Family IIa $(n\leqslant 1)$

$$K_f(\sigma;\infty)=\frac{\Gamma(2\sigma+3)}{1-\frac{1}{2}e^{-n}}\left[\frac{1}{2}e^{n}-\sum_{k=0}^{\infty}\frac{n^{2\sigma+5+2k}}{\Gamma(2\sigma+6+2k)}\right],$$

$$L_f(\infty)=\{(2/15)n^5+(2/3)n^3+(5/4)n^2-2n+(21/8)+e^{-n}(n^2-2)-(5/16)e^{-2n}\}/\{(1-\tfrac{1}{2}e^{-n})[e^{-n}+2n+(1/3)n^3]\}.$$

Family IIb $(n\geqslant 1)$

$$[K_f(\sigma;\infty)]_{\mathrm{IIb}}=(1/n^{2\sigma+3})[K_f(\sigma;\infty)]_{\mathrm{IIa}},$$

$$[L_f(\infty)]_{\mathrm{IIb}}=(1/n^2)[L_f(\infty)]_{\mathrm{IIa}}.$$

Family IV

Exponential

$$K_f(\sigma;\infty)=\Gamma(2\sigma+3),\quad L_f(\infty)=\tfrac{5}{8}.$$

Modified Exponential

$$K_f(\sigma;\infty)=(2\sigma+4)\Gamma(2\sigma+3),\quad L_f(\infty)=63/32.$$

Gaussian

$$K_f(\sigma;\infty)=\tfrac{1}{2}\Gamma(\sigma+(3/2)),\quad L_f(\infty)=2^{-3/2}.$$

Modified Gaussian

$$K_f(\sigma;\infty)=\tfrac{1}{2}(\sigma+(5/2))\Gamma(\sigma+(3/2)),$$
$$L_f(\infty)=(83/80)2^{-1/2}.$$

Uniform

$$K_f(\sigma;\infty)=(1/2\sigma+3),\quad L_f(\infty)=\tfrac{2}{5}.$$

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Search for Anomalous Positively Charged Particles from P^{32}*

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With a small β-ray spectrometer of unique design, the electrically charged emanations of radioactive P^{32} have been analyzed in an attempt to verify evidence found by others of the emission of positively charged particles in concentrations of the order of 10^{-3} to 10^{-4} per β decay. The ratio of the yield of positively charged particles to that of negatively charged particles in the momentum interval $H\rho=700$ to 2700 gauss cm was found to be less than 8×10^{-6}. This ratio is about 100 times smaller than earlier determinations in the same momentum interval obtained with cloud chambers and small spectrometers, but agrees in order of magnitude with a previous result obtained with an ordinary-sized spectrometer. The hypothesis that the anomalous "positive particles" in question are unstable and detectable only at short distances from the source would account for a low positive-particle yield measured with an ordinary spectrometer but cannot account for the disparity between the present results and those arrived at repeatedly with cloud chambers and other "short path length" detectors. It appears that the previously reported "positive particle" ratios in the range 10^{-3} to 10^{-4} arise from spurious background effects.

INTRODUCTION

When a β emitter is placed in a magnetic cloud chamber there appear among the tracks which ostensibly emanate from the source a certain small fraction which exhibit a sense of curvature characteristic of positively charged particles. Tracks of this nature have been observed in studies of such diverse substances as RaA, RaC, RaE, Th(C+C″), UX, and P^{32}.[1] In some cases[2,3] the positive particle yields (per β decay) from the same substance as determined with different source and chamber geometries have differed by several orders of magnitude, but to the best of our knowledge the lowest yield observed in any cloud chamber study is 10^{-4} "positives" per β decay. In every cloud chamber investigation the "positive" yield has exceeded by at least one order of magnitude that expected from positrons created in the source by electrons (electron pair-production), source bremsstrahlung or nuclear γ rays.

Some investigators have chosen to regard the "positives" as a completely spurious phenomenon attributable to one or more of the following effects: (1) electrons scattered from the walls back to the source, (2) electrons returning to the source after traversing a complete circle partially out of view, (3) electrons emerging from the source and being multiply scattered so as to assume a reversed curvature. Others have examined the spurious effects in more or less detail and have concluded that the "positive" tracks are really produced by positively charged particles—either positrons or some light particle distinct from the positron.

