The Beta-Ray Spectra of Phosphorus, Sodium and Cobalt

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The beta-ray spectra of phosphorus, sodium and cobalt have been obtained by means of a magnetic spectrometer of high resolving power. In the cases of phosphorus and sodium, where the most accurate work was possible, the shapes of the spectra differ from the results previously reported by other investigators in that there are fewer low energy particles. The reduction in this number of particles has been traced to the relative absence of scattering in the radioactive source and its mounting. The general shape of the spectra is found to agree more satisfactorily with that predicted from the original theory of Fermi than that given by the modification of this theory proposed by Konopinski and Uhlenbeck. The maximum energy of the continuous electrons emitted from phosphorus and sodium are found to be 1.72 and 1.4 Mev, respectively. The value for sodium electrons is considerably lower than has been previously observed. The shape of the cobalt positron spectrum suggests two superimposed continuous distributions. The observed upper energy limit of 1.50 Mev agrees fairly well with the previously reported value. The excellent resolution of the spectrometer is illustrated by the separation of the K and L shell conversion electrons arising from a gamma-ray in indium. The observed resolution is only slightly less than the calculated value due to the absorption of electrons in the source.

ONE of the most accurate methods available for the measurement of the beta-ray spectra of radioactive materials is by means of a magnetic spectrometer. A complete description of such a spectrometer having a high resolution is now being published. The instrument has been so designed that scattering from internal surfaces has been minimized. Particular emphasis has been placed upon the necessary corrections which must be made to the observed results due to various instrumental difficulties. Those corrections pertaining to the resolution of the instrument, the efficiency of the Geiger-Müller counter and the absorption in the window of the counter, have been computed. The resolution of the instrument has been set at about 1.6 percent, which represents the observed fractional momentum spread at $\frac{1}{2}$ maximum intensity of a monochromatic beta-ray spectrum. The resolving power can be easily increased, but the intensity of the available samples were insufficient to warrant higher resolution.

PHOSPHORUS

Newson[1] and others have shown that a very strong radioactivity of half-life 14.5 days can be induced by bombarding phosphorus with deuterons. This activity has been ascribed to the negative electrons emitted in the disintegration of P^{32} into S^{32}. The energy spectrum of these electrons was first measured by J. Ambrosen.[2] Using a Wilson cloud chamber, he obtained a distribution of electrons with an observed upper energy limit of about 2 Mev. Alichanow *et al.*,[3] using tablets of activated ammonium phosphomolybdate in a magnetic spectrometer of low resolving power, find the upper limit of the electron energy to be 1.95 Mev. Kurie, Richardson and Paxton[4] have observed this upper limit to be approximately 1.8 Mev. This work was done with a six-inch cloud chamber, and the results were obtained from a distribution involving about 1500 tracks. Paxton[5] has investigated only the upper regions of the spectrum with the same cloud chamber, and reports that all observed tracks above 1.64 Mev can be accounted for by the errors in the method. E. M. Lyman[6] was the first investigator to determine accurately the spectrum of phosphorus by means of a magnetic spectrometer. The upper limit of the spectrum which he has obtained is 1.7 ± 0.04 Mev. The relatively small probable error in the final value is the result of the high

[1] H. W. Newson, Phys. Rev. **51**, 624 (1937).

[2] J. Ambrosen, Zeits. f. Physik **91**, 43 (1934).
[3] Alichanow *et al*, Nature **137**, 314 (1936).
[4] Kurie, Richardson and Paxton, Phys. Rev. **49**, 368 (1936).
[5] H. C. Paxton, Phys. Rev. **51**, 170 (1937).
[6] E. M. Lyman, Phys. Rev. **51**, 1 (1937).

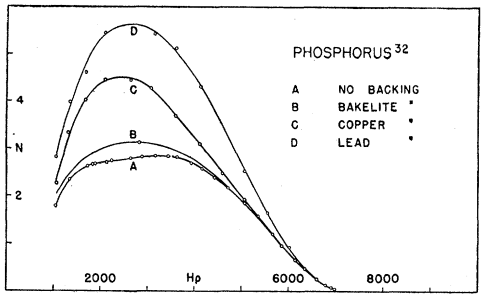

FIG. 1. The effect of various back scattering agents upon the spectrum of phosphorus.

resolving power of the instrument and the small statistical scatter in the observed points. The target used in his investigation was composed of a thin layer of red phosphorus backed by a thick copper plate. The whole assembly had been directly bombarded with deuterons in the cyclotron. In order to allow the shorter activities induced in the copper etc. from affecting the final distribution, the target was allowed to "age" for several days.

