Internal Pair Conversion in Mg^{24}

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The positron spectra from the internal pair conversion of the two γ-rays following the β^- decay of Na^{24} have been observed, and the internal pair conversion coefficients found to be 7.1×10^{-4} in the case of the 2.758-Mev γ-ray and 0.6×10^{-4} in the case of the 1.380-Mev γ-ray. The value of the coefficients and the shape of the spectra lead to the conclusion that both γ-rays are electric quadrupole transitions.

INTRODUCTION

THE γ-rays resulting from the excited states of nuclei suffer two types of internal conversion in general. In the first type the entire energy of the γ-ray is given up to an orbital electron, resulting in an essentially monochromatic line. In the second type the γ-ray is converted into an electron-positron pair in the vicinity of the nucleus. This latter type of process differs from the first type (atomic internal conversion) principally in that an electron comes from a negative energy state, whereas in atomic internal conversion all electrons begin and end in positive energy states. Since the pair conversion is a three-body process, the electrons and positrons resulting from it exhibit continuous spectra. Moreover, the γ-ray undergoing such conversion must have an energy of at least $2m_0c^2$ (1.022 Mev), and the process, therefore, does not compete with internal conversion below this energy. However, above this energy, pair conversion not only competes with, but rapidly becomes more frequent than internal conversion. The former increases, while the latter decreases with energy. For instance, for electric dipole radiation ($Z=0$) the total pair conversion coefficient is $\sim3\times10^{-4}$ at 1.5 Mev and $\sim1\times10^{-3}$ at 2.5 Mev. For the same two energies, respectively, the coefficient of internal conversion ($Z=10$, K-shell) decreases from 2.5×10^{-6} to 1.2×10^{-6} for electric dipole radiation, and from 2.3×10^{-5} to 5.4×10^{-6} for electric 5-pole radiation. Furthermore, pair conversion possesses a marked advantage over internal conversion as far as detectability goes, when using β-ray spectrometers: namely, that while the monochromatic lines due to internal conversion may be concealed in the negatron spectrum, the positron spectrum, due to pair conversion, may be observed free from these effects by simply reversing the field of the spectrometer.

TABLE I. Tabulation of observed and theoretical values of I_1 and I_2.

	Observed value $\times10^4$	Theoretical values $E1\times10^4$	$E2\times10^4$	$E3 \times10^4$	$M1 \times10^4$	$M2 \times10^4$	$M3 \times10^4$
$I_1(\gamma_1=2.76$ Mev)	7.1 ± 0.2	11.20[a]	6.95[a]	4.62[a]	5.36[a]	3.45[a]	2.58[a]
$I_2(\gamma_2=1.38$ Mev)	0.6 ± 0.1	1.87[b]	0.57 ($Z=0$) 0.38 ($Z=84$) [b]	0.19[c]	0.25[c]	0.07[c]	0.02[c]

[a] See reference 4.
[b] See reference 1.
[c] M. E. Rose (private communication).

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Aside from the intrinsic interest of the process of pair conversion itself, additional interest stems from the fact that conclusions may be drawn concerning the spin and parity assignments of the excited levels of the relevant nuclei from the value of the internal pair conversion coefficients and also the shape of the continuous spectra of the electron-positron pair. This may lead further, to information concerning the internal structure of nuclei in general.

At the time this present work was begun, the major aspects of the process had been well described in theory[1–4] and the work of Alichanov *et al.*[5] as well as of Rae[6] had demonstrated the feasibility of the experimental observation of the event. Both Alichanov and Rae utilized the 180° type β-ray spectrometer in their investigation, Alichanov in the case of the ThC″ and RaC, Rae in the case of Na^{24}, thus making effective use of the advantage of positron detection mentioned above. This same advantage may be utilized in a lens-type β-ray spectrometer by installing twisted vanes between the source and the detector conforming to the helical trajectories of the electrons (or positrons). In the lens-type spectrometer there is the further advantage that the transmission may be from ten to a hundred times larger than it is in simple semicircular type spectrometers.

