On the Scattering of Protons in Hydrogen

C. L. CRITCHFIELD AND D. C. DODDER
Department of Physics, University of Minnesota, Minneapolis, Minnesota
(Received October 25, 1948)

Results of the recent proton-proton scattering experiments at the University of Minnesota in which measurements were made at angles in the laboratory system from 8° to 45° using incident proton energies of from 2.4 to 3.5 Mev, are used to calculate phase shifts for the interaction. S-wave scattering is found which agrees with previous work in corresponding to the potential of an attractive rectangular well of radius e^2/mc^2 and depth 10.5 Mev, or to a Yukawa-type potential with a meson of mass in the neighborhood of 300 electron masses. An anomaly which remains at the smaller angles is not removed by a careful treatment of the geometry of the scattering chamber, but is tentatively accounted for with a combination of repulsive p-wave scattering and a systematic experimental error of approximately one percent. The p-wave phase shifts are several times larger than those expected from a repulsive rectangular well of the same dimensions as the well for the s-wave scattering.

PRECISE measurements of the intensity with which protons are scattered by gaseous hydrogen have been extended by Blair, Freier, Lampi, Sleator, and Williams[1] to higher energies of bombardment and to smaller angles of scattering than those measured hitherto.[2] The general method of the experiment, however, is the same as that used by Tuve *et al.*, at the Department of Terrestrial Magnetism, and Her. *et al.*, at Wisconsin.

This method is to direct a narrow beam of protons from an electrostatic generator through a scattering chamber filled with hydrogen gas and to count the protons that emerge from a small volume at the center of the chamber along a line forming an angle θ with the axis of the incident beam. Apertures are placed along the axis of the detector window so that only those rays forming a narrow "beam" will be counted and the volume of gas effective in scattering is determined by the intersection of the incident beam with the detecting "beam." Since the scattering geometry can be very closely defined in this way and since the energy can be controlled quite accurately in the electrostatic machines, the method used in these experiments leads to results that are valid to about one percent. In the work at Minnesota the energy of the bombarding protons has been advanced from 2.4 Mev, the highest energy used at Wisconsin, to 3.5 Mev and the scattered intensity was measured at 8°, 10° and 12.5°, as well as in the range 15°–45° which was studied in preceding work.

The method of theoretical reduction of data on proton-proton scattering appears in the literature in the classic work of Breit[3] and his collaborators. This method is adopted here in its essential features but with certain modifications in application. In the first place, since new data were gathered at angles of scattering smaller than those previously used, we had to compute the Coulomb scattering and interference terms for arguments not appearing in existing tables. We did this by substituting directly into the formula for the differential cross section at the particular energies and angles concerned in the experiments of reference 1. Secondly, the great care taken by the experimenters to eliminate errors in alignment makes it unnecessary to consider corrections that are of first order in such errors. However, special attention is paid to "second order geometry," the corrections arising from the finite width and height of the incident and scattered beams.

The notation introduced in Breit's work will be adopted, for the most part, in the presentation of the fundamental scattering formula. The "phase shift" due to nuclear forces in singlet S collisions of two protons will be denoted by K_0,

[1] Blair, Freier, Lampi, Sleator, and Williams, Phys. Rev. 74, 553 (1948).
[2] Herb, Kerst, Parkinson, and Plain, Phys. Rev. 55, 998 (1939). References to the earlier work are listed here.
[3] Cf. especially G. Breit, H. M. Thaxton and L. Eisenbud, Phys. Rev. 55, 1018 (1939). A complete list of background references appears in that paper.

and k and η have the meanings

$$k=(Mv/2\hbar) \quad \eta=(e^2/\hbar v)$$

where M is the mass of the proton, v the velocity of the bombarding proton upon entering the scattering volume and $\hbar$ and e have their conventional significance. Using the fundamental constants reported by Birge[4] we obtain

$$k\eta=1.7352\times10'' \text{ cm}^{-1} \quad \eta=.15806/E_{\mathrm{Mev}}^{\frac{1}{2}} \quad (1)$$

where E_{Mev} is the energy per proton in millions of electron volts, in the incident beam. The velocities of bombardment are small compared with that of light and relativistic effects amount to only a few tenths of a percent. The differential cross section for scattering $\sigma(\theta)$ as measured in the laboratory at the angle θ, may be written