Because the distribution might be affected by the scattering of electrons from the copper backing of the target used by Lyman, it was considered worth while to investigate the effects upon the spectrum of various backing materials. Accordingly a sample of iron phosphide was prepared in essentially the same fashion as suggested by Wilson and Kamen.[7] This target was bombarded with deuterons from the University of Michigan cyclotron for several days. The average deuteron current during this period was approximately 20 microamperes. After bombardment the iron phosphide and its copper backing were placed in nitric acid. The cleared iron phosphide was then fused with sodium peroxide in a small nickel crucible. Cobalt and nickel were added as carriers to bring down those elements, and the solution was then filtered. The phosphorus was precipitated from the filtrate as lead phosphate. This was then filtered on a flat paper so that the residue settled evenly. Strips cut from this final filter paper containing the lead phosphate were used as the source in the magnetic spectrometer. The average weight of the precipitate was approximately 5 mg per cm^2, and the only backing to the source consisted of the filter paper itself.

This source yielded the spectrum shown in curve *A*, Fig. 1. This spectrum was obtained by observing the counting rate of the Geiger-Müller counter for various magnetic field settings. The observed counting rate was corrected for losses due to the counting rate, background, counter efficiency and window absorption. The finally corrected counting rate for each point was then divided by the value of the magnetic field in order to express the relative numbers of particles emitted in equal momentum intervals. The magnetic field was measured accurately at each point and is considered to be reliable to one part in 1000 relative, or one part in 500 absolute. Each measured point is the result of an observation of sufficient duration to reduce the statistical variations in counting rate to about one percent. The region of very low energies (momenta below 1000 $H\rho$) has not been investigated because of the large error due to the absorption in the $1\frac{1}{2}$ micron pyroxylin window of the Geiger-Müller counter.

In order to investigate the effects of back scattering of electrons near the source, sheets of various materials were placed directly behind the source. Curves *B*, *C* and *D* (Fig. 1) were thus obtained when $\frac{1}{16}''$ of Bakelite, 0.02″ of copper, and 0.02″ of lead, respectively, were used as back scattering agents. The spectrum obtained with the copper backing appears quite similar to that obtained previously under similar conditions.[6] The relatively small scattering from the Bakelite sheet shows that the expected scattering from the filter paper source mounting is negligible. It is interesting that the increase in counting rate due to scattering should be most pronounced in an intermediate region of momentum. This is probably due to absorption effects of low energy particles within the scattering material. The general effect of back scattering seems to be a shift of the maximum on the curve towards lower energies. As one would expect, the scattering from materials of high atomic number is much more noticeable in the high energy regions. The back scattering from the lead can be detected almost to the upper limit of the spectrum; whereas that from copper is negligible above a momentum of 5000 $H\rho$.

[7] R. R. Wilson and M. D. Kamen, Phys. Rev. **54**, 1031 (1938).

The general shape of the observed spectrum of phosphorus leads one to suspect two superimposed beta-ray spectra. There appears to be a low energy group with an apparent upper momentum limit of 3000 $H\rho$. That this group of electrons is probably not due to phosphorus of the 14.5-day period is borne out by the decay curves taken on this sample. Electrons of momentum 3250 $H\rho$ decayed with a pure half-life of 14.5 days with no indication of other activity. At a momentum of 1680 $H\rho$ subtractions were made from this spectrum determined from the correct spectrum subsequently obtained (Fig. 2). The decay of the remainder showed a half-life of 13.0 days which suggests that this part of the activity was due to some other radioactive material carried along with the 14.5-day phosphorus. A sufficiently long time (2 months) was used in these observations to make the discrimination between these rather similar half-lives possible

In order to obtain a pure sample of smaller scattering power, a sample of red phosphorus was bombarded in the cyclotron for 8 hours at a current of 0.5 microampere. A small part of the activated sample was brushed on thin paper and covered with an exceedingly thin layer of collodion. The resulting source of pure phosphorus weighed approximately 3 mg per cm^2. The results for this source are shown in Fig. 2. It can be seen that the low energy group of electrons previously mentioned is not present. No chemistry was performed on this sample.

The region of the upper limit of the phosphorus spectrum is shown in Fig. 3. The experimental points can be seen to fluctuate somewhat about curve A. Curve B was constructed so that when the calculated transmission factor of the spectrometer was passed over it, curve A was obtained. Therefore, curve B should represent

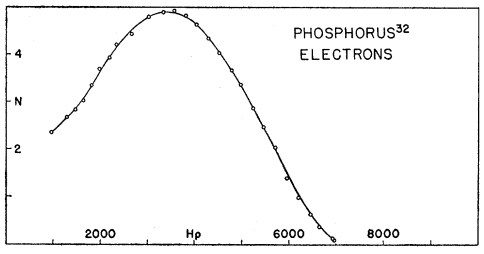

FIG. 2. Momentum spectrum of phosphorus.