With the above considerations in mind it seemed that the high luminosity and low instrumental scattering of the lens-type spectrometer[7] in this laboratory was well adapted, with a few minor modifications, to a detailed study of the phenomenon. Na^{24} was chosen for the subject of the study because of the apparent discrepancy between Rae's[6] deduction of an electric dipole character for the 2.758-Mev γ-ray (hereinafter to be referred to as γ_1), and the work of Brady and Deutsch,[8]

[1] J. C. Jaeger and H. R. Hulme, Proc. Roy. Soc. (London) **148**, 708 (1935).
[2] M. E. Rose and G. E. Uhlenbeck, Phys. Rev. **48**, 211 (1935).
[3] G. K. Horton, Proc. Phys. Soc. (London) **60**, 457 (1948).
[4] M. E. Rose, Phys. Rev. **76**, 678 (1949).
[5] G. D. Latyshev, Revs. Modern Phys. **19**, 132 (1947).
[6] E. R. Rae, Phil. Mag. **40**, 1155 (1949).
[7] H. M. Agnew and H. L. Anderson, Rev. Sci. Instr. **20**, 869 (1949).
[8] E. L. Brady and M. Deutsch, Phys. Rev. **74**, 1541 (1948).

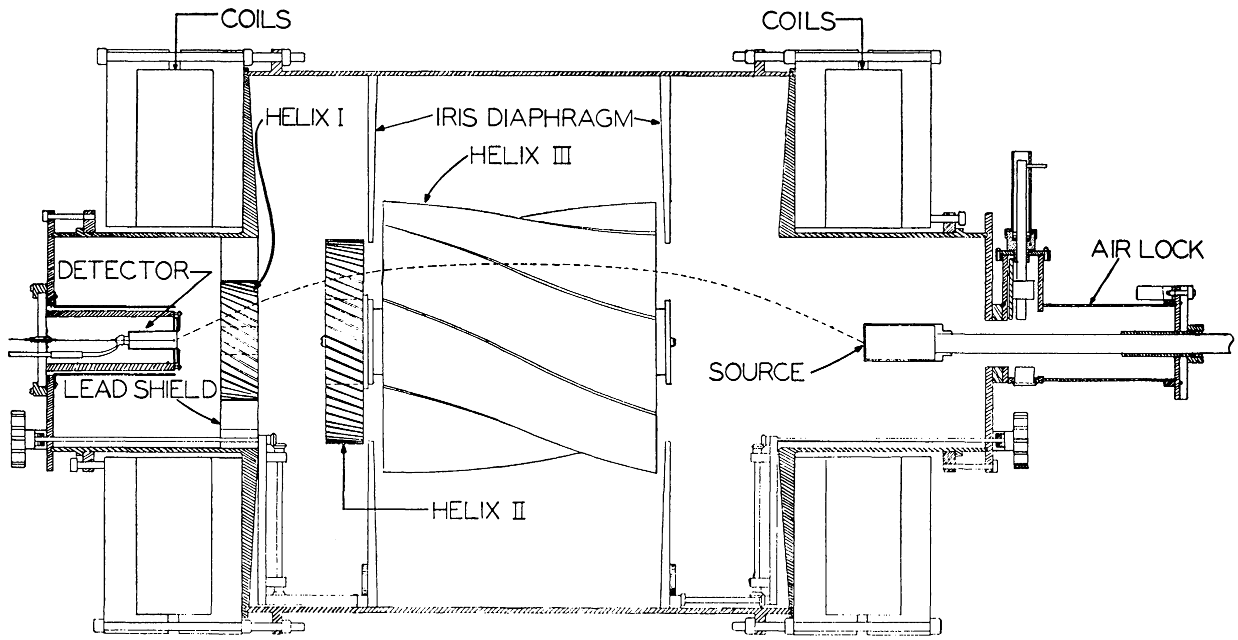

FIG. 1. Diagram of spectrometer.

who had studied the angular correlation of γ_1 and γ_2 (the 1.380-Mev γ-ray) by $\gamma-\gamma$ coincidences, and had found a scheme consistent with two electric quadrupole transitions. Furthermore, as yet the value of the internal pair conversion coefficient of γ_2 (hereinafter to be referred to as I_2) was unknown.

