Positrons from the Decay of P^{32} and Y^{90}†

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A magnetic focusing arrangement is combined with coincidence counting of the annihilation radiation to permit detection of very low positron intensities in the presence of other radiations. Sources of P^{32} yielded $(7.5\pm2)\times10^{-10}$ positrons per beta decay. An experiment with a gold-covered source showed that secondary effects in the source material may contribute an important fraction of these positrons. One may conclude that the number of positrons per beta decay of P^{32} does not exceed by more than a factor two the value 5.5×10^{-10} expected theoretically from electromagnetic effects and is probably close to the theoretical value.

Sources of Y^{90} emit $(3.6\pm0.9)\times10^{-5}$ positrons per beta decay, due primarily to the 1.75-Mev electric monopole transition in Zr^{90}.

A. INTRODUCTION

THE growing refinement of the experimental evidence and theoretical analysis concerning beta decay processes has recently turned attention to the various electromagnetic phenomena modifying beta decay.[1] Besides the obvious effect of the screened nuclear Coulomb field in determining the electron wave functions, three such phenomena have been considered, appearing as higher order terms in the usual perturbation treatment of the theory. They result in the transfer of part of the decay energy to a particle other than the electron-neutrino pair: (1) Internal bremsstrahlung resulting in the emission of one or more photons. (2) Ionization or excitation of the electron cloud (in addition to the ionization due to the increase in nuclear charge in negative beta decay and the K or L shell excitation in K- and L-electron capture). (3) Internal pair creation resulting in the emission of a positive and a negative electron besides the primary beta ray and neutrino. The last-named process is, of course, possible only when the available decay energy E_0 exceeds $3m_0c^2$.

Considerable experimental and theoretical work has been done on internal bremsstrahlung and atomic excitation, and our understanding of these processes seems, in the main, adequate. Some unresolved difficulties remain, apparently due to the difficulty of treating the theory of transitions involving a rearrangement of the entire electron cloud, rather than to any aspects of the basic phenomena. On the other hand, the experimental evidence concerning pair emission in beta decay has been inadequate and contradictory, both between different experimenters and between experiment and theory. This is not surprising if we note that in a typical case we expect only one pair to be formed for 10^9 beta decays, whereas there is about one detectable photon for 10^2 decays and one K-shell excitation for 10^4 decays.

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[1] Some of these phenomena were discussed at the Colloquium on Nuclear Effects of the Electron Cloud (Paris 1954), the proceedings of which appear in J. phys. radium **16**, 497 (1955).

The theory of the pair production has been given by Arley and Møller[2] and, independently, by Tisza.[3] Huang[4] has re-examined the work of the former authors. He has carried out explicit calculations using Coulomb wave functions for the electrons and evaluated some of the angular integrals which were only estimated in the earlier work. Figure 1 shows the probability of pair creation per beta decay, N^+/N^-, as a function of the decay energy E_0 for $Z=16$, as calculated by the approximate expressions of Arley and Møller. Figure 2 shows the positron spectrum expected from the decay of $P^{32}(Z=16,\ E_0=4.4mc^2)$. In comparing the pair production probability with that for the other two electromagnetic processes, we note that in each case three types of virtual intermediate states are considered. Specifically,

(a) $\psi_Z\rightarrow\psi_{Z+1}+\beta'+\nu\rightarrow\psi_{Z+1}+e^++e^-+\beta+\nu.$

(b) $\psi_Z\rightarrow\psi_Z'+e^++e^-\rightarrow\psi_{Z+1}+e^++e^-+\beta+\nu.$

(c) $\psi_Z\rightarrow\psi_{Z+1}'+\beta+\nu\rightarrow\psi_{Z+1}+e^++e^-+\beta+\nu.$

Here ψ refers to the nuclear wave function and the prime denotes the virtual intermediate state. It is found that

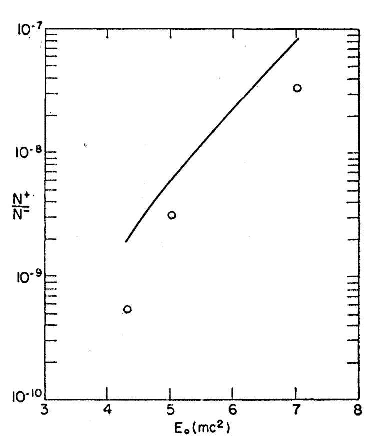

FIG. 1. Theoretical probability of pair creation in beta decay as a function of decay energy E_0 for $Z=16$. Solid curve: Calculation of Arley and Møller.[2] Circles: Calculation of Huang.[4]

[2] N. Arley and C. Møller, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **15**, 9 (1938).