$$\sigma(\theta)=(\cos\theta/k^2)f(\theta). \quad (2)$$

Neglecting relativistic effects as well as nuclear phase shifts in collisions of angular moments greater than zero, the function $f(\theta)$ takes the well-known form:

$$\begin{aligned} f(\theta)=\eta^2\{&\csc^4\theta+\sec^4\theta \\ &-\sec^2\theta\csc^2\theta\cos(\eta\ln\tan^2\theta)\} \\ &-2\eta\{\csc^2\theta\cos(K_0+\eta\ln\sin^2\theta) \\ &+\sec^2\theta\cos(K_0+\eta\ln\cos^2\theta)\}\sin K_0 \\ &+4\sin^2K_0. \quad (3)\end{aligned}$$

In computing $f(\theta)$ for the various values of η, θ, and K_0 it was found convenient to transform to a new notation:

$$\begin{aligned} \xi&=(8\eta/1-\cos4\theta) \\ a&=\eta[2+\cos(\eta\ln\tan^2\theta)] \\ b&=\cos^2\theta\cos(\eta\ln\sin^2\theta)+\sin^2\theta\cos(\eta\ln\cos^2\theta) \\ c&=-\cos^2\theta\sin(\eta\ln\sin^2\theta) \\ &\quad-\sin^2\theta\sin(\eta\ln\cos^2\theta) \quad (4)\end{aligned}$$

so that:

$$\begin{aligned} f(\theta)=\xi^2+4\sin^2K_0-\xi& \\ \times\{a+b\sin2K_0+2c\sin^2K_0\}.& \quad (5)\end{aligned}$$

Equation (5) can be solved for $2K_0$ with the result:

$$2K_0=\sin^{-1}\left\{\frac{\xi^2-\xi(a+c)+2-f(\theta)}{\xi b}\right. \\ \left.\times\cos\left(\tan^{-1}\frac{2-\xi c}{\xi b}\right)\right\}-\tan^{-1}\frac{2-\xi c}{\xi b}. \quad (6)$$

[4] R. J. Birge, Rev. Mod. Phys. 13, 233 (1941).

The measurements required in order to determine K_0 from Eq. (6) are those of the energy, E_{Mev}, the angle of scattering θ, and a value of $f(\theta)$, which is calculated from the observed $\sigma(\theta)$. In practice, however $\sigma(\theta)$ is not observed directly since the differential cross section is a function of the angle of scattering and the latter is not defined exactly by the system of apertures. Since the correction for "second order geometry" becomes of increasing importance as the measured angle of scattering is diminished, an attempt is made here to refine the formula for this correction.

We assume that the incident beam of protons is accurately defined by the small circular (Nylon) "source" window that separates the scattering chamber from the accelerating tube and by a second circular aperture placed between the window and the center of the chamber. The line of centers of the circles forms the axis of the incident beam and the planes of the circles are taken perpendicular to this axis. The optical rays forming the incident beam then form a family of conical bundles, each member of the family originating on a particular element of area, *dudv*, of the source window. This description of the incident beam relies on the su position that the accelerator side of the Nylon window is bombarded by a uniform current density of protons and that the the protons in passing through the Nylon are scattered sufficiently to supply all the conical rays that pass through the second aperture with the same current. In fact, multiple scattering in the window is adequate to give an essentially uniform distribution of emergent protons within the angles concerned. However, subsequent scattering of the protons from the rectilinear paths by collisions in the gas is a possible source of departure of the description of the actual beam from the model we have assumed. Since the effect of multiple scattering in the gas decreases to zero as the density of the gas decreases to zero, we should rather assert that the ray description of the incident beam holds only in the limit of very low density of gas. The over-all effect of gas density on the observed cross section was tested (cf. reference 1) and found to be negligible at the pressures used in obtaining the data. On this basis, therefore, we assume that the description of the paths of the protons by straight lines is adequate for computing the geometrical corrections.

