The Radiations Emitted from Artificially Produced Radioactive Substances

III. Details of the Beta-Ray Spectrum of P^{32}

HUGH C. PAXTON
Radiation Laboratory, Department of Physics, University of California, Berkeley, California

(Received October 19, 1936)

The high energy portion of the distribution of β-rays from P^{32} was investigated by means of a hydrogen-filled cloud chamber in a magnetic field. A Konopinski-Uhlenbeck distribution was followed practically to the cutoff of 8200 $H\rho$ predicted by an extrapolation of the K-U plot. But it is possible to account for all tracks in excess of a straight line dropping to 6950 $H\rho$ by a spreading due to the estimated probable error of ± 3.8 percent. Accordingly, this work is best interpreted as indicating a sharp deviation from the K-U relation near the high energy limit, dropping to an upper limit of about 6950 $H\rho$. This discrepancy might be eliminated by modifying the K-U formula to apply to a doubly forbidden type of disintegration. However, for the allowed transitions from N^{13} and F^{17}, there is evidence from disintegration data that experimental upper limits are to be taken instead of the K-U extrapolations. The low energy part of the P^{32} β-spectrum was obtained from a very thin source suspended at the center of the expansion chamber. This distribution approached the origin almost as predicted by the K-U relation. There appeared to be no irregularities such as those observed by H. O. W. Richardson in the case of RaE.

WITHIN the past year several groups of workers[1-3] have used cloud chamber methods to investigate β-ray spectra from a number of artificially produced radioactive substances. All have found promising agreement between experimental curves and those predicted by the Konopinski-Uhlenbeck[4] modification of the Fermi theory. However, data in the neighborhood of the high energy limit have been so meagre that they present almost no evidence concerning the extremely flat tail of the K-U distribution.

The present work is an attempt to obtain detailed information about the upper limit of the β-ray spectrum of radio-phosphorus (P^{32}). This activity was chosen because of its comparatively long half-life ($14\frac{1}{2}$ days) and its freedom from γ-radiation. Further, this spectrum is the one investigated most completely by Kurie, Richardson and Paxton.

EXPERIMENTAL SET-UP

A target of red amorphous phosphorus pressed onto a pitted copper surface was activated by means of deuterons from the magnetic resonance accelerator of Lawrence and Livingston.[5] The target was liquid air-cooled during the course of bombardment in vacuum to prevent sublimation of the phosphorus. The active target was put away for three weeks before finally being investigated, in order to eliminate any known β-ray contaminant which may have been present in the phosphorus or its copper backing. The copper was allowed to remain an integral part of the source because reflected electrons would have little effect on the high energy portion of the β-spectrum.

The β-ray distribution was determined by measuring magnetically produced curvatures of electron tracks in a hydrogen-filled expansion chamber. The apparatus used was that described by Kurie, Richardson and Paxton with the addition of an external collimating channel between the source and chamber. Because this work is primarily concerned with the small fraction of tracks lying near the high energy spectrum limit, it was believed desirable to have some dispersing arrangement to prevent too much interference by the great body of low energy tracks. The method used was to collimate the beam of β-rays from the target, this being accomplished in an evacuated arm separated from the chamber itself by a thin (0.001″) mica window in the chamber wall. Thus, all β-particles enter the chamber not only at nearly the same place, but in essentially the same direction. Under these circumstances the analyzing magnetic field

[1] Kurie, Richardson and Paxton, Phys. Rev. **49**, 368 (1936).
[2] Fowler, Delsasso and Lauritsen, Phys. Rev. **49**, 561 (1936).
[3] Gaerttner, Turin and Crane, Phys. Rev. **49**, 793 (1936).
[4] Konopinski and Uhlenbeck, Phys. Rev. **48**, 7 (1935).
[5] Lawrence and Livingston, Phys. Rev. **45**, 608 (1934).

tends to fan out the spectrum, curling the lower energy tracks to one side, taking them out of the way of those of higher energy which continue in a more nearly forward direction.

A check calibration of the Helmholtz coils providing the analyzing magnetic field differed from that given by Kurie, Richardson and Paxton. A careful recalibration by several methods gave a best value of 31.5 gauss per amp. on field ammeter. This value applies to the magnetic field at the chamber center. The field decreased radially from this point, dropping to 97 percent at an inch from the chamber edge. The working area was consequently kept within this region. The ammeter in series with the coils was found to read 1.8 percent lower than when used by Kurie, Richardson and Paxton. As the change may have taken place after the present work, the results here reported may be too low by this amount.

Experimental Results on the Upper Limit

2660 exposures were obtained with an analyzing field of about 500 gauss. This gave a radius of curvature of 16 cm to the highest energy track found. Consequently, it was possible to measure radii of curvature to the nearest half centimeter by fitting arcs of circles scratched on celluloid to reprojections of normal size. In the case of higher energy tracks template measurements were checked by means of a traveling microscope focused on the negative itself. Because a comparatively heavy background made tracks on them more difficult to follow under the microscope, the first 860 photographs were disregarded in the final results. This was done in spite of the close agreement between the distribution of template measured tracks from the discarded pictures and that remaining.

Each track was critically examined in the course of measurement, the following points being kept in view. (1) It was necessary that the portions between apparent nuclear deflections be sufficiently distinct to permit fitting to the nearest half centimeter radius on the template. (2) Any track was discarded if there was an apparent change in curvature over its course. (3) Because of field nonuniformities near the chamber edge, portions of tracks appearing within an inch of the edge were disregarded. To avoid poor judgment due to fatigue, no more than fifty tracks were measured at a sitting. It is believed that in maintaining the above criteria for measurable tracks, very little distortion was introduced into the natural β-particle distribution, until one reaches a region far enough below the upper limit that the tracks belonging there were mostly lost in the large number with lower energy.