[3] L. Tisza, Physik Z. Sowjetunion **11**, 425 (1937).

[4] K. Huang, following paper [Phys. Rev. **102**, 422 (1956)].

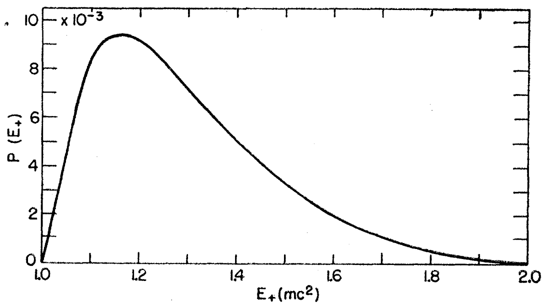

FIG. 2. Theoretical positron spectrum of P^{32}.

processes (a) and (c) contribute about equally to pair creation, i.e., the pairs are formed by the field of the beta ray and of the residual nucleus. On the other hand, the internal bremsstrahlung is almost entirely due to the field of the electron (a) while atomic excitation can be ascribed overwhelmingly to the change in the nuclear Coulomb field (c). We note also that the pairs are created predominantly in the "close" region, i.e., within an electron Compton wavelength from the nucleus. Because of the small magnitude of the effect and its relatively short-range nature, there remained at least the remote possibility that it might be significantly modified by some unknown process connected with the beta decay interaction.

Attempts to detect positrons from (negative) beta emitters have been made by three methods.[5,6] Only one of these, the use of a cloud chamber with magnetic field, has repeatedly yielded results which have been interpreted as positive. The earliest results, which indicated N^+/N^- of the order of 10^{-2}, were manifestly spurious. More recent experiments seemed to indicate N^+/N^- of the order of 10^{-4}. Some experimenters ascribe this number of "positive" tracks to scattering and other spurious phenomena, while others consider the effect genuine. Attempts to detect these particles by magnetic deflection in vacuum, using beta-ray spectrometers or trochoidal focusing, have been negative[6,7] (with two exceptions[8,9] which indicated $N^+/N^- \simeq 10^{-4}$). Upper limits to N^+/N^- of the order of 10^{-5} to 10^{-6} were set by these experiments. Measurements of the scattering of the "positive" tracks in cloud chambers had suggested that the specific charge of these particles might differ from that of electrons, some experiments indicating larger, some smaller masses. It has been conjectured that these particles might escape detection by decay in flight. It is therefore significant that negative results were also obtained[7] with a small spectrometer, designed specifically to afford path lengths comparable to those observed in cloud chambers. Finally, some rather crude attempts to detect annihilation radiation from negatron sources, using a coincidence method[10] or a magnetic secondary electron spectrometer,[11] have also shown negative results. It should be noted that none of the experiments, whatever their apparent result, would have been capable of detecting an effect of the magnitude predicted theoretically.

In view of these contradictory results, we decided to design an experiment of sufficient sensitivity to permit comparison with theory. Our apparatus detects only positrons and yields no information concerning the possible emission of other positive particles with unknown properties. We might also seriously underestimate the relative number of positrons if their energy spectrum is radically different from that expected theoretically. At the time the experiment was designed we had only the calculations of Arley and Møller to guide us. Our results show clearly that N^+/N^- is smaller than predicted by their estimate. The more complete calculation of Huang lowers the theoretical estimate close to the limit of detectability by our method, in agreement with the experimental result.

B. APPARATUS AND PROCEDURE

Our experimental problem consisted of the detection of a very small number of primary positrons in the presence of an overwhelmingly larger number of other radiations: beta rays, inner bremsstrahlung, external bremsstrahlung, and secondary positrons produced by the impact of photons and beta rays. The low relative intensity of the effect sought made it imperative to use a very selective detection method. Such a method is afforded by the annihilation radiation produced when the positrons are stopped in some material, referred to hereafter as the "catcher." The two annihilation quanta were counted in coincidence, identified by their energy and by their emission from the catcher in opposite directions. To minimize the formation of positrons by energetic electrons or photons striking the catcher, the latter was located in a magnetic field in