A model similar to that for the incident beam is assumed for the family of trajectories that pass through the window of the detector. The detector window is circular and the normal at its center is assumed to intersect the axis of the incident beam at a certain angle, θ. This normal is the axis of the scattered beam and the intersection with the axis of the incident beam is the center of the scattering volume. Between the detector window and the scattering volume is placed a rectangular aperture, normal to and centered on the axis of the scattered beam. The long sides of the rectangle are perpendicular to the plane of scattering, i.e., the plane formed by the incident and the scattered axis. The optical rays that may enter the detector then form a family of pyramidal bundles, each member of the family being designated by having the apex of the pyramid on a certain element of area, $d\xi d\zeta$ on the detector window. The long side of the rectangular aperture is long enough so that every pyramid with apex on the detector window encompasses the entire section of the incident beam. Hence the scattering volume is defined by the intersection of cones with pyramids with axes inclined at an angle near θ and such that the lines of intersection form complete ellipses on the broad faces of the pyramids.

If a proton in the incident beam collides with a proton in the gas within the volume of intersection defined above it may be detected. The intensity of protons originating on the source window in an area $dudv$, scattered in the volume $dxdydz$ and detected on the area $d\xi d\zeta$ of the counter window is

$$d^7I = I_0N_0\frac{\sigma(\phi)}{R^2S^2}\cos\theta_R dudvdxdydzd\xi d\zeta \qquad (7)$$

where

I_0 is the intensity (per cm²) emerging from source window
R is vector distance from scattering volume $dxdydz$ to detecting area $d\xi d\zeta$
N_0 is the density of hydrogen nuclei in the gas
S is vector distance from source area $dudv$ to scattering volume $dxdydz$
ϕ is the angle of scattering for the particular paths **R** and **S** (i.e., $\cos\phi = \mathbf{R}\cdot\mathbf{S}/RS$)
$\sigma(\phi)$ is the differential cross section at angle ϕ
θ_R is the angle between R and normal to detecting window.

The measured intensity for a given setting of the detector is the sevenfold integral of Eq. (7). In general, ϕ will be a function of all seven independent variables $\mathbf{R}=\mathbf{R}(x, y, z, \xi, \zeta)$ and $\mathbf{S}=\mathbf{S}(x, y, z, u, v)$ and $\theta_R=\theta_R(x, y, z, \xi, \zeta)$. However, ϕ differs from θ and θ_R differs from zero only by infinitesimal angles, and **R** and **S** differ from R_0 and S_0 only by infinitesimal lengths, where R_0 and S_0 are the distances from the scattering center to the center of the detector window and to the center of the source window, respectively. Since the integral of Eq. (7) cannot be calculated in closed form it is necessary to expand ϕ, $\sigma(\phi)$, $\cos\theta_R$, R^2, and S^2 in ascending powers of the infinitesimal departures from their principal values and perform the integration on the individual terms. For the purposes of analysis of the proton-proton scattering one requires only the leading terms and the terms of one and two higher orders of infinitesimals.

The limits of integration of Eq. (7) are as follows: $dudv$ is to be integrated over the circular area of the source window the radius of which will be denoted by c. Similarly, $d\xi d\zeta$ is integrated over the detector window the radius of which is a. On the other hand, the limits on the $dxdydz$ integration are complicated functions of u, v, ξ, ζ, and are not, in the least way, convenient. In order to obtain an integration over the scattering volume for which the limits are formally independent of the source point and the detecting point we make a transformation so as to describe the scattering point x, y, z, as the intersection of one of the incident rays with a plane formed of detecting rays. The plane is taken parallel to the long side of the rectangular aperture and is then uniquely specified by the detecting point ξ, ζ, and by giving its angle with the corresponding plane through the scattering axis. Actually, if the rectangular aperture stands the distance H before the detector window, a convenient way of describing the angle of the plane is through the parameter t such that the angle is $\arctan t/H$. The limits of integration of the variable t are then evidently $\pm$ the half-width of the rectangular slit, provided the thickness of the aperture walls may be neglected. (The effect of aper-

TABLE I. Calculation of S-wave phase shift K_0.