Fig. 1 shows representative exposures, tracks that were actually measured being indicated by the arrows. All tracks of 7000 $H\rho$ or above are included in this figure. The distribution of tracks against $H\rho$ values is shown in Fig. 2. Ordinates corresponding to $H\rho$ values of less than about 5750 are certainly deficient because the interference of low energy tracks cuts out an appreciable number that should be included. The complete spectrum from P^{32} as obtained by Kurie, Richardson and Paxton is shown in Fig. 3. The upper limit distribution adjusted to fit the main curve as well as possible at the $H\rho$ values 5875, 6125 and 6375 is represented by the circles.

Error Considerations

As mentioned above, the curvature of each track above 7000 $H\rho$ was checked by measuring coordinates of the droplets constituting it. The number of points so obtained ran from 46 to 83 per track. These were plotted, allowing curvature measurements to be made independent of other tracks in the neighborhood, varying droplet sizes, background influences, etc. In a few cases small angle nuclear scattering (1° to 2.5°) showed up where it had been obscured in ordinary reprojection. Typical plots of tracks so measured are shown in Fig. 4. By comparing microscope and corresponding reprojection determinations of radii of curvature it was indicated that the ordinary measuring process contributes about ± 2.3 percent to the probable error of radius of curvature near the spectral upper limit.

The influence of small angle nuclear scattering of β-rays was estimated through an expression for the probable total angular deflection in terms of the differential elastic scattering cross section for an electron in hydrogen. This was obtained by geometrical addition of the contributions from

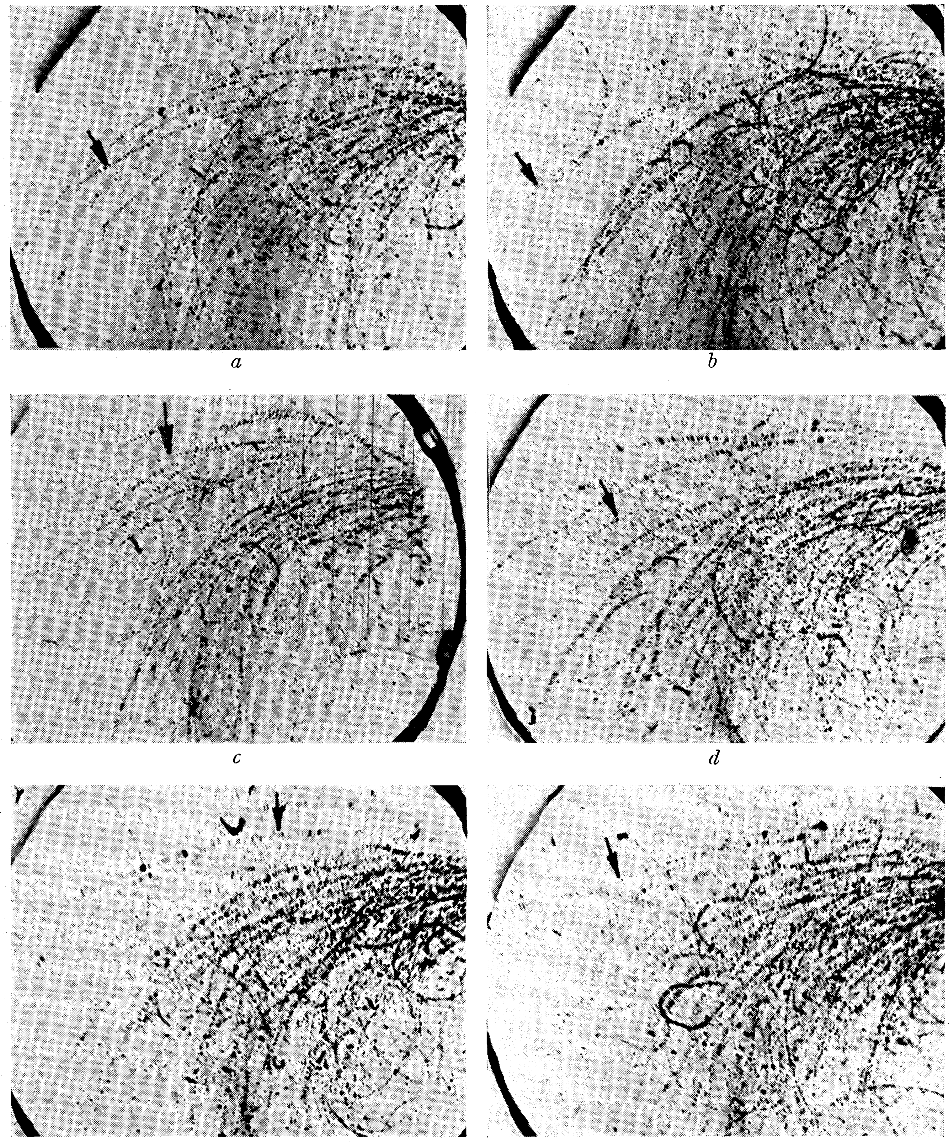

FIG. 1. Photographs including all measured P^{32} β-ray tracks of $H\rho$ above 7000. Track numbers and $H\rho$ values are: (*a*) No. 1912, 7380 $H\rho$; (*b*) No. 2162, 7260 $H\rho$; (*c*) No. 2247, 7210 $H\rho$; (*d*) No. 2762, 7150 $H\rho$; (*e*) No. 2695, 8200 $H\rho$; (*f*) No. 2697, 7480 $H\rho$.

all increments of scattered angle between 0° and the maximum individual deflection which one would just fail to detect by microscopic examination of a track (about 1°). The evaluation was made by a graphical integration involving values of differential cross section tabulated against scattering angle which Mott and Massey[6] have obtained from Born's first approximation, valid for the elastic scattering of high velocity electrons. The contribution to probable error in radius of curvature by the scattering influence of hydrogen and isopropyl alcohol vapor was finally estimated to be about ± 0.1 percent at the upper limit.