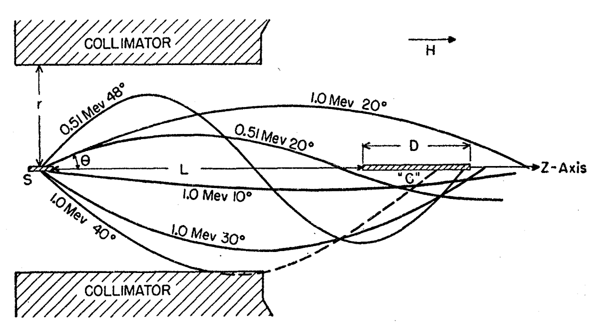

FIG. 3. Projected electron trajectories in our apparatus for $H=2850$ gauss. All trajectories of electrons with $E \geqslant 1.0$ Mev either miss the catcher C or are intercepted by the collimator.

[5] G. Groetzinger and F. Ribe, Phys. Rev. **87**, 1003 (1952). This paper contains an extensive bibliography of the earlier literature.
[6] G. W. McClure, Phys. Rev. **94**, 1637 (1954). This article contains references to the recent literature.
[7] P. Weinzierl, Z. Naturforsch. **9A**, 69 (1954).
[8] G. Groetzinger and D. Kahn, Phys. Rev. **80**, 108 (1950).
[9] T. Yuasa, Compt. rend. **234**, 619 (1954).
[10] H. Bradt, Helv. Phys. Acta **17**, 59 (1954).
[11] K. Siegbahn and H. Slätis, Arkiv. Mat. Astron. Fysik **34A**, 6 (1947).

such a position that about one-half of all the positrons emitted by the source in the interesting energy interval would strike it; while the probability for electrons or photons with energy above $2mc^2$ reaching it from the source or surrounding scattering material was very small.

1. Magnetic Focusing

The principle of the apparatus is illustrated in Fig. 3. A point source S and the catcher C are located on the axis of the apparatus which is placed in a uniform axial magnetic field H. The length of the catcher is D and its distance from the source L. A cylindrical collimator of radius r extends for a length slightly greater than $(L+D)/2$. Electrons (positive or negative) leaving S at an angle θ with momentum p describe helical paths which return to the axis for the first time at a distance $z=(2\pi pc/eH)\cos\theta$. If the source emits, isotropically, $N(p)$ electrons of momentum p, the number $N(p,z)dz$ of trajectories striking the axis for the first time in the interval dz at z is $N(p,z)dz=N(p,\theta)2\pi\sin\theta(d\theta/dz)dz=(eH/4\pi pc)N(p)dz$.

The points of first crossing are therefore distributed uniformly between $z=0$ and $z=z_0$, where $z_0=2\pi pc/eH$. However, for electrons with sufficiently high momentum, such that $z_0>\pi r$, the collimator will intercept all trajectories for which $z<z_m$, where $z_m=(z_0^2-\pi^2r^2)^{\frac{1}{2}}$. For $D\geqslant L$, every trajectory with $z<(L+D)$ not intercepted by the collimator must eventually cross the catcher. Thus the fraction of all the electrons with momentum p which will be collected by the catcher,

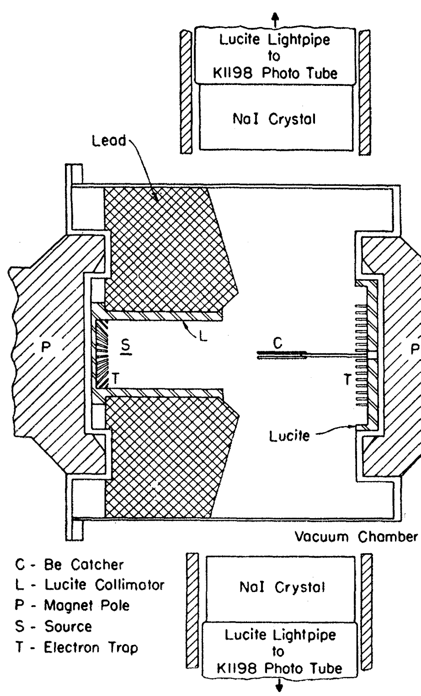

FIG. 4. Diagram of the apparatus.