θ	$\Delta_2(\theta)$	$E=2.42$ Mev $\sigma_{obs}(\theta)$ Barns	$f(\theta)$	K_0	$\Delta_2(\theta)$	$E=3.04$ Mev $\sigma_{obs}(\theta)$ Barns	$f(\theta)$	K_0
25°	0.0004	0.528	1.699	48°11'.1	0.0004	0.483	1.952	51°15'.4
30°	0.0001	0.528	1.778	48°37'.2	0.0001	0.469	1.984	50°51'.4
35°	−0.0001	0.503	1.791	48° 9'.6	0.0000	0.450	2.013	50°37'.6
40°	−0.0001	0.475	1.809	48° 1'.6	−0.0001	0.425	2.033	50°18'.7
45°	−0.0001	0.446	1.840	48°21'.2	−0.0001	0.402	2.083	51° 1'.8
		Average K_0=48°16'.1				Average K_0=50°49'.0		

θ	$\Delta_2(\theta)$	$E=3.27$ Mev $\sigma_{obs}(\theta)$ Barns	$f(\theta)$	K_0	$\Delta_2(\theta)$	$E=3.53$ Mev $\sigma_{obs}(\theta)$ Barns	$f(\theta)$	K_0
25°	0.0003	0.473	2.057	53°34'.1	0.0002	0.442	2.075	52°38'.1
30°	0.0001	0.450	2.048	51°38'.5	0.0001	0.428	2.103	52°13'.4
35°	0.0000	0.441	2.122	52° 5'.3	0.0000	0.418	2.171	52°35'.8
40°	−0.0001	0.410	2.100	51°32'.7	−0.0001	0.397	2.205	52°44'.0
45°	−0.0001	0.380	2.118	51°33'.1	−0.0001	0.366	2.202	52°38'.7
		Average K_0=51°52'.7				Average K_0=52°34'.0		

ture thickness has been checked experimentally, cf. reference 1.) This half-width is called w. The incident ray needed to define an intersection point with the plane may be specified by giving the point (u, v) on the source window and by giving the point in the plane of the circular aperture (that defines the incident beam) through which the ray passes. It was found convenient to use polar coordinates for this point, ρ the radius from the center of the aperture and ψ the angle from the plane of scattering. The limits on ρ are zero and the radius of the circular aperture which is denoted by b.

The procedure in integrating Eq. (7) is then to substitute for x, y, z in terms of t, ρ, ψ, defined above and replace $dxdydz$ by $[\partial(x,y,z)/\partial\rho,\psi,t)]\times d\rho d\psi dt$, whereupon the integration becomes straight forward. The type of calculation is so evident that we omit the details and present the result with a tabulation of the symbols:

$$I=\frac{I_0N_0\sigma(\theta)2\pi^3wa^2b^2c^2}{L^2HR_0\sin\theta}\Bigg\{1-\frac{b^2+c^2}{2L^2}-\frac{w^2}{2H^2} -\frac{3}{8}\frac{a^2}{H^2}-\frac{3}{8R_0^2}\left[a^2+\frac{b^2S_0^2+c^2G^2}{L^2}\right]+\frac{\cot^2\theta}{4R_0^2} \times\left[a^2+\frac{b^2}{L^2}(R_0+S_0\sec\theta)^2+\frac{c^2}{L^2}(R_0+G\sec\theta)^2\right] +\cot\theta\frac{\sigma'(\theta)}{\sigma(\theta)}\left[\frac{a^2}{8R_0^2}-\frac{a^2}{4HR_0} +\frac{b^2(S_0^2-R_0^2)+c^2(G^2-R_0^2)}{8L^2R_0^2}\right]+\frac{\sigma''(\theta)}{\sigma(\theta)}\left[\frac{a^2}{8H^2} +\frac{w^2}{6H^2}+\frac{b^2+c^2}{8L^2}\right]+\text{higher order terms}\Bigg\}$$

where

L is distance from source window to circular aperture
S_0 is distance from source window to scattering center
$G=S_0-L$ is from circular aperture to scattering center
H is distance from detector window to rectangular aperture

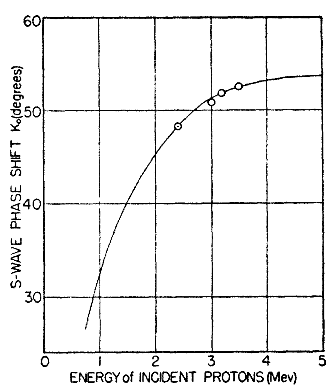

FIG. 1. S-wave phase shift K_0 in degrees is plotted against energy E_p of incident protons in Mev. Values of K_0 determined from experimental cross sections for the proton-proton scattering are shown as open circles. The solid line represents the values of K_0 corresponding to a nuclear potential well of depth 10.5 Mev and range e^2/mc^2 as calculated by Thaxton and Hoisington.