A third error factor comes about through unknown variations in the analyzing magnetic

[6] Mott and Massey, *The Theory of Atomic Collisions* (Oxford, 1933), p. 120.

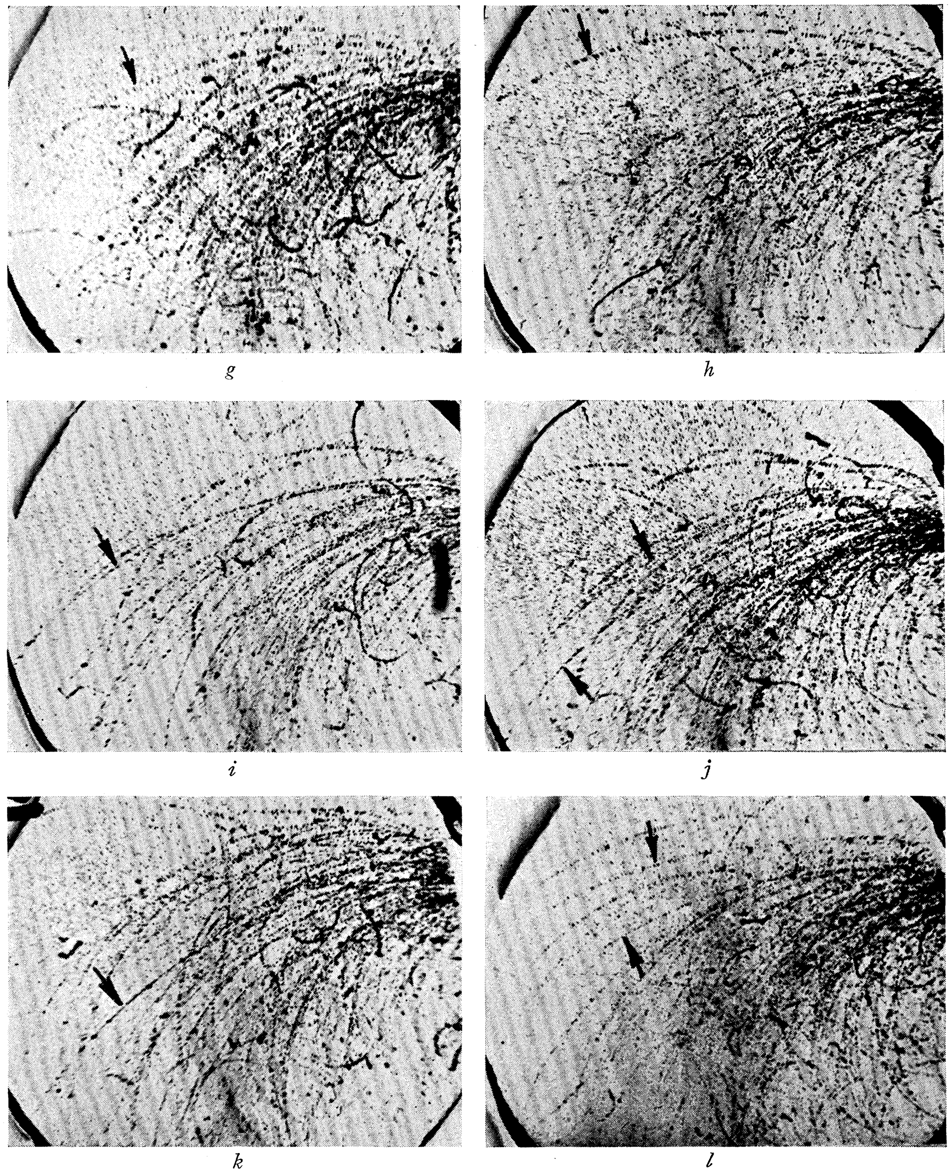

FIG. 1. Photographs including all measured P^{32} β-ray tracks of $H\rho$ above 7000. Track numbers and $H\rho$ values are: (*g*) No. 2853, 7240 $H\rho$; (*h*) No. 3028, 7240 $H\rho$; (*i*) No. 3178, 7140 $H\rho$; (*j*) No. 3146A, 7780 $H\rho$; No. 3146B, 7780 $H\rho$; (*k*) No. 3470, 7580 $H\rho$; (*l*) No. 3789A, 7300 $H\rho$; (No. 3789B, 6410 $H\rho$).

field. Power for the field was provided by a 50 kw motor generator set, each of the two generators delivering about 110 volts d.c. During operation, this generator set was used exclusively for the cloud chamber, the chief power drains being the magnetic field current supplied by one generator, and the flashing carbon arc for chamber illumination being fed by the other. As no fluctuations in Helmholtz coil current greater than one percent had been observed in much previous work, it was considered suitable to read the current about every 25 expansions, this being sufficient to follow changes in field due to heating of resistances. However, doubt was thrown on the constancy of field when it was noticed that two of the three tracks of highest energy

