alpha)B^8$.

The positrons from B^8 have been observed in this laboratory in the current study from the gamma-ray betatron irradiations of B and C. During these same irradiations, a 0.19-sec negative beta-activity was also observed. Gardner, Knable, and Moyer[2] have described

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[1] L. Alvarez, Phys. Rev. 80, 519 (1950).
[2] Gardner, Knable, and Moyer, Phys. Rev. 83, 1054 (1951).