R_0 is distance from detector window to scattering center
θ is measured angle of scattering
$2w$ is width of rectangular aperture
a is radius of detector window
b is radius of circular aperture
c radius of source window
$\sigma(\theta)$ is Eq. (2) evaluated at θ
$\sigma'(\theta)$ is first derivative by θ evaluated at θ
$\sigma''(\theta)$ is second derivative by θ evaluated at θ.

If we denote the curly brackets in Eq. (8) by $\{1+\Delta_2(\theta)\}$ and write the factor in terms of the number of protons registered per second in the incident beam, n,

$$n=(\pi^2b^2c^2/L^2)I_0$$

the expression for the measured intensity becomes

$$I=nN_0\frac{2\pi wa^2}{HR_0\sin\theta}\sigma(\theta)\{1+\Delta_2(\theta)\}. \qquad (9)$$

Through Eqs. (9) and (8) the value of $\sigma(\theta)$ may be computed from the observed I and subsequently $f(\theta)$ and K_0 can be determined. Owing to the fact that quite small apertures were used in the experiments reported in reference 1, the corrections for second order geometry are quite small, amounting to only 2 percent at the smallest angle of scattering.

In Table I we present the results of calculations for angles of scattering larger than 20°. These larger angles were used to obtain the values of K_0 because they are most sensitive to the S-wave anomaly (cf. Breit reference 3) and because the lower angles are more sensitive to errors in voltage, etc., as well as to effects of higher angular momentum. The "observed" differential cross section is that computed from the yield without geometrical correction, i.e.,

$$\sigma_{\text{obs}}(\theta)=\sigma(\theta)\{1+\Delta_2(\theta)\}. \qquad (10)$$

In Fig. 1, the average values of K_0, shown in Table I are plotted against the energy of bombardment as open circles. The solid line shown in Fig. 1 represents the theoretical prediction for K_0 as calculated by Hoisington and Thaxton[5] for a nuclear potential well of constant depth of 10.5 Mev and range e^2/mc^2. The phase shifts due to a Yukawa potential corresponding to a mass of around 300 electron masses are also in this region.[6] These potentials are those which fit the experiments on proton-proton scattering below 2.4 Mev. It is evident that the new experimentally determined values of K_0 are satisfactorily accounted for.

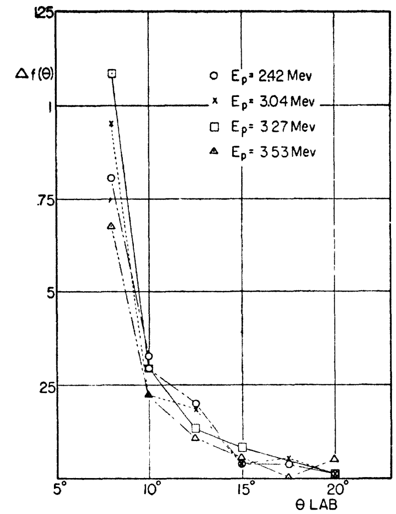

FIG. 2. $\Delta f(\theta)=f(\theta)_{\text{obs}}-f(\theta)_{\text{calc}}$ is plotted against θ_1, the angle of scattering in the laboratory system, for each value E_p of incident proton energy. The calculated values of $f(\theta)$ correspond to values of K_0 determined from the cross sections at the scattering angles from 25° to 45°.

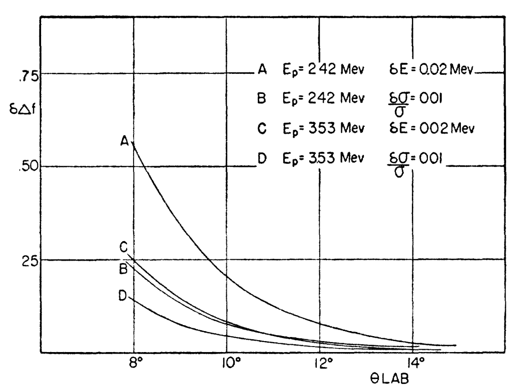

FIG. 3. $\delta\Delta f(\theta)$, the change in the value of $f(\theta)$ which would result from a change in the value of experimentally determined quantities, is plotted against scattering angle in the laboratory system for bombarding energies of 2.42 and 3.53 Mev. $f(\theta)$ is shown corresponding to systematic errors of 0.02 Mev in measurement of bombarding energy and of 1 percent in measured cross section. Other errors in experimental values will produce similar effects.