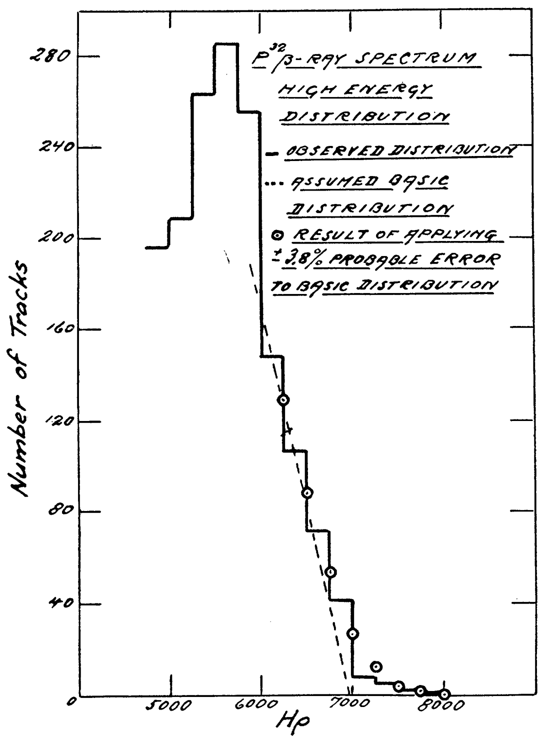

FIG. 2. Distribution of high energy tracks from P^{32}. The peak is introduced by geometrical discrimination against tracks of low energy.

appeared on the same photograph and that the third was but two exposures from another track of moderately high energy. Other high energy tracks were apparently distributed at random among expansions. As the result of this, 830 expansions were taken solely to investigate field fluctuations. It was found that all deviations from the normal heating drift could be connected with a change in sound of the carbon arc, the current sometimes decreasing as much as 5 or 6 percent in the expansion (sometimes two expansions) during which the arc would sputter just before extinguishing itself. This variation had not been noticed in regular operation because the adjustment of a sputtering arc had always held precedence over the reading of current.

It is difficult to estimate the probable error contribution to $H\rho$ by these field fluctuations; so it was rather arbitrarily taken as ± 3 percent. The asymmetric error tending to increase the apparent $H\rho$ may legitimately be replaced by a symmetrical error because the difference introduces a very slight change at the upper limit.

Further error is introduced because the magnetic field, due to its falling off near the chamber edge averages about 1 percent below its value at the center. This might give something near $\pm\frac{1}{2}$ percent to the probable error in $H\rho$ from the chance that some tracks lie along the edge of this region, while most cut across it not far from the center.

A summary of the main contributions to probable error in $H\rho$ (those which may be approximated by a gaussian distribution) at the upper limit of the spectrum is:

1. Measurement uncertainties	± 2.3 percent
2. Elastic scattering	± 0.1 percent
3. Field fluctuations	± 3.0 percent
4. Field nonuniformities	± 0.5 percent.

The total probable error from these influences is then about ± 3.8 percent.

An additional uncertainty comes from the fact that all tracks are treated as though lying in the median plane of the chamber, whereas they are actually distributed through a region one centimeter deep (45 cm from the camera lens). The error so introduced, which is ± 1 percent maximum, is not included in the above group because of its distinctly nongaussian nature. If it were put in as a $\pm\frac{1}{2}$ percent probable error component, its effect on the total probable error would be completely negligible.

Analysis of Upper Limit Data

The histogram representing the experimental distribution of tracks against $H\rho$ (Fig. 2) was transferred to the K-U plot shown in Fig. 5. The

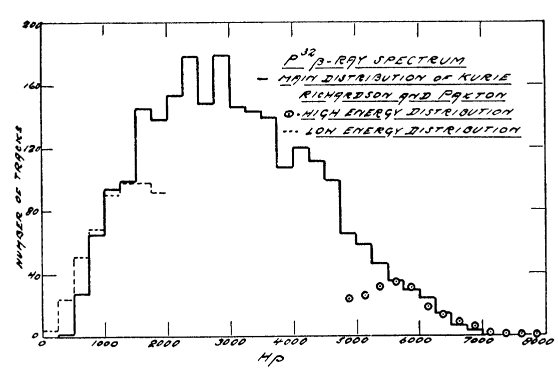

FIG. 3. High energy and low energy distributions of tracks from P^{32} fitted to the main distribution of Kurie, Richardson and Paxton.

main distribution of Kurie, Richardson and Paxton is shown by the circles in Fig. 6, the filled circles giving the upper limit curve adjusted to agree with the main distribution at 5875, 6125 and 6375 $H\rho$. These K-U plots were made as described by Kurie, Richardson and Paxton, and so involve approximations which are strictly applicable only to allowed transitions. When corrected to apply to a spin change of two as is involved in the disintegration $P^{32}\rightarrow S^{32}+e^-$, the functions plotted should drop below the straight line of Fig. 6 as the upper limit is approached, according to unpublished calculations by Lamb.

Before accepting the apparent confirmation of the uncorrected Konopinski-Uhlenbeck relation, it is well to follow the lead of Fowler, Delsasso and Lauritsen in estimating the influence of the probable error on the upper limit tail. By trial the line $y=-0.175x$ representing the actual spectrum cutoff (x being measured from the upper limit so defined) was found to give the distribution corresponding to the circles superposed on the upper limit histogram in Fig. 2, when each element is spread out by a probable error of 3.8 percent. Accordingly, it is hardly permissible to insist that these data support a tail of higher order contact than the straight line shown in Fig. 2. When represented as a K-U plot, this line gives the crosses on Fig. 5.