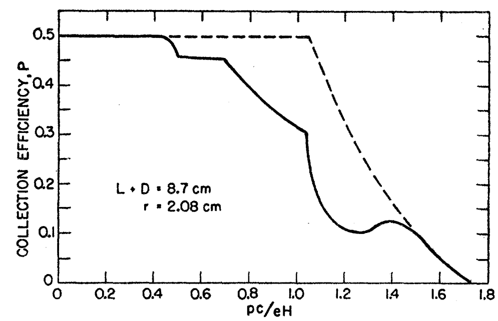

FIG. 5. Collection efficiency as a function of electron momentum. Dotted line: $D\geqslant 4.35$ cm. Solid line: Actual apparatus ($D=2.2$ cm).

i.e., the collection efficiency P would be

$$P(p)=(\tfrac{1}{2}z_0)\begin{cases}\displaystyle\int_{z_m}^{(L+D)}dz=(L+D-z_m)/2z_0 & \text{for } z_0>(L+D)\\[2ex] \displaystyle\int_{z_m}^{z_0}dz=(z_0-z_m)/2z_0 & \text{for } z_0<(L+D).\end{cases}$$

For $z_0<\pi r$, i.e., for low-energy electrons, the lower limit on the integrals is zero.

Limitations on the available magnetic field made it necessary to use smaller than optimal values of D and r in our apparatus (Fig. 4). Specifically, we used $D=0.34L$, and $r=L/\pi$. As a result of this there are two gaps where trajectories may cross the axis for the first time in the range of $z<L$ and still miss the catcher, namely: $(L+D)/2<z<L$ and $(L+D)/3<z<L/2$. These gaps must therefore be omitted from the integrals in the expression for P.

Figure 5 shows the collection efficiency of our apparatus as a function of electron momentum. For comparison we show also the collection efficiency obtainable with $L=D=4.35$ cm. The abscissa, $z_0/2\pi=pc/eH$, is numerically equal to $H\rho/H$, where $H\rho$ is the "magnetic rigidity" of the electrons. P vanishes for $z_m\geqslant(L+D)$, i.e., for $pc/eH\geqslant[(L+D)^2+\pi^2r^2]^{\frac{1}{2}}/2\pi$. In our apparatus the cutoff value of pc/eH is 1.73 cm. A sharp drop occurs in P for $pc/eH=1.04$ cm, where z_m first exceeds zero. In a field of 2800 gauss no electrons with energy above 1 Mev are collected. In this field the drop-off in P occurs at 500 kev. Thus no secondary pairs can be produced by impinging electrons, while the efficiency for collecting positrons with the expected spectrum (Fig. 2) remains high. The average collection efficiency $\bar{P}$ for these positrons is calculated by integrating P, obtained from Fig. 5 over the spectrum. The result is $\bar{P}=0.47$. The validity of our calculation was established by observing the variation of the over-all detection efficiency with magnetic field for the positrons

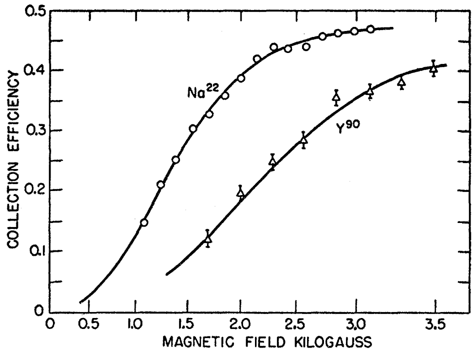

FIG. 6. Collection efficiency as a function of magnetic field for positrons emitted in the beta decay of Na^{22} (circles) and in internal pair conversion of Zr^{90} (triangles). The solid curves are calculated with the aid of Fig. 5.

from Na^{22} which have a spectrum quite similar to that shown in Fig. 2. The experimental result, together with the calculated one, is shown in Fig. 6.

The design of our apparatus is shown schematically in Fig 4. The vacuum chamber, 5 in. in length and 10 in. in diameter, is made of nonmagnetic stainless steel. All surfaces from which secondary radiations might reach the catcher are covered with Lucite to minimize pair creation and to reduce backscattering of energetic electrons. At the ends of the chamber the scattering is further reduced by an array of $\frac{1}{4}$-in. long polystyrene tubes acting as an electron trap. A positron arising in the chamber will be detected by the counter system only if it is annihilated either in the catcher or in the area of the chamber wall which lies directly between the counters. The latter area is shielded by a heavy lead cylinder from energetic bremsstrahlung or other gamma rays originating in or near the source. It would have been advantageous to provide a similar shield for the opposite end of the chamber where some energetic radiations are produced by the impact of the electrons, but the available pole gap did not permit this.