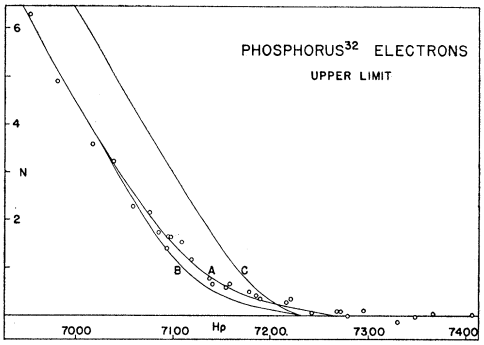

FIG. 3. Spectrum of phosphorus near the upper limit.

the true spectrum of phosphorus near its upper limit, except for the absorption in the source. An accurate correction for this absorption is difficult to make. If one assumes a constant energy loss per unit thickness of material, given by known energy loss measurements, he can reconstruct the original spectrum from the observed data. When this is done approximately, curve C (Fig. 3) is obtained. It can be seen that the final tailing of the spectrum is very small and may be due to the discrepancies caused by inaccurate corrections. However, the final upper limit of the spectrum so obtained is $H\rho=7210 \pm 30$ gauss cm or $E=1.72$ Mev. This result is in very satisfactory agreement with that found by Lyman.

In order to investigate the effect of intensity upon the observed upper momentum limit, a source having approximately 1/20 the intensity was inserted in the spectrometer. The number maximum with this source was approximately 50 counts per minute, which is about 10 times the background counting rate of the counter. The observed upper limit with this source was 7170 ± 60 $H\rho$, which is only slightly lower than the value obtained with the stronger source. This indicates that an accurate evaluation of the end point of any spectrum can be made with a relatively weak source.

SODIUM

Sodium, bombarded with deuterons, exhibits a very strong activity of 14.8 hours half-life, due to Na^{24}. The gamma-rays associated with this activity have been studied in a cloud chamber by Richardson and Kurie.[8] Their

[8] J. R. Richardson and F. N. D. Kurie, Phys. Rev. **50**, 999 (1936).

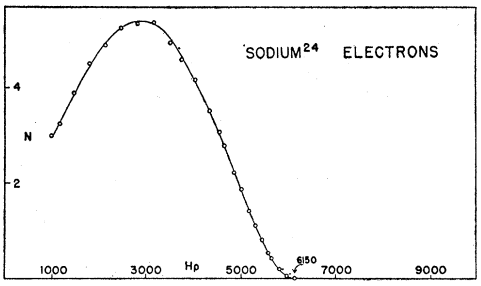

FIG. 4. Momentum spectrum of sodium.

findings show the existence of three very strong gamma-rays of energies 0.95, 1.93 and 3.08 Mev, respectively. The electron spectrum also has been investigated by means of the cloud chamber by Kurie, Richardson and Paxton.[9] The result for the upper limit of the spectrum was 1.7 Mev, which may have been influenced somewhat by the presence of the strong 2-Mev gamma-ray.

A sample of sodium fluoride was bombarded in the University of Michigan cyclotron for 8 hours at an average deuteron current of 0.5 microampere. A small part of the activated target was brushed onto a thin piece of paper, and the particles affixed with a thin covering of collodion. The weights of sample and backing were 3.5 and 7.4 mg per cm^2, respectively. The spectrum of sodium obtained from this sample is shown in Fig. 4. The points are statistically accurate to approximately one percent. All regions of this spectrum were observed to decay with a half-life of 14.8 hours. The end point of this spectrum is 6150 $H\rho$ by inspection, or 1.4 Mev. This is in disagreement with the result previously given,[9] probably due to the elimination of the effects of Compton electrons ejected by gamma-rays.

COBALT

Iron bombarded with deuterons gives rise to a strong cobalt positron activity of half-life 18 hours.[10, 11] This has been tentatively ascribed to Co^{55}, and were this the case it would be necessary to assume either a double positron emission, or a single positron emission with a corresponding K-electron capture. The possibility of a double positron emission can be checked by an investigation of the energy spectrum of cobalt. Accordingly a sample of electrolytically pure iron was bombarded by deuterons from the cyclotron for 10 hours at an average current of 0.8 microampere. This sample was allowed to age for nearly 24 hours to remove the shorter activities which were originally present. The iron, which had been rolled to a thickness of 0.0007", was removed from the target holder and mounted in the spectrometer. The resulting spectrum of cobalt positrons is shown in Fig. 5, and was observed to decay with the expected 18-hour half-life. It can be seen that the shape of the spectrum suggests more than one continuous distribution, but no accurate separation can be made from these data. The end-point of the observed spectrum is approximately 6500 $H\rho$ or 1.50 Mev. This agrees fairly well with the value of 1.6 Mev reported by Curtis, Darling and Cork.[11] Because the intensity of this source was relatively low (number maximum of 50 per minute), the statistical accuracy of the points is noticeably poorer than that connected with the previous spectra.