In recent years several cloud-chamber investiga-

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[1] As the present paper concerns only P^{32} and as extensive bibliographies relating to the other substances listed have been given elsewhere (see, e.g., reference 2) we omit references to the latter.

[2] L. Smith and G. Groetzinger, Phys. Rev. **70**, 96 (1946).

[3] G. Groetzinger and F. Ribe, Phys. Rev. **87**, 1003 (1952).

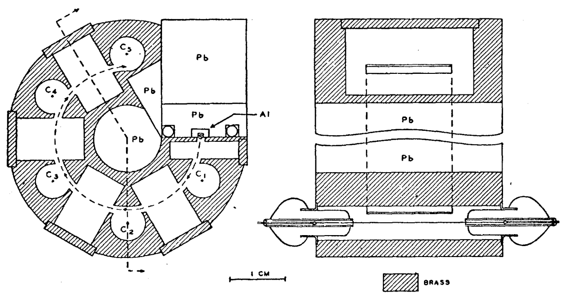

FIG. 1. Cross-sectional diagram of spectrometer showing G-M counters C, source S, and lead absorber Pb.

tions[3–6] of P^{32} (no nuclear γ rays) have given "positive-particle" yields between 10^{-3} and 10^{-4}. Of these studies perhaps the most thorough from the point of view of attention to spurious effects is that of Groetzinger and Ribe.[3] These investigators observed 2.9×10^{-4} positive particles per β decay and felt that the "positives" could not be explained by any of the effects enumerated above. An unsuccessful attempt to detect the particles in question with an ordinary β ray spectrometer[7] (upper limit 1.3×10^{-5} positives per β decay) led Groetzinger and Kahn[8] to suggest that the particles observed in the cloud chamber might be unstable and have so short a half-life that they would be difficult to detect in instruments (such as ordinary spectrometers) with distances greater than a few cm between source and detector. Groetzinger and Kahn[8] and also Yuasa[6] have sought to detect the "positives" with specially built small-sized spectrometers, and have arrived at yields of the same order of magnitude as given by the cloud chambers. The former investigators utilized an unevacuated 180° spectrometer with a 4-cm path length and an emulsion detector and the latter used an evacuated 180° instrument with a 7-cm path length and a G-M counter detector.

This communication describes an attempt to verify the last-mentioned results with a small spectrometer designed with particular care to eliminate some of the background effects which could give rise to an erroneous "positive-particle" indication.

APPARATUS

Two cross-sectional views of the spectrometer are shown in Fig. 1. The instrument is made of a brass cylinder with an internal annular channel. Around the annulus are spaced a series of five G-M counters so arranged that particles which start at the source S and pass completely around the channel traverse the sensitive volume of each counter. The channel has a central radius of curvature of 1.35 cm and a rectangular cross section measuring 0.16 cm by 1.59 cm. The distance along the channel between the source and the last counter C_5 is 6 cm. Rectangular cavities between adjacent pairs of counters serve to break up the continuity of the channel walls and thus reduce the probability that an electron which once impinges upon the wall can completely traverse the channel. The open space formed by the channel and counters is sealed at one end by a permanent plug and at the other end by a Pb block with an "0" ring gasket. The P^{32} source[9] was evaporated into a small $\frac{1}{32}$-in. thick Al boat which nested into the Pb block, exposing the bare source directly to the channel.

The entire instrument was filled with a self-quenching G-M counter gas mixture (90 percent argon, 10 percent butane) at a total pressure of 5 cm Hg. In traversing the 6-cm path length around the channel, a particle encounters no windows of solid material and is required to penetrate only 0.7 mg/cm² of gas.

The lead blocks behind the source and in the center of the spectrometer cylinder partially shield the counters from the source bremsstrahlung so as to minimize the probability of accidental coincidences and reduce the production in C_5 of photoelectrons which might traverse the channel in the backward direction and give spurious positive-particle counts.