The catcher is made of beryllium, $\frac{1}{16}$ in. thick and $\frac{9}{16}$ in. wide, and is supported from the endplate by a thin polystyrene rod. The low atomic number of beryllium minimizes pair creation in the catcher by hard radiations which can reach it in substantially straight paths from the source. The solid angle subtended by the catcher at the source is about 3×10^{-3} steradian.

2. Sources

The sources of P^{32}, about 1 cm^2 in area, were deposited on a 0.9-mg/cm^2 "Mylar" strip supported on a semicylindrical Lucite holder fitted into the collimator. One-half of the positrons must pass through the supporting film which lies in a plane containing the axis of the system. The effect of absorption in the film is negligible for particles above about 50 kev. The radioactive P^{32} was provided by the Chalk River Laboratory of Atomic Energy of Canada, Ltd., who performed two special preparations to provide material of very high specific activity. Nevertheless, each of the two sources contained about one milligram of solid material. We were unable to obtain sufficiently high and reproducible yields with methods such as volatilization in vacuum which produce truly uniform sources. Our sources were prepared by drying a solution of PO_4^- in dilute HCl in a rapid stream of dry nitrogen with gentle warming. A 5% solution of insulin was used as wetting agent to help spread the deposit. Visual inspection in a microscope indicated a rather uniform microcrystalline deposit without gross clumping.

After completion of the measurements, each source was dissolved in hydrochloric acid. Several small volumetric aliquots were then taken from these solutions, and very thin sources deposited from these were counted in a 4π counter. The strength of each source calculated from the several aliquot samples showed the procedure to be reproducible to better than two percent.

Sources of Y^{90} (see Sec. D) with a strength of about 0.15 mC were separated, carrier-free, from the long-lived parent Sr^{90}. They were then deposited and calibrated like those of P^{32}.

3. Detecting System

The gamma-ray counters used to detect the annihilation radiation consist of NaI(Tl) crystals, 3 in. in in diameter, 2 in. thick, coupled to DuMond K-1198 photomultipliers by 6 inch long light pipes. The light pipes were required to remove the multipliers from the large stray field of the magnet. Considerable magnetic shielding was used around the tubes so that their response was practically independent of the magnetic field.

The electronic coincidence and pulse height selection system was of the fast-slow type. The "fast" coincidence pulses, taken without pulse-height analysis, gate the inputs to the single-channel pulse-height selectors. The outputs of the latter are then mixed in the final "slow" coincidence circuit. This arrangement permits the use of relatively slow pulse-height analyzers. In most of the measurements we use a "fast" coincidence resolving time of about $2\tau=210$ mμsec. This was later shortened to 85 mμsec. These relatively long resolving times permitted the use of stable, fed-back amplifiers throughout without causing an undue accidental coincidence rate with the source strength available. The pulse-height analyzers were set to accept pulses in a 150-kev wide energy interval centered at 510 kev. This low-energy resolution, like the low time resolution, was determined by the requirement of great stability over many hours imposed by the very low counting rates.

The over-all detection efficiency of the apparatus was determined and checked periodically by means of a Na^{22} source. The number of positrons emitted by this source per second was measured in a 4π counter. As mentioned above, the positron spectrum of Na^{22} resembles the theoretical spectrum of P^{32} (Fig. 2) so closely that the detection efficiencies may be taken to be the same within the accuracy of our measurements. The over-all efficiency, including the collection efficiency of the catcher, the solid angle subtended by the counters, and their counting efficiencies, was 1.26×10^{-3}. The counting rates expected, and observed, with this efficiency and the source strength of P^{32} used—about 30 mC—were of the order of a few counts per hour.

4. Background

Because of the extremely small magnitude of the effect investigated, great precautions had to be taken to minimize and account for all other phenomena which cause spurious, or background counts. The main sources of background were the following: (1) Ambient background due to cosmic rays and radioactivity. This was the most important contribution, about 7 counts/hr. Because of the large size of the apparatus it did not seem practicable to reduce this significantly by shielding or anticoincidence counters. This background was determined directly by interspersing runs in which the source was removed from the apparatus between those with the P^{32} source in place. (2) Accidental coincidences. These were calculated in the usual fashion from the counting rates which were monitored continuously during each run. (3) Positrons formed in the walls of the chamber which find their way to the catcher. By placing a Na^{22} source at various representative points in the chamber, the detection efficiency for such positrons was found to be between 10^{-3} and 10^{-4} of that for positrons starting on the axis. (4) Positrons which are annihilated in the region between the counters at points other than the catcher. (5) Positrons formed in the catcher itself by hard radiations from the source. As mentioned above, the solid angle subtended by the catcher at the source is about 3×10^{-3} steradian. (6) Secondary radiations scattered in such a manner that they register in both counters. For example, a hard bremsstrahlung quantum could be scattered in one counter crystal, losing an energy of 500 kev, and then reach the other counter. The geometry of our apparatus is such that only very unusual *multiple* scattering events could give rise to such coincidence counts.