Assuming the linear cutoff of Fig. 2, the upper limit is 6950 $H\rho$ (corrected to the mean analyzing field which is 1 percent below that at the chamber center; also the stopping power of the mica window is taken into account). This is to be compared with a K-U limit of 8200 $H\rho$. This interpretation gives results essentially in agreement with recent findings of Lyman.[7] In working with his magnetic spectrograph of very high resolving power, he has found the K-U plot for P^{32} to drop sharply away from a straight line just before striking an upper limit at 7150 $H\rho$. This limit, however, includes a slight tail beyond a nearly linear drop on the distribution in $H\rho$ curve.

This difference is of the order indicated by Lamb's correction terms for a doubly forbidden disintegration. However, if this explanation holds, the K-U limits should apply to allowed

[7] Lyman, Phys. Rev. **51**, 1 (1937).

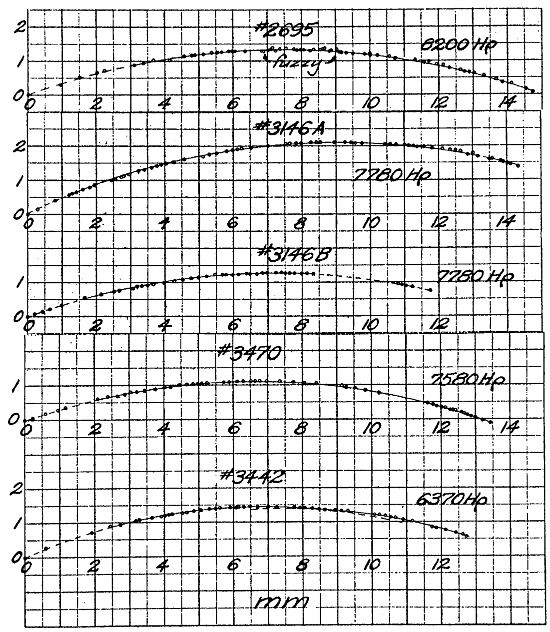

FIG. 4. Typical plots of droplets constituting higher energy tracks. Coordinates were determined by comparator measurements on the photographic film. These tracks are listed in Fig. 1; they may be identified by the noted track numbers and $H\rho$ values. Uncertain parts of the plots are indicated by dotted portions of the approximately fitted circles. Some elastic deflections are indicated by overlapping arcs of equal radii.

transitions such as the disintegration of N^{13} and F^{17}. These are involved in the following sets of reactions which Dr. E. McMillan has kindly detailed.

$$C^{12}+H^2\rightarrow C^{13}+H^1+\begin{cases}2.66\pm 0.06\text{ Mev}^8\\ \text{or } 2.71\pm 0.04\text{ Mev}\end{cases}$$

the second value which includes a correction by Bethe (unpublished) will be used in the following.

Further, $C^{12}+H^2\rightarrow N^{13}+n-0.37\pm 0.05$ Mev[9]

and $N^{13}\rightarrow C^{13}+e^+ +(e^-)+E_1$.

E_1 is interpreted as the upper limit of the positron distribution, as no γ-radiation appears in this decay. These relations give $E_1=H^1-n+(2.71\pm 0.04)+(0.37\pm 0.05)-(1.03)$. A weighted mean of the results on the photo-disintegration of the deuteron by Chadwick and

[8] Cockcroft and Lewis, Proc. Roy. Soc. **A154**, 261 (1936).
[9] Bonner and Brubaker, Phys. Rev. **50**, 308 (1936).

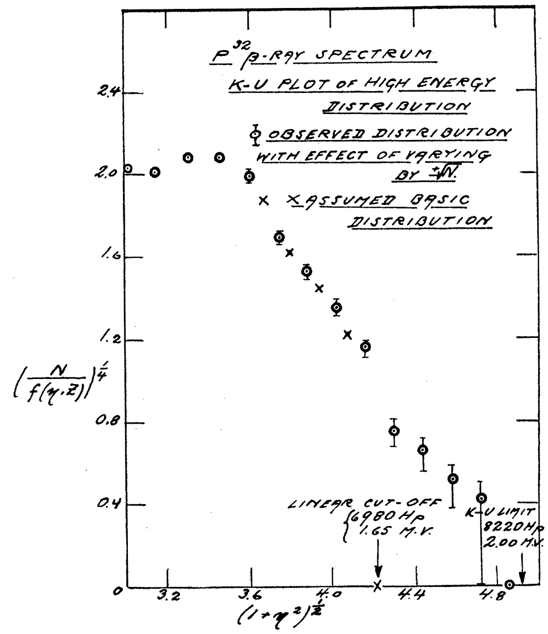

FIG. 5. Konopinski-Uhlenbeck plot of the high energy P^{32} distribution of Fig. 2. The crosses correspond to points on the dotted line of Fig. 2, assumed to be the normal distribution undistorted by probable error.