The instrument was mounted in a magnetic field variable from 0 to 2000 gauss supplied by an electromagnet with 2.5-in. diameter pole faces spaced 2.5-in. apart. The field was measured by means of a ballistic galvanometer and flip-coil and was essentially uniform over the volume of the spectrometer.

PROCEDURE

The detection of fivefold coincidences between all of the circumferential G-M counters was originally conceived as a method of obtaining good suppression of cosmic-ray background and of insuring that only particles which completely traversed the channel would be counted. While the former objective was satisfactorily met by the original arrangement, there existed a weak tendency for adjacent counters to discharge one another by photoelectric interaction. Measurements of the cross-triggering probabilities between C_3 and C_4, and C_4 and C_5 (about 10^{-2} in each case) implied that an electron which traversed counters C_1, C_2, C_3, and not C_4, C_5 could give rise to a fivefold coincidence with probability of about 10^{-4}. While this effect introduced practically no distortion into the β spectrum, it led to excessive "positive-particle" yields in preliminary experiments.

After several unsuccessful attempts to eliminate the interactions between adjacent counters, it was decided to perform the experiment with twofold coincidences between counters C_3 and C_5 and to use an anticoincidence tray of G-M counters placed directly above the instrument as a means of rejecting cosmic-ray counts. This tray had a solid sensitive area measuring 4 in. by

[4] T. Pi and C. Chao, Phys. Rev. **72**, 639 (1947).
[5] J. Barlow and F. Rogers, Phys. Rev. **74**, 700 (1948).
[6] T. Yuasa, Compt. rend. **234**, 619 (1952).
[7] K. Bainbridge (report on Harwell Conference), Nature **160**, 492 (1947).
[8] G. Groetzinger and D. Kahn, Phys. Rev. **80**, 108 (1950).

[9] PO_4 in weak HCl. Procured from the U. S. Atomic Energy Commission, Isotope Division, Oak Ridge, Tennessee.

8 in. and was centered 3 inches above the central axis of the spectrometer. In this location the tray overlapped considerably the solid angle defined by counters C_3 and C_5, and was very effective in reducing cosmic-ray background.

EXPERIMENTAL RESULTS

The results of principal interest are shown in Fig. 2. Anticoincidence rates measured with the field oriented to favor the detection of β particles from the source are indicated by the $(-)$ curve, and rates with corresponding fields of the opposite polarity are indicated by the $(+)$ curve. The data were obtained over a period of approximately 10 days and were corrected for decay of the P^{32} source during the period. Within the statistical uncertainties the $(+)$ rates are independent of field strength.

The cosmic-ray background anticoincidence rate, measured with the source removed, was approximately 5×10^{-4} min^{-1}, or about one-tenth of the average rate represented by the $(+)$ points. Accidental coincidences and false anticoincidences caused by the "dead-time" of the anticoincidence tray were negligible in all experiments described herein.

Subsidiary experiments were performed to seek a correlation between the recorded $(+)$ rates and the rate at which counter 5 was discharged by P^{32} bremsstrahlung. It was discovered that an additional P^{32} source placed between the two Pb blocks behind the regular source increased the $(+)$ anticoincidence rate in about the same proportion as the bremsstrahlung rate of counter five at several different $(+)$ field-settings above 400 gauss. This suggested that many of the observed $(+)$ counts (at least 50 percent on the basis of rather crude statistics) were caused by bremsstrahlung-produced secondary electrons which were released in counter 5 and traversed the channel in the backward direction to counter 3. Even without correcting the $(+)$ data for this and other possible spurious effects which tend to enlarge the $(+)$ rates, the $(+)$ to $(-)$ ratios in the interval $H\rho=700$ to 2700 gauss cm are considerably smaller than expected from the cloud-chamber results and the prior small-spectrometer data.