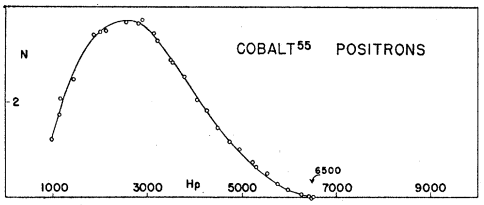

FIG. 5. Momentum spectrum of cobalt.

Kurie, Richardson and Paxton have shown[4] that the validity of the Fermi theory regarding beta-ray emission can be tested by plotting $(N/f)^{\frac{1}{2}}$ against the energy of the particles, where N is the observed number of particles emitted in a given momentum interval, and f is a function, which for light elements can be well approximated by: $f=\eta^2(2\pi y/1-e^{-2\pi y})$ where $y=Z(1+\eta^2)^{\frac{1}{2}}/137\eta$ and η is the momentum in units of mc. This plot should be a straight line according to the Fermi theory, with an intercept on the energy axis equal to the upper limit of the spectrum. Similarly a plot of $(N/f)^{\frac{1}{4}}$ against energy should be a straight line with a similar

[9] Kurie, Richardson and Paxton, Phys. Rev. **48**, 167 (1935).
[10] Livingood, Fairbrother and Seaborg, Phys. Rev. **51**, 135 (1937).
[11] Darling, Curtis and Cork, Phys. Rev. **51**, 1010 (1937).

intercept if the modification of the Fermi theory by Konopinski and Uhlenbeck is validated by experiment.

The Fermi and K-U plots for phosphorus are shown in Fig. 6. The experimental points deviate from the Fermi theory at low energies. However, the upper half of the energy spectrum agrees well with the predictions of this theory. The K-U plot deviates markedly from a straight line in the upper energy regions. Since this part

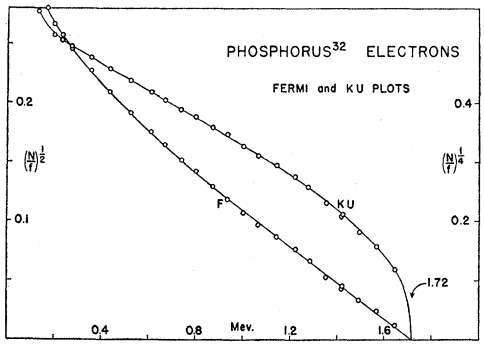

FIG. 6. Fermi and K-U plots for electrons from phosphorus.

of the spectrum is most accurately known, it must be inferred that the K-U theory is not satisfactory. The extrapolated upper limit obtained from the K-U plot is 2.45 Mev, which is 43 percent too high. Lyman has reported a similar discrepancy in his results, but the extrapolated limit was only 23 percent too high. This was no doubt due to the different shape of electron distribution caused by the copper backing on his source. To check this possibility a K-U plot for the spectrum obtained with the copper backing (curve *C*, Fig. 1) was made. The extrapolated upper limit was found to be 2.18 Mev or 26 percent too high.

The Fermi and K-U plots for sodium are very similar in appearance to those of phosphorus. These are shown in Fig. 7. Again the Fermi theory is well validated by the upper half of the spectrum, but more than the predicted number of particles are found at the low energy end. The extrapolated K-U upper limit is 2.0 Mev which also is 43 percent higher than the observed upper limit of 1.4 Mev. Fermi and K-U plots for the spectrum of cobalt were not made because of the probable distortion due to the moderately thick source.