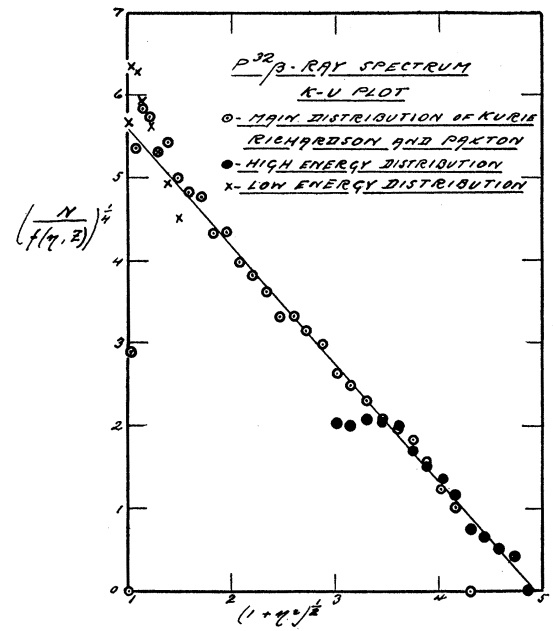

FIG. 6. Konopinski-Uhlenbeck plots of the high energy, low energy and main distributions of P^{32} fitted together in Fig. 3.

Goldhaber[10] and by Feather[11] as recalculated by Bethe and Bacher[12] gives

$$H^2 \rightarrow H^1 + n - 2.20 \pm 0.06 \text{ Mev.}$$

Also $$2H^1 - H^2 = 1.42 \pm 0.03 \text{ Mev,}$$

from the almost identical mass-spectrographic measurements of Bainbridge and Jordan[13] and Aston.[14] These combine to give $n - H^1 = 0.78 \pm 0.07$ Mev which leads to $E_1 = 1.27 \pm 0.10$ Mev as the upper limit of the N^{13} positron spectrum.

For F^{17}

$$O^{16} + H^2 \rightarrow O^{17} + H^1 + 1.91 \pm 0.03 \text{ Mev}^8$$
$$O^{16} + H^2 \rightarrow F^{17} + n - 1.8 \pm 0.2 \text{ Mev,}^{15}$$

the excess energy being obtained from the reaction threshold rather than from the neutron energy as in the case of carbon. These, with $F^{17} \rightarrow O^{17} + e^+ + (e^-) + E_2$, give as the upper limit of the positron spectrum from F^{17}:

$$E_2 = 1.90 \pm 0.22 \text{ Mev.}$$

[10] Chadwick and Goldhaber, Proc. Roy. Soc. **A151**, 479 (1935).
[11] Feather, Nature **136**, 467 (1935).
[12] Bethe and Bacher, Rev. Mod. Phys. **8**, 123 (1936).
[13] Bainbridge and Jordan, Phys. Rev. **49**, 883 (1936).
[14] Aston, Nature **137**, 357 (1936).
[15] Newson, Phys. Rev. **48**, 790 (1935).

Expressed in terms of $H\rho$, these limits are 5700 ± 310 $H\rho$ for N^{13} and 7900 ± 750 $H\rho$ for F^{17}. The K-U limits[16] of 6000 $H\rho$ and 9100 $H\rho$ differ from these values by $5\frac{1}{2}$ percent and 15 percent, respectively. These might be compared with the 18 percent difference between the K-U limit and the straight line cutoff for P^{32}. Upper limits[16] of 5600 $H\rho$ for N^{13} and 8150 $H\rho$ for F^{17} which were obtained by inspection from the positron distributions of Kurie, Richardson and Paxton are on the other hand consistent with the disintegration values. Consequently, it appears that these experimental data are not completely consistent with the Fermi-Konopinski-Uhlenbeck theory.

The Lower Limit of the Beta-Spectrum of P^{32}

H. O. W. Richardson[17] in a cloud chamber investigation of the low energy part of the RaE β-spectrum found that there appeared frequency peaks near 500 $H\rho$ and 750 $H\rho$. It was believed worth while to look at the lower limit of the P^{32} β-ray distribution in more detail than had been done previously, to see whether any such rise at

[16] Corrected for magnetic field recalibration.
[17] Richardson, Proc. Roy. Soc. **147**, 442 (1934).

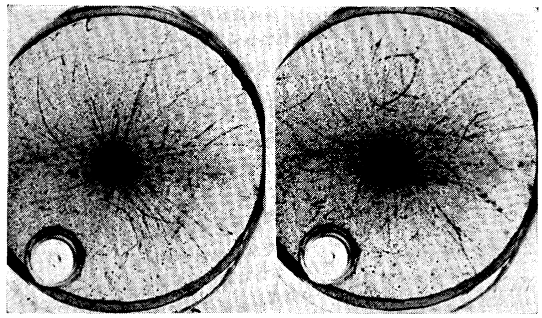

FIG. 7. Exposures representative of those from which the low energy distribution of P^{32} was obtained.

the low energy end of the spectrum might be present in this case.

To do this, a thin collodion film containing some active phosphorus which had stood for $2\frac{1}{2}$ weeks was suspended at the center of the cloud chamber described above. 225 expansions were photographed with the analyzing field reduced to 168 gauss. Conditions were otherwise the same as for the upper limit work. Representative exposures are shown in Fig. 7.

Because β-ray scattering becomes increasingly serious as the energy decreases, all tracks of sufficient length were measured as well as possible in spite of bad curvature changes, in order to prevent distribution distortion from selection criteria. Measurements were made by reprojection and template fitting. A length of track equal to about two-thirds of its diameter was roughly considered as just measurable, until limited further by the chamber radius. This, of course, introduced a variable effective solid angle, increasing with decreasing energy.