Order of magnitude estimates of the effects (3)–(6) show them to be small compared with the statistical uncertainty of our experiment. In addition, these and other similar background effects were accounted for in first approximation by the following procedure: With the P^{32} source in its usual position, the catcher was placed one centimeter off the axis. In this arrangement the detection efficiency for positrons starting from the source is reduced tenfold while the background should be very nearly the same as with the axial catcher. The counting rate obtained in this arrangement was indistinguishable from that obtained without a source, after a small correction for the different accidental coincidence rates. This confirms our estimate that the effects (3)–(6) are negligible. (7) Positrons created in the source or its supporting foil by secondary processes.

TABLE I. Summary of experimental results.

Source	Total counts/hr	Background counts/hr	Net true counts/hr	Corrected for decay	N^+/N^-
No. 1, 23.7 mC	10.5 ± 1.2	7.6 ± 1.1	2.9 ± 1.6	3.2 ± 1.8	$(8.3\pm4.6)\times10^{-10}$
No. 2, 39.1 mC	11.1 ± 1.2	6.8 ± 1.3	4.3 ± 1.7	4.8 ± 2.0	$(7.2\pm2.9)\times10^{-10}$
No. 2, with gold foil	10.2 ± 0.8	7.2 ± 0.7	3.0 ± 1.1	8.1 ± 3.0	

This source of spurious counts is the most serious cause of uncertainty in our results, since the experiment cannot distinguish between these and the phenomenon sought. Positron-electron pairs can be created either by energetic beta rays or by the internal bremsstrahlung. Both of these processes are proportional to the source thickness and to $\langle Z^2\rangle_{Av}$, the mean square atomic number. In addition, there may occur a tertiary process in which an external bremsstrahlung photon is first created which in turn creates a pair. This process is proportional to the squares of the source thickness and of $\langle Z^2\rangle_{Av}$. A rough calculation[12] shows that the pair formation by the very small number of hard quanta emitted by our sources is at least one order of magnitude smaller than the effect sought. On the other hand, the cross section for pair creation by electrons in the energy range of interest—1.02 Mev to 1.7 Mev—is not well known either theoretically or experimentally. Bhabha's calculation[13] cannot be extrapolated into this energy range with any degree of confidence because of the breakdown of the Born approximation. Experimentally established upper limits are well above the expected magnitude of the phenomenon. A rough estimate, based on a linear extrapolation[10] of Bhabha's results predicts an effective cross section in lead between 10^{-29} and 10^{-28} cm^2 for the beta rays of P^{32} averaged over the entire spectrum. This order of magnitude leads to the conclusion that the secondary process may contribute a significant fraction of the positrons observed by us. This conclusion was confirmed and an attempt at an approximate estimate of this contribution was made by measuring the number of positrons produced when the source was covered with 2.5 mg/cm^2 of gold. Details of this procedure are discussed below.

C. RESULTS FOR P^{32}

The results of our experiments with two sources of P^{32} are summarized in Table I. The statistical errors indicated are standard deviations, accounting only for counting statistics. The disintegration rates indicated in column 1 refer to the beginning of each of the two series of measurements. Column 2 lists the average coincidence rates, corrected for accidentals, but not for source decay or background. The background tabulated in column 3 for each series was obtained from measurements without the source, interspersed with the series.

[12] W. Heitler, *Quantum Theory of Radiation* (Oxford University Press, Oxford, 1944).
[13] H. J. Bhabha, Proc. Roy. Soc. (London) **A152**, 559 (1935).