During the course of this work two experiments[9,10] were done which measured I_1 (the internal pair conversion coefficient of γ_1) using essentially the same technique as Brady and Deutsch.[8] In the paper of Cleland *et al.*[10] the results of these two experiments are combined in the value $I_1=(7.5\pm0.8)\times10^{-4}$, strongly suggesting the $E2$ (electric quadrupole) nature of γ_1. This may be compared with the results of this experiment and theoretical prediction by referring to Table I.

While the present work was in progress a similar investigation was carried out by Slatis and Siegbahn[11] for the case of Na^{24} as well as for ThC″, Mn^{56}, and Co^{60}, using a lens-type spectrometer. The method they used was the same, in the essentials, as the one used here, and is described below. They found the values $I_1=8.0\pm0.4\times10^{-4}$ and $I_2=3.0\times10^{-5}$. Although these values differ from the ones obtained here, they yet indicate clearly the $E2$ nature of γ_2 as well as γ_1 (see Table I).

It should be especially noted that in spite of the differences among the various values obtained for I_1 and I_2 in different experiments, with the one exception of Rae's work, they all agree as to the multipolar nature of γ_1 and γ_2. This can be understood from a glance at the graphs of I *versus* γ-ray energy for the various multipole orders as given by Rose.[4] The lower the energy the larger the difference, in percent of any particular coefficient, between coefficients for different multipolarities (see Table I). For γ_1, for instance, it is easy to discriminate between pure $E3$, $E2$, or $E1$ radiation, since I for these changes, respectively, in the ratio 1.0:1.5:2.4 (as predicted by Rose).[4] For γ_2, I (as predicted by Jaeger and Hulme)[12] varies by a factor of more than three from $E3$ to $E1$ radiation. However, I_2 is very low and must be expected to be measured with far less precision than I_1. Nevertheless, in this experiment, as in the experiment of Slatis and Siegbahn, the precision turned out to be adequate to indicate the $E2$ character of the γ_2 radiation. The same considerations apply to magnetic transitions and to comparisons between magnetic and electric transitions.

The possibility of mixed radiation (not considered in any of the above remarks) was examined in this work by comparing the positron spectrum with theoretically predicted spectra for various multipole orders, as well as by considering the absolute value of I.

SPECTROMETER

The beta-ray spectrometer used in this work was the instrument of Agnew and Anderson[7] with modifications to adapt it to the special purposes involved here. The basic outline of the spectrometer is given in Fig. 1. It is double-lensed, the source being located at the

[9] Mims, Halban, and Wilson, Nature **166**, 1027 (1950).
[10] Cleland, Townsend, and Hughes, Phys. Rev. **84**, 298 (1951).
[11] H. Slatis and K. Siegbahn, "*Determination of Multipole Orders from Internal Pair Formation*," *Manne Siegbahn; 1886–3/12–1951* (Almqvist and Wicksell, 1951), p. 153.

[12] See reference 1. The graphs for I *vs* γ-ray energy as given by Rose (reference 4) were calculated only as far down on the energy scale as $3m_0c^2$ (private communication from M. E. Rose).

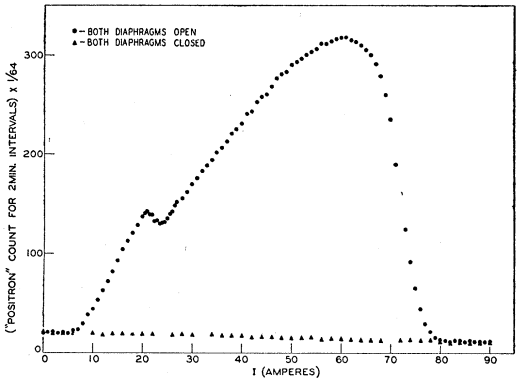

FIG. 2. Actual positron count *vs* current.

center of one coil and the detector at the center of the other coil.