The distribution of tracks obtained directly is given by the full line in Fig. 8. The dotted line involves an approximate correction for the variation in solid angle just mentioned. This distribution when adjusted to agree with the main distribution at 875, 1125 and 1375 $H\rho$ is given by the dotted line in Fig. 3. From its contribution to

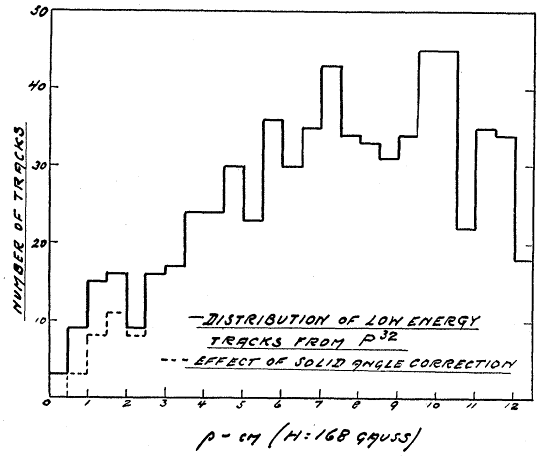

FIG. 8. Distribution of low energy tracks from P^{32}. The dropping off for larger radii is introduced by geometrical discrimination against tracks in that range.

the K-U plot as shown by the crosses on Fig. 6, the distribution appears to go into the origin not quite as rapidly as predicted by the K-U relation. But the difference is within experimental error.

To look into the possibility of there being many tracks of $H\rho$ less than 100, on the first 50 photographs the number of short uncertain tracks originating within one centimeter of the source was compared with the number apparently arising in the gas in the annular region between $1\frac{1}{2}$ and $2\frac{1}{2}$ cm from the source. These numbers were found to be nearly identical, 54 in the first case and 52 in the other, although more secondaries might be expected to come from the region containing the solid material. So there is no indication of a sudden rise in distribution in the neighborhood of the origin such as that found by Richardson in the β-spectrum of Ra E.

I wish to thank Professor E. O. Lawrence, Dr. F. N. D. Kurie and Mr. W. E. Lamb for many discussions concerning this work. This investigation has been aided by grants from the Research Corporation, the Chemical Foundation and the Josiah Macy, Jr. Foundation.

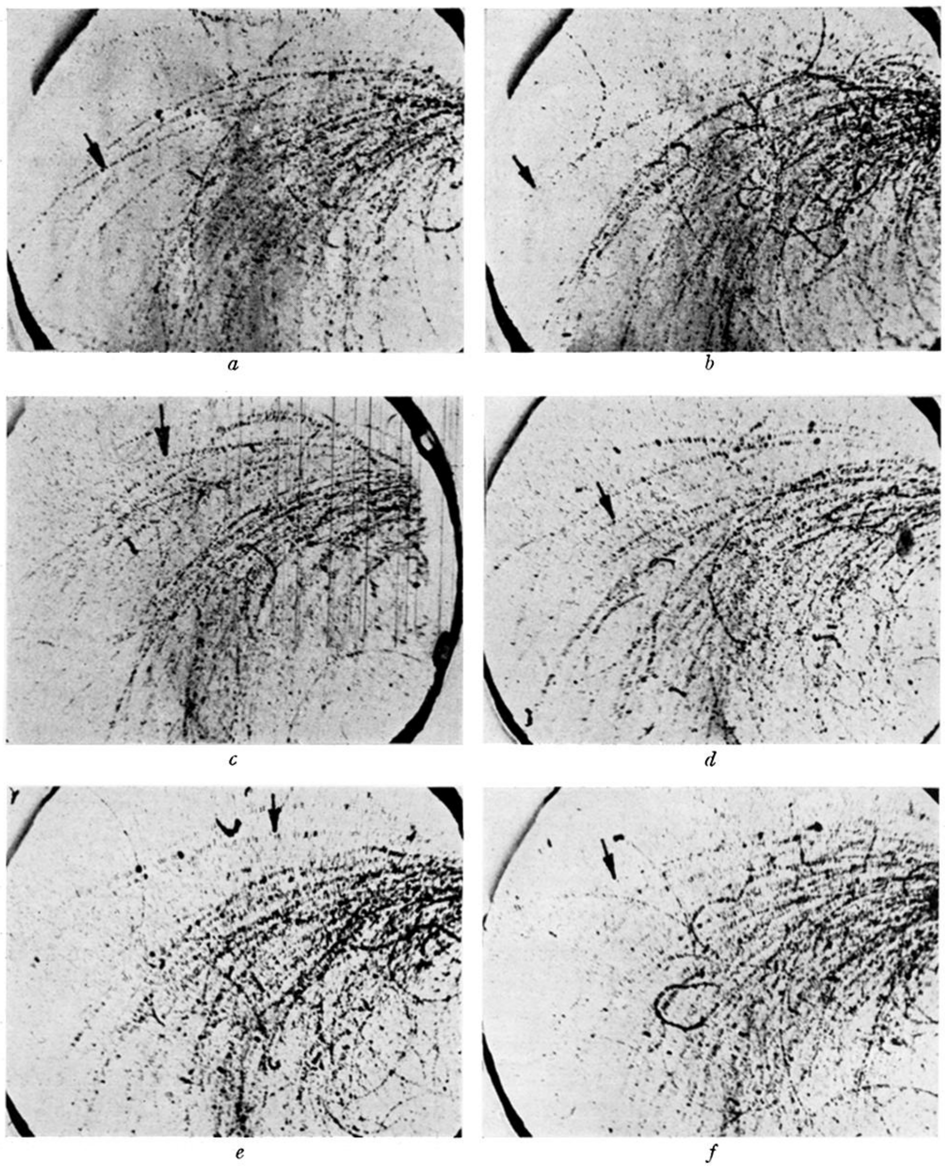

FIG. 1. Photographs including all measured P^{32} β-ray tracks of $H\rho$ above 7000. Track numbers and $H\rho$ values are: (*a*) No. 1912, 7380 $H\rho$; (*b*) No. 2162, 7260 $H\rho$; (*c*) No. 2247, 7210 $H\rho$; (*d*) No. 2762, 7150 $H\rho$; (*e*) No. 2695, 8200 $H\rho$; (*f*) No. 2697, 7480 $H\rho$.