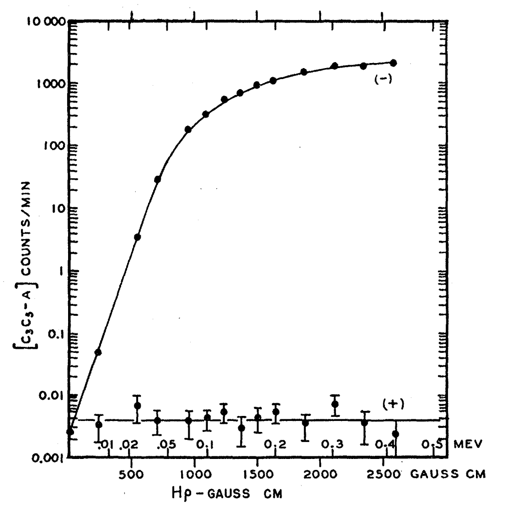

FIG. 2. Measured anticoincidence rates with P^{32} source. The $(-)$ curve was obtained with the magnetic field polarity favoring the passage through the spectrometer of negatively charged particles, and the $(+)$ curve with the opposite field polarity.

TABLE I. Efficiency of counter C_3 *vs* $H\rho$.

$H\rho$	820	1090	1370	1630	1870	2120	2350	2580
Efficiency of C_3	0.72	0.65	0.57	0.56	0.49	0.45	0.45	0.41

TABLE II. Calculated fraction of β rays removed from the channel by multiple scatterings *vs* $H\rho$.

$H\rho$	750	1000	1500	2000	2500	3000
Fraction removed	0.92	0.75	0.65	0.52	0.43	0.37

Because of the low pressure of the gas mixture and the short path length of the β rays through the G-M counters, particles which traversed the channel were not counted with 100 percent efficiency. The efficiency of counter C_3 was determined by taking the ratio of the threefold coincidence rate (C_3, C_4, C_5) to the twofold rate (C_4, C_5) at several different $(-)$ field settings. The results of these measurements, given in Table I, are affected only to the extent of about one percent by adjacent-counter interactions.

The variation of the counting efficiency over the $H\rho$ range investigated together with the scattering introduced by the gas and the finite thickness of the source render the $(-)$ curve in Fig. 2 only a crude approximation to the true β spectrum of P^{32}. A rough estimate of the multiple scattering loss as a function of $H\rho$ has been made by calculating the probability that a ray leaving the source with the proper direction and momentum to allow traversal of the center of the channel under the influence of the magnetic field alone will, owing to the presence of the gas, be scattered so as to miss the entrance slit of counter C_5. The results of this calculation, based upon empirical scattering data for argon[10] and a theoretical estimate of the (relatively small) contribution of the butane to the scattering, is shown in Table II.

The measured β spectrum corrected for: (1) the efficiency variation of counters C_3 and C_5 (the efficiency of C_5 is assumed identical to that of C_3 because of the similar geometries of the two counters), (2) the multiple-scattering loss as approximated above, and (3) the linear variation of the $\Delta H\rho$ acceptance interval as a function of $H\rho$ yields the dashed curve shown in Fig. 3. Comparison with the true spectrum of P^{32} as measured by Agnew[11] indicates fairly good agreement above $H\rho=1200$, but considerable departure at low momenta where the scattering calculation is least accurate and

[10] Groetzinger, Berger, and Ribe, Phys. Rev. **77**, 584 (1952).
[11] H. Agnew, Phys. Rev. **77**, 655 (1950).

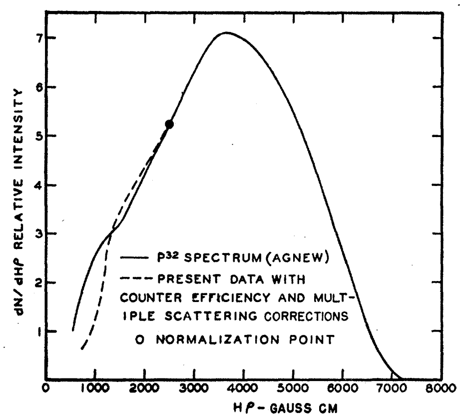

FIG. 3. Comparison of present β spectrum of P^{32} (after corrections noted in text) with the more precise spectrum of Agnew (reference 11).

where the form of the spectrum is most sensitive to the thickness of the source and the nature of the source backing.