[5] L. E. Hoisington and H. M. Thaxton, Phys. Rev. 56, 1196 (1939), Fig. 2.

[6] Private communication from Professor Gregory Breit, who has calculated the phase shifts corresponding to mesons of various masses. A paper of his on the subject is forthcoming.

TABLE II.

Values of P-wave phase shift in radians for:
(a) rectangular potential well of range e^2/mc^2 and depth 10.5 Mev,
(b) corresponding to observed cross section.

E in Mev		2.42	3.04	3.27	3.53
K_1	(a)	-0.00302	-0.00413	-0.00460	-0.00515
	(b)	-0.00794	-0.0112	-0.0125	-0.0395

The possibility that the $p-p$ S-wave scattering can be accounted for by a meson potential function with a meson mass of 326, in. was put forward in 1939 by Hoisington, Share, and Breit.[7] At that time, however, the only independent measurements of the mass of mesons in cosmic rays showed that mass to be about 200M. Recently, independent evidence of a meson in cosmic rays with mass in the neighborhood of 300M has been found.[8, 9] Furthermore, these heavier mesons are created by nuclear bombardment with the 184-in. cyclotron at Berkeley indicating that they are probably associated with nuclear forces. It is quite possible, therefore, that the proton-proton scattering is directly associated with the properties of a neutral π meson.

The values of K_0 from Table I were used with Eq. (5) to compute $f_{\mathrm{calc}}(\theta)$ due to Coulomb and s-wave scattering (Table II) at angles from 8° to 20°. A comparison of the results with the values of $f(\theta)$ obtained from the observations of $\sigma_{\mathrm{obs}}(\theta)$ and Eqs. (10) and (2) is plotted as a function of angle in Fig. 2. The difference between the values is seen to increase with decreasing angle, and to show no marked energy dependence. Two possible factors which might cause such a discrepancy are: the presence of scattering of particles with higher angular momenta, and possible systematic experimental errors in energy, cross section or related measured quantities. The angular dependence of the effect of such errors in energy and cross section is plotted in Fig. 3 for the $E=3.53$ Mev and 2.42 Mev. The amount of error is taken to be that of probable error estimated by the experimenters. The observed anomaly in $f(\theta)$ is also shown for comparison. It is seen that the effect of such errors decreases more rapidly with increasing angle than does the anomaly.

On the other hand the discrepancy does not show the increase with increasing energy to be expected of nuclear p-wave scattering. Thus attempts to explain the difference in terms of either alone are not successful. It has been possible, however, to choose a combination of p-wave scattering with phase shifts varying as $E^{\frac{3}{2}}$ and systematic experimental error to account for the anomaly with some consistency. The relative amounts of the two effects are not very precisely determined by the available data. However, the choice made gives results which are plausible. The systematic experimental error which seems to fit is one of about one percent. The p-wave shifts are shown in Table II. Also shown are values of the p-wave phase shifts obtained by extrapolation of the calculations of Thaxton and Hoisington[6] on the basis of a rectangular repulsive well of range e^2/mc^2 and depth 10.5 Mev.

The results of the analysis presented above are that the S-wave phase shifts fit very well with the interpretations previously found for those at lower energy. Especially interesting among these interpretations is the one that appears to connect the proton-proton forces with the new π-meson. However, the S-wave phase shifts are not adequate to account for the observed scattering at angles of 15° and below. In fact, the discrepancies at small angles do not appear to originate from any one source but can be understood as a systematic error in the energy scale of about one percent superposed upon a small, negative P-wave phase shift. The magnitude and sign of the P-wave shift are within reason but the error in energy or other related quantity is very difficult to understand. It must be kept in mind, however, that measurements of scattering at small angles are very sensitive to geometry so that the discrepancies might possibly arise through some undetected effect of this type. In any event the numerical values for K_1 are not accurate.

ACKNOWLEDGMENTS

We should like to thank Professor Williams and the members of the Minnesota electrostatic

[7] L. E. Hoisington, S. S. Share, and G. Breit, Phys. Rev. 56, 884 (1939).
[8] C. M. G. Lattes, G. P. S. Occhialini, and C. F. Powell, Nature 60, 453 (1947).
[9] E. Gardner and C. M. G. Lattes, Science 107, 270 (1948).

generator group for their cooperation in obtaining results especially suitable for the type of calculations used here, including their exceedingly careful elimination of other conceivable causes of the anomaly for which an interpretation is given above. We are also indebted to Professor Breit for sending us the values of the S-wave phase shifts corresponding to Yukawa meson potentials. This work was supported in part by the Office of Naval Research.