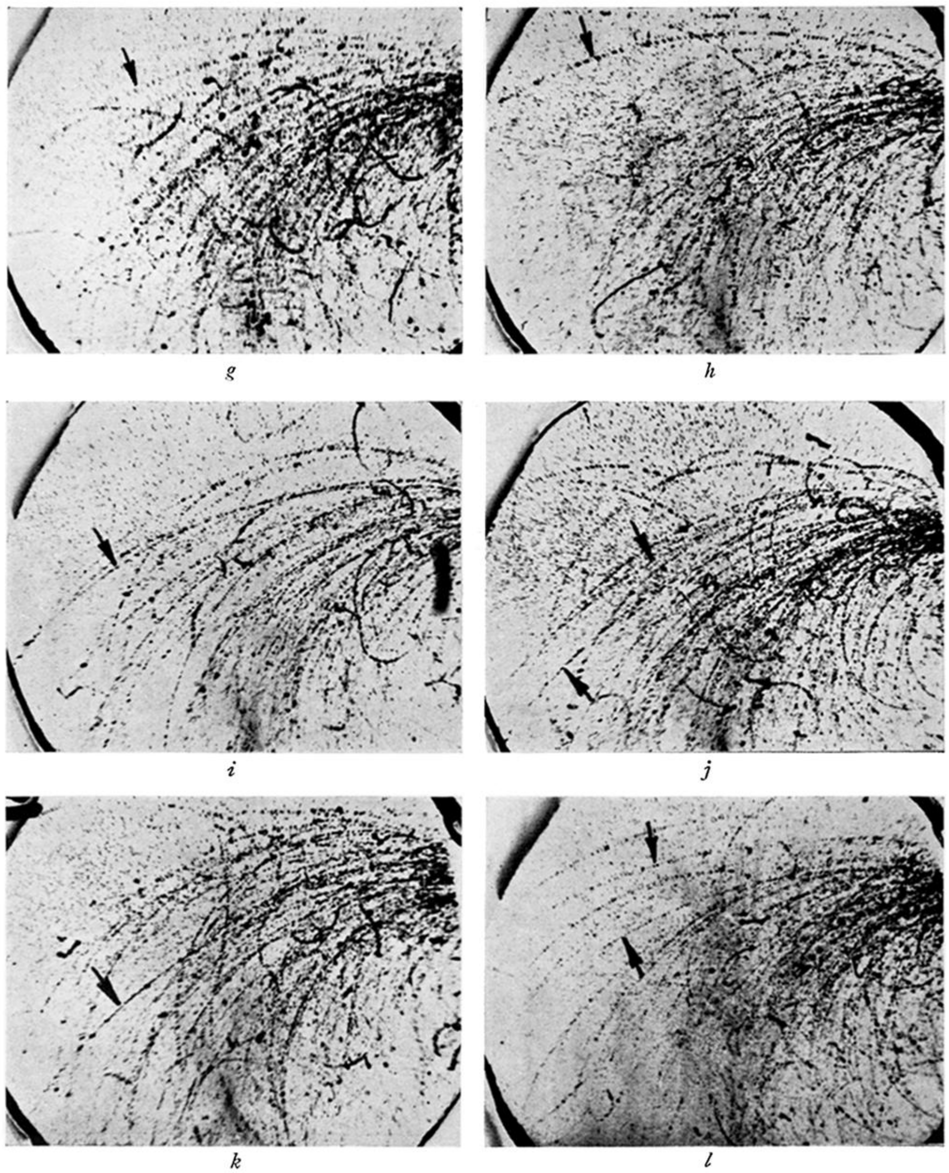

FIG. 1. Photographs including all measured P^{32} β-ray tracks of $H\rho$ above 7000. Track numbers and $H\rho$ values are: (*g*) No. 2853, 7240 $H\rho$; (*h*) No. 3028, 7240 $H\rho$; (*i*) No. 3178, 7140 $H\rho$; (*j*) No. 3146A, 7780 $H\rho$; No. 3146B, 7780 $H\rho$; (*k*) No. 3470, 7580 $H\rho$; (*l*) No. 3789A, 7300 $H\rho$; (No. 3789B, 6410 $H\rho$).

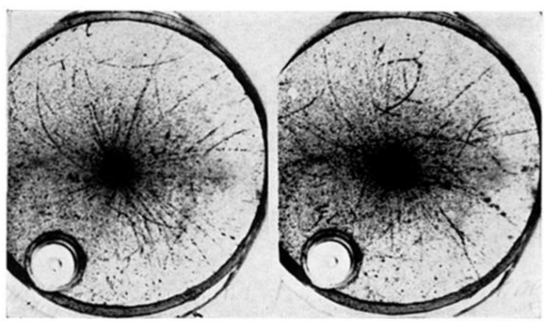

FIG. 7. Exposures representative of those from which the low energy distribution of P^{32} was obtained.