DISCUSSION

Since electrons and positrons of the same momentum are scattered similarly (if anything, positrons are somewhat less strongly scattered), the curves of Fig. 2 give directly at each $H\rho$ value an upper limit to the ratio of positrons to electrons emitted from the source. This ratio varies from 1.6×10^{-4} at $H\rho=700$ gauss cm to 2×10^{-6} at $H\rho=2700$ gauss cm.

At $H\rho=1600$ gauss cm the (+) to (−) ratio is 3×10^{-6}, while the corresponding value measured by Groetzinger and Kahn[8] with a small (unevacuated) spectrometer is 8×10^{-4}. For particles with $H\rho>700$ gauss cm, the cloud-chamber data of Groetzinger and Ribe[3] indicate an over-all positive-particle to negative-particle ratio of $\sim2\times10^{-4}$. If one breaks down the "positive-particle" spectrum of the aforementioned authors into momentum-intervals and assumes that the cloud-chamber electron spectrum is the same as that measured with a β-ray spectrograph, it is found that the positive-to-negative ratio in each of the $H\rho$ intervals 700–1400, 1400–2100, and 2100–2800 gauss cm exceeds the corresponding value measured with the present instrument by a factor of about 100. (Most of the "positive" tracks observed in the cloud chamber investigation[3] are included in the $H\rho$ intervals selected for comparison.)

The small spectrograph measurements of Yuasa[6] (250–2500 gauss cm) yield positive-to-negative ratios which are in agreement with the cloud-chamber data of the same author and also in rough agreement with the results of Groetzinger and Ribe.

If one chooses to adopt the point of view that the larger upper limits given by other investigators for the positive-particle yield from P^{32} reflect the presence of a real positively charged particle and not just a spurious effect, one must at the same time endow the particle with properties which might cause it to escape detection in the present instrument. One may propose, for example, that the particle is much more strongly scattered or has a much lower specific ionization than an electron of the same momentum. Although the existing data on multiple-scattering of the cloud chamber "positives"[12] are of somewhat limited statistical accuracy, it seems safe to say that the rms scattering angle of the positives in a given distance is not more than twice that of electrons of the same $H\rho$. If one assumes a factor of 2 for the sake of argument, it can be shown that the "positives" should not be suppressed in their passage through the instrument by more than a factor of 2 over the calculated electron suppression. The multiple scattering effect does not, therefore, seem adequate to explain the discrepancy between the present results and the cloud-chamber results.

The effect of specific ionization upon the detection efficiency of the instrument may be investigated by the use of an experimentally verified theoretical expression for the efficiency of a G-M counter as a function of the average number of primary-ionization events per incident-particle traversal.[13] From this expression, one finds that a specific ionization less than $\frac{1}{4}$ that of an electron of the same $H\rho$ must be attributed to the "positive" particle in question in order that its detection efficiency be suppressed by the amount required to explain the factor of discrepancy with the earlier results. Although there has been no detailed investigation of the ionization of the cloud chamber "positives" relative to electrons, if a ratio as high as 1 to 4 existed, it could hardly have escaped notice, for even electron tracks are quite thin and difficult to photograph clearly.

It is difficult to conceive of any factors other than those discussed above which could prevent the present instrument from detecting the positive particles if they exist. Certainly, the path length between the source and the last counter (C_5) is short enough to allow detection of the "positives" on the same efficiency basis as the cloud chamber, insofar as the instability hypothesized by Groetzinger and Kahn[8] is concerned.

In view of the negative evidence presented here, the author feels that the alleged "positive particles" from P^{32} in concentrations of the order of 10^{-4} or greater must be the result of some sort of spurious background effect which has not been properly accounted for in the earlier experiments.

ACKNOWLEDGMENT

The author is indebted to Dr. W. F. G. Swann, Director of the Bartol Foundation, for several helpful discussions during the course of this work, and to Mr. R. C. Pfeiffer for his assistance in the design and construction of the spectrometer.

[12] G. Groetzinger and F. Ribe, Phys. Rev. **79**, 904 (1950).
[13] See, e.g., G. McClure, Phys. Rev. **90**, 796 (1953).