The experimental excess of particles in the low energy regions of the Fermi plot can be due to several causes. One possibility is the inclusion of a finite mass for the neutrino. However it has not been found possible to straighten out the plot in the low energy regions unless one assumes a neutrino mass several times that of the electron. Moreover, if this is done the experimental points deviate from a straight line in the region of the upper end-point. Furthermore, Lyman[12] has shown the mass of the neutrino to be 0.0 ± 0.2 the mass of the electron. Bethe, Hoyle and Peierls[13] have attempted to explain similar discrepancies observed in the Fermi plots for the spectra of B^{12}, F^{20}, N^{13}, O^{15} and F^{17} by successive subtractions of straight lines. They have found that only two or three straight lines are necessary to bring about agreement with the data. However, this procedure has been tried for the spectra of phosphorus and sodium, and it has not been found possible to satisfy the experimental data with as few as three straight lines. Scattering in the source itself might increase the number of particles observed at the lower energies. However, the sources which have been used are very thin and are composed of materials of low atomic number. If the magnitude of the scattering from the backing of the source is an indication of the amount of scattering taking place in the source itself, it would seem very unlikely that enough scattering could take place to cause the observed discrepancy. However, this is a possibility that should be remembered, and effort should be made to further reduce the scattering

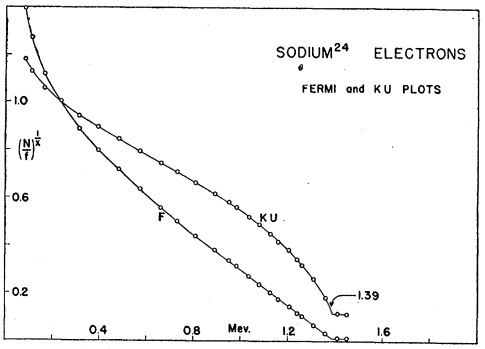

FIG. 7. Fermi and K-U plots for electrons from sodium.

[12] E. M. Lyman, Phys. Rev. **55**, 234 (1939).
[13] Bethe, Hoyle and Peierls, Nature **143**, 200 (1939).

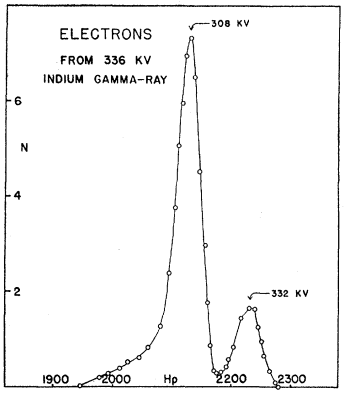

FIG. 8. Conversion electrons in indium.

within the source. It is very difficult to make thinner sources which are sufficiently intense to obtain an accurate spectrum.

AN INTERNALLY CONVERTED INDIUM GAMMA-RAY

Goldhaber, Hill and Szilard[14] have observed an indium activity which can be produced by the bombardment of cadmium with neutrons. This activity can also be induced very strongly by the bombardment of cadmium with deuterons. It probably consists entirely of an internally converted gamma-ray. The conversion electrons from this gamma-ray have been observed in the magnetic spectrometer. The highly converted K electrons are emitted with the complete energy of the original gamma-ray minus the K shell atomic binding energy. The less intensely converted L electrons are emitted with a higher energy due to their smaller atomic binding energy. Thus the energy difference between the K and L shell conversion electrons should be just the difference between the K and L shell binding energies within the atom, which can be found by x-ray studies. It should also be possible to observe the conversion of the M, N, etc., electrons. These, however, are not only weak in intensity, but are very close in energy to the L conversion electrons. With a spectrometer resolving power of 1.6 percent, it is not possible to separate these groups.

Cadmium was bombarded with deuterons from the cyclotron for 16 hours at a current of 2.2 microamperes. The target was then dissolved in concentrated nitric acid, then subsequently diluted and made slightly ammoniacal. About 1 mg of indium was added as carrier for the indium precipitate. This precipitate was laid on a small strip of filter paper which served as the source mounting. The weight of the source was approximately 1 mg per cm^2. The spectrum of electrons in the region of the gamma-ray momentum is shown in Fig. 8. It can be seen that there are two distinct groups of electrons whose energies are 308 and 332 kv, respectively. These undoubtedly correspond to the K and L shell conversion electrons of indium. Because the external gamma-ray intensity of this sample is low compared to the emitted electron intensity, the observed electrons are conversion electrons with a high conversion coefficient rather than photoelectrons. The difference in energy of these two electron groups is experimentally 24 kv, and the result predicted from x-ray data is 23.6 kv. The agreement is as good as can be expected. This places the energy of the converted gamma-ray at 335.8 kv. Decay curves have been taken on this activity and show it to have a half-life of 4.5 hours. There is no indication of a continuous beta-ray spectrum associated with this gamma-ray. The theoretical width of a monochromatic line spectrum is slightly less than that which is observed. However the increase in width can be easily attributed to the energy loss of electrons due to absorption in the source.

The author is indebted to Professor J. M. Cork and other members of the department for their interest and encouragement. This work has been made possible through a grant from the Horace H. Rackham trust fund.

[14] Goldhaber, Hill and Szilard, Phys. Rev. **55**, 47 (1939).