PHYSICAL REVIEW VOLUME 75, NUMBER 3 FEBRUARY 1, 1949

An Investigation of Bremsstrahlung by Means of the Nuclear Isomerism of Indium*

WALTER C. MILLER AND BERNARD WALDMAN
Department of Physics, University of Notre Dame, Notre Dame, Indiana
(Received October 4, 1948)

The metastable state of In^{115} has been used as a detector of a narrow energy band in the continuous x-ray spectrum produced by a monoenergetic electron beam on gold targets. The thin target x-ray isochromat ($h\nu = 1.04$ Mev) has been investigated in the neighborhood of the short wave-length limit. This isochromat is finite at the threshold and constant for at least 400 kev. This in agreement with Guth's theory and verifies the assumption that the excitation of In^{115*} is a line absorption. Both the thin target and thick target x-ray excitation curves for In^{115} have been obtained in the region from 1.0 to 2.6 Mev. The thin target curve exhibits a step-like character from 1.0 to 1.9 Mev. The thick target curve below 2.0 Mev exhibits straight line segments as expected from the thin target curve, but above 2.0 Mev there are no straight line segments, in good agreement with the thin target data and theory. Activation levels have been found at 1.04 ± 0.02 Mev and at 1.42 ± 0.02 Mev. The over-all cross section (per electron incident on a 34 mg/cm² gold target) is 10^{-34} cm² in the region of the threshold. Evidence is presented for the existence of a lower activation level between 0.8 and 0.9 Mev with an over-all cross section (for a similar target) of the order of 10^{-36} cm².

INTRODUCTION

THE x-ray excitation of the isomeric state of indium (In^{115*}) was first observed almost ten years ago.[1,2] The early work of Collins and Waldman[3] indicated that new information could be obtained about (a) the character of the continuous x-ray spectrum (bremsstrahlung) produced by a monoenergetic electron beam and (b) some nuclear energy levels of the excited nucleus. The latter is exemplified by the work of Waldman and Wiedenbeck[4] on indium and by Wiedenbeck[5] on many other elements.

The first conclusive evidence of nuclear isomerism in a stable nucleus was reported by Goldhaber, Hill, and Szilard.[6] They found that the 4.1-hour negative electron activity of indium could be produced by fast neutrons but not by slow neutrons; in fact, there seemed to be a threshold for the process. This activity was assigned to a metastable state of In^{115} excited by the neutron impact and designated by In^{115*}. They postulated that this metastable state can be reached by a spontaneous transition from a higher energy activation level, and that the negative electron activity may be the internal conversion electrons from the gamma-ray transition, In^{115*} to In^{115}. Lawson and Cork[7] have shown that the energy of the gamma-ray is 338 kev and the conversion coefficient is 0.5.

A. Activation by X-Rays

Pontecorvo and Lazard[1] produced In^{115*} by irradiation with x-rays of 1.85-Mev maximum

* The results of this paper were presented at the M.I.T. Accelerator Conference on June 8, 1948.
[1] B. Pontecorvo and A. Lazard, Comptes Rendus 208, 99 (1939).
[2] Collins, Waldman, Stubblefield, and Goldhaber, Phys. Rev. 55, 507 (1939).
[3] G. B. Collins and B. Waldman, Phys. Rev. 59, 109 (1941).
[4] B. Waldman and M. L. Wiedenbeck, Phys. Rev. 63, 60 (1943).
[5] M. L. Wiedenbeck, Phys. Rev. 67, 92 (1945); Phys. Rev. 68, 1 (1945); Phys. Rev. 67, 267 (1945); Phys. Rev. 68, 237 (1945).
[6] M. Goldhaber, R. D. Hill, and L. Szilard, Nature 142, 521 (1938); Phys. Rev. 55, 47 (1939). See also M. Dode and B. Pontecorvo, Comptes Rendus 207, 287 (1938).
[7] J. L. Lawson and J. M. Cork, Phys. Rev. 57, 982 (1940).