The modifications consisted in the addition of a lead shield inside the spectrometer and two brass helices[13] (see Fig. 1), one of sixty leaves (Helix II), and the other of thirty-six leaves (Helix I). The nine-leaved helix (Helix III) originally in the machine was found to be inadequate for discriminating sufficiently between electrons and positrons. In a test run with P^{32} (before any additions were made to the spectrometer) it was found that with the current in the coils adjusted for positrons, a false "positron" spectrum was observed which roughly followed the shape of the negatron spectrum. The total number of these "positrons" was about 10^{-3} of the negatrons observed and actually consisted of electrons fortuitously scattered through the helix. The addition of the two brass helices and the lead shield in the positions shown (see Fig. 1) brought this figure down to less than 10^{-6}. This electron-positron discrimination ratio was more than sufficient, even for detecting γ_2 internal pair conversion.

A danger of drastically reduced transmission was involved in the use of these helices. Therefore, considerable care was taken to insure that the leaves of the helices were twisted to fit the shape of the trajectories for all values of the radial displacement (r) of the electrons from the axis of the spectrometer. The angle of rotation of the orbit (the angle through which the radial displacement vector moves as the electron moves along its trajectory) is approximately independent of r and is given[7] by

$$\theta_2-\theta_1=K\int_{z1}^{z2} H(z)dz,$$

where $\theta_2-\theta_1$ is the angle of rotation between z_1 and z_2, K is a constant, and $H(z)$ is the magnetic field along the axis. The $\frac{1}{32}$ in. thick brass leaves were made to conform to this turbine-like shape by being stamped between appropriately machined forms.

The original helix used had nine leaves and a $36\frac{1}{2}°$ rotation over its 39-cm length. If the fields in the region were altered so as to produce one degree more or less rotation than might be expected theoretically, its transmission would be reduced 2.74 percent, whereas for the same percentage errors in the fields at the regions of Helices II and I, the reduction would be 7.02 percent and 17.62 percent, respectively. Furthermore, the region over which the negatron or positron beam is spread (as defined by the iris diaphragms) is largest at Helix III and smallest at Helix I, so that the accuracy of the shape of the leaves at any particular value of r has the least effect in the former and the largest effect in the latter, as far as reducing the transmission is concerned. Actually, the transmission was reduced about 35 percent after Helices I and II were introduced. This is not too bad if it is considered that the introduction of Helix III alone reduced the transmission by 5 percent, according to Agnew and Anderson.[7] The combination of Helices I and II is about nine times as sensitive to field irregularities as Helix III and, furthermore, cuts off 16 percent of the beam by the cross section of the leaves alone.

The only other change was the addition of the lead shield in which Helix I was supported (see Fig. 1). This was introduced to shield against the background effects due to γ-radiation from the source hitting various parts of the spectrometer and scattering electrons into the counter or being scattered into the counter itself. A series of experiments using a 200-μC Co^{60} source was performed and the characteristics of this type of background were investigated. Co^{60} has two γ-rays (1.16 Mev, 1.32 Mev) and is therefore closely analogous to Na^{24} in that it would produce very much the same type of background as far as γ-radiation alone is concerned.

With the Co^{60} source it was found that when the current in the spectrometer coils was adjusted for positrons and a current survey made, a current-dependent background was found which was unchanged in character whether both or either one of the iris diaphragms (see Fig. 1) were completely closed or open. This meant that all current-dependent background effects due to the γ-radiation were produced by electrons scattered beyond the diaphragm closest to the counter. An experiment with the counter enclosed in a brass shield