The average of a large number of such background measurements, before, during, and after the two series, was 7.2 ± 0.3 counts/hr. The series of runs in which the catcher was placed off the axis, referred to in the section on background effects, gave an average counting rate of 6.9 ± 0.6 counts/hr. Column 4 gives the difference between the two preceding ones, while column 5 is corrected for source decay to refer the result to the activity at the beginning of the series of measurements, as given in column 1. Column 6 gives the number of positrons per disintegration of P^{32} as deduced from the numbers in columns 1 and 5, using the known detection efficiency of 1.26×10^{-3}. The weighted average of the values obtained with the two sources is $N^+/N^-=7.6\pm2.5\times10^{-10}$. If the average background counting rate of 7.2 ± 0.3 counts/hr is used, rather than the statistically less certain values in column 3, we obtain $N^+/N^-=(7.3\pm1.8)\times10^{-10}$. It is therefore practically certain that we have observed positrons emitted by the P^{32} sources.[14] This conclusion is not affected by the uncertainties in source and efficiency calibrations, estimated not to exceed 7%.

The measurement with the gold-covered source (third line in Table I) gave an excess of 3.3 ± 3.6 counts/hr over that with a bare source, corrected for source decay and calculated with separate background measurements. If we assume, instead, a constant background, the excess becomes 3.7 ± 3.0 counts/hr. The large statistical uncertainty is due to the fact that the source had decayed by nearly a factor of three when it was covered with the gold foil.

If we assume, for purposes of calculation, the mean value of 3.3 counts/hr due to secondary positrons produced in the gold, then a calculation of the average path length travelled by the electrons in the gold foil (including scattering) leads to a cross section for pair creation in gold, averaged over the entire P^{32} spectrum, of about 5×10^{-29} cm^2. We then assume that the cross section varies with Z^2 and that each P^{32} source had a total mass of one milligram, with average atomic number $Z=25$. With these assumptions, a calculation similar to the one carried out for gold indicates that the source material, if uniformly and continuously spread over one cm^2, would contribute secondary positrons at a rate of about 0.9×10^{-10} per P^{32} beta ray, or about thirteen percent of the observed rate with a bare source. The sources were certainly not deposited quite uniformly. If the material actually covers only an area smaller than the full cm^2, the number of secondaries calculated above should be multiplied by a factor somewhat smaller than the reciprocal of the fraction of the area occupied. This is due to two effects: For a more or less uniform deposit the number of secondaries rises less than linearly with thickness because of the tendency for very oblique rays to be scattered out of the deposit. For a deposit consisting of isolated crystals the number is further decreased because of the larger area for escape of the electrons. For example, if the source consisted of uniformly spaced cubic crystals occupying only one-eighth of the area, we should expect about 2.3×10^{-10} secondary positrons per beta ray or only about two and one-half times as many as from a uniform source.

We may now summarize our results as follows: The number of positrons emitted in the beta decay of P^{32} does not exceed $N^+/N^-=1.3\times10^{-9}$. (This value would have yielded counting rates exceeding our result by two standard deviations.) This upper limit is three orders of magnitude lower than any reported heretofore. It is also lower than the value calculated from the approximate theory of Arley and Møller which our experiment was designed to test. On the other hand, this limit is still twice as high as the value $N^+/N^-=5.5\times10^{-10}$ calculated by Huang.

The most probable value deduced from our results is about $N^+/N^-=5\times10^{-10}$. This is in excellent agreement with Huang's theoretical result for a purely electromagnetic process. However, the experimental value involves a correction for the contribution by secondary processes which is so uncertain that the true value could be smaller by an order of magnitude without being in contradiction with our experiment.

We have failed in our objective to provide a close quantitative check on the theory of pair creation in beta decay. This failure is due in part to the fact that the experiment was designed on the basis of the estimates of Arley and Møller[2] which proved to be substantially higher than a more sophisticated calculation, and in part to the somewhat unexpected difficulty in obtaining a P^{32} source of sufficient specific activity. If future experiments should show that our rough determination of the cross section for *external* pair creation by electrons is a substantial overestimate, then our result may be interpreted as verifying Huang's[4] calculation within about a factor two.

D. Yttrium-90

It was originally our intention to follow up the measurements with P^{32} by a similar experiment using a Y^{90} source. This nuclide emits beta rays with a maximum energy of 2.26 Mev and no energetic gamma rays. The theoretically expected pair yield for this disintegration energy (Fig. 1) is more than ten times as great as for P^{32}. Some uncertainty is introduced into this calculation by the fact that the Y^{90} spectrum is of "forbidden" ($\Delta J=2$) type. Nevertheless, Y^{90} seemed to be the only nuclide with properties permitting a more precise measurement of the internal pair creation in beta decay. In the meantime, however, Johnson, Johnson, and Langer[15] reported an internal conversion line and a

[14] Statistically, the odds are 369:1 against our result being an accidental background fluctuation if we accept the larger statistical error (±2.5 counts/hr), or 16 000:1 if we accept the smaller error. These odds are increased still further when the several runs in each series are considered separately.