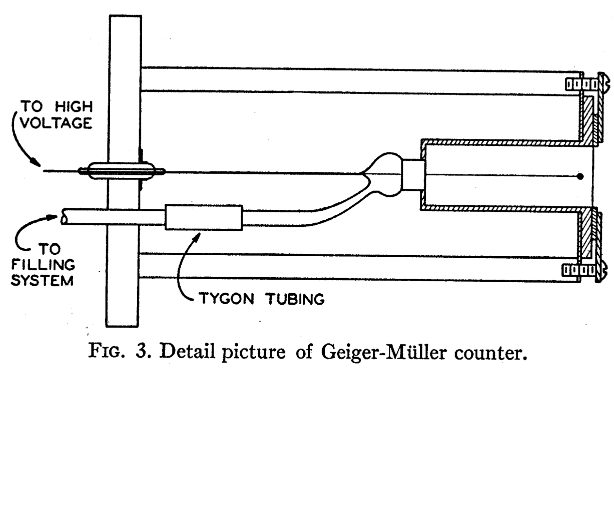

FIG. 3. Detail picture of Geiger-Müller counter.

[13] The original model for these helices was one made by Dr. M. Friedman of the Argonne National Laboratory.

showed that about $\frac{1}{3}$ of the background was due to these scattered electrons.

Because this type of background is independent of the opening or closing of the iris diaphragms, a genuine positron spectrum is corrected for background of this nature by closing the iris diaphragms, repeating the survey, and taking the difference of the two resulting spectra, which is the desired true positron spectrum. An important consideration when measuring the γ-background in this fashion is whether electrons or positrons can leak through small openings between the closed down iris diaphragm and the lead core (see Fig. 1). This contingency was provided against by arranging for the iris diaphragm closest to the counter to close down behind a $\frac{1}{4}$-in. high aluminum lip. Penetration through the iris diaphragm to the detector is quite unlikely, since at the openings used each iris diaphragm had a mean thickness of 0.635 cm ($\frac{1}{4}$-in. Al) except at the edges, where the thickness was that of the individual leaves ($\frac{1}{32}$ in.). The mean thickness corresponds to a range of 3.41 Mev for electrons (using a modified Feather's Rule),[14] more than twice greater than the maximum negatron energy involved here. The individual leaf thicknesses were enough to scatter the electrons so that they would not be detected. All this is also true for the positrons, since the same considerations apply to both.[15]

The introduction of the lead shield alone lead to a reduction in the γ-background by a factor of two. The addition, then, of Helix I accounted for an additional factor of two. This can easily be understood since all scattered electrons entering the window of the Geiger-Müller counter must first pass through the spiral leaves of Helix I, and few of them could be expected to have either the proper momentum or the proper orbit orientation. The effect of Helix II was negligible in this connection, which is consistent with the experimental evidence described above.

The high efficiency of this type of shielding against high energy γ-radiation background can be clearly seen from Fig. 2, which shows a plot of the actual number of counts counted on the Geiger-Müller counter *versus* the positron current, in the case of Na^{24}. The true positron count is, on the average, about ten times as large as the γ-background count obtained with both iris diaphragms closed. Since the magnitude of the positron effect in this case is 7×10^{-4}, it could be expected that under similar conditions spectra spreading over roughly the same momentum interval could be measured reasonably accurately down as low as 7×10^{-5}; and if the momentum interval should be shorter, the lower limit of the coefficient would be smaller but still determinable to a comparable accuracy.

In its final running condition the spectrometer had a transmission of 2.2 percent and a resolution of 10.23 percent. The poor resolution was largely the result of two factors: (1) The relatively wide openings used in the iris diaphragms (see Fig. 1); (2) The large size of the source (diameter = 1.2 cm). The wide opening of the iris diaphragms was necessary in order to have a high transmission, and the large size of the source was dictated by the need of having a low source thickness so as to distort the positron and negatron spectra as little as possible (see below).