[15] Johnson, Johnson, and Langer, Phys. Rev. 98, 1517 (1955).

continuous positron spectrum accompanying the decay of Y^{90}. These positrons are ascribed to a purely electromagnetic 0^+–0^+ transition in Zr^{90} with an energy of 1.75 Mev. These authors reported the number of positrons as: $N^+/N^- = (2-1)\times 10^{-4}$ relative to the main beta spectrum, four orders of magnitude more numerous than the expected yield from the beta-decay process which is therefore completely masked. Formally, the theoretical treatment of the two processes is rather similar: The pairs accompanying the beta-decay process arise in part from nuclear transitions between a *virtual* excited 0^+ state and the ground state. Physically, however, the *real* transition does not yield the same type of information since the beta-ray transition probability to the *real* excited state is simply determined by the nuclear matrix element in the same order as for other beta transitions and does not involve the subsequent transition probability to the ground state. In addition, it may be noted that the pairs created in the electromagnetic transition arise inside the nuclear volume.

The theory of electromagnetic 0^+–0^+ transitions has been discussed by many authors. For our discussion, the relevant calculation has been given by Thomas.[16] The transition rate involves the nuclear matrix element of Σr_i^2, where r_i is the position of the ith proton. This matrix element can only be estimated from some nuclear model. On the other hand, the *relative* probabilities for the emission of a conversion electron or of a positron-electron pair involve only an evaluation of electron wave functions at the nuclear surface. In the usual approximation no specifically nuclear property, not even the nuclear radius, enters the ratio of internal conversion to pair creation. Thomas has given the relevant formulas, using relativistic wave functions but neglecting screening. Evaluation for the appropriate energy and atomic number yields, for the ratio of K-conversion to pair creation, $N^K/N^+ = 2.6$. On the other hand, Johnson *et al.* report 5×10^{-5} for the relative intensity of the conversion electrons, which, combined with their value for the number of positrons, gives $N^K/N^+ = 0.25$, uncertain to about a factor two. Conversion electrons arising from other shells, which may have been included in their measurement, account for about 15% of the total. In view of this substantial discrepancy, it seemed worth while to measure the number of positrons per beta decay of Y^{90} with our apparatus.

[16] P. Thomas, Phys. Rev. 58, 714 (1940).

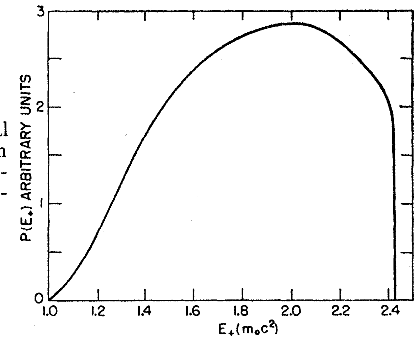

FIG. 7. Theoretical positron spectrum from the 0–0 transition in Zr^{90}, according to Thomas.[16]

Carrier-free Y^{90} sources of about 0.15-mC strength were prepared by precipitation from the long-lived Sr^{90} parent. The procedure of the experiment followed closely that for P^{32}. The counting rates obtained were so high that background and statistical counting errors were nearly negligible. Our experimental uncertainty arises almost entirely from the uncertainties in source strength and efficiency calibration. The theoretical positron spectrum, calculated from Thomas' formula is shown in Fig. 7. Because of the higher maximum energy —730 kev—and the predominance of higher energy particles the collection efficiency for Y^{90} is somewhat lower than for P^{32} and Na^{22}. In Fig. 6 we have plotted this efficiency as a function of magnetic field, calculated from Figs. 5 and 7. We also show the experimentally obtained counting rates from one of the Y^{90} sources as a function of magnetic field, normalized to best fit the calculated curve. The generally good agreement may be interpreted as a rough measurement of the positron spectrum. The over-all detection efficiency is again deduced from the calibration with Na^{22}.

From these, and similar data, we obtain $N^+/N^- = (3.6\pm 0.9)\times 10^{-5}$. Combined with the Indiana group's value for the intensity of the conversion line, we obtain $N^K/N^+ = 1.4$, in tolerable agreement with the calculation of Thomas. No probable error is given for the number of conversion electrons.[15] Therefore we cannot know the uncertainty in the ratio.

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