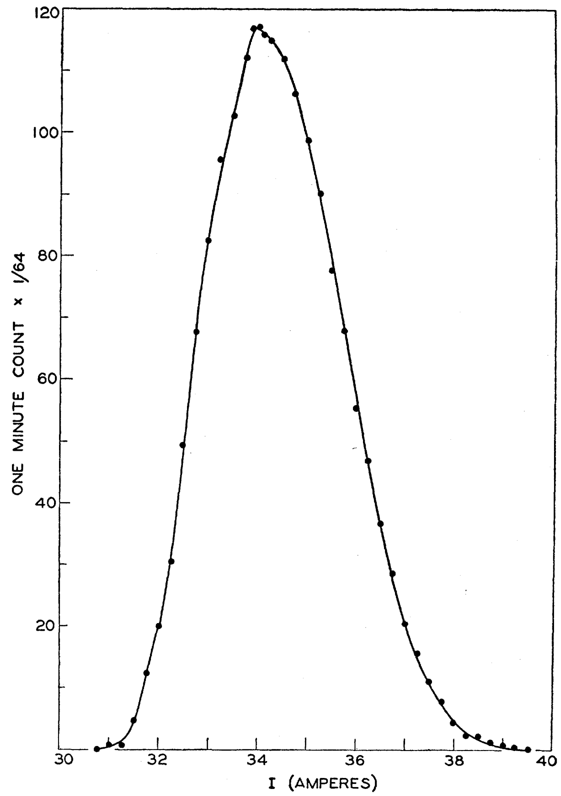

FIG. 4. Ba^{137} K-conversion line.

DETECTOR

The detector used was a Geiger-Müller counter (see Fig. 3) with a 1.19 mg/cm² window sealed in place with Araldite. The center wire was made of 5-mil platinum wire with a 2-millimeter bead on the unsupported end. The counter was pumped and filled *in situ*, since the window was too thin and too large to sustain atmospheric pressure.

Thin window counters (<0.1 mg/cm²) were tried in the initial phases of the experiment but abandoned because they necessitated the use of grids reducing the transmission by $\frac{2}{3}$ or more.

The counter had a plateau of 20-volts width using a filling mixture of ethyl acetate vapor (7 percent) and neon at a total pressure of 8.9 cm. Since batteries were used for the high voltage supply, the short plateau was no serious problem, although the region of the plateau did shift upwards for a period of a day immediately

[14] L. E. Glendenin, Nucleonics 2, No. 1, 12 (1948).
[15] W. Heitler, *The Quantum Theory of Radiation* (Oxford University Press, London, 1947).

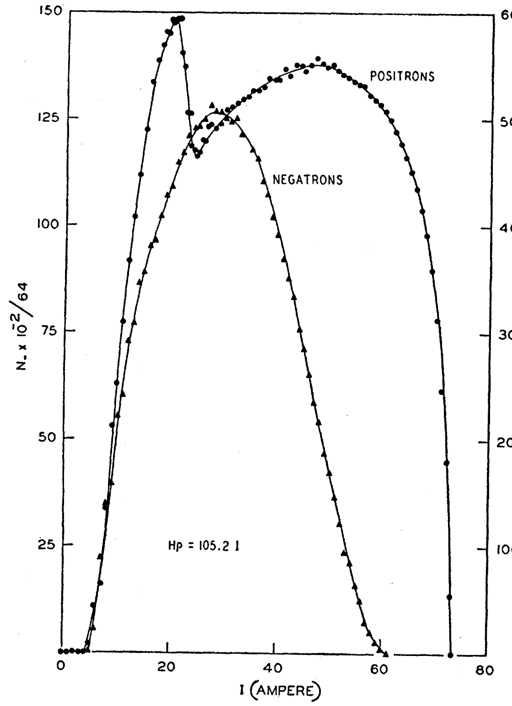

FIG. 5. Experimental negatron and positron momentum spectra (resolution corrected).

after filling. At the end of this period the counter remained stable for the rest of the experiment.

SOURCES

There were three sources used in the experiment. The first was the Na^{24} source, the second Cs^{137}, and the third Co^{60}. The cesium source was used for calibrating the spectrometer and for measuring its resolution, using the 0.6253-Mev K-conversion line[16] of Ba^{137}. The Co^{60} source was used in source and window thickness corrections (see below).

The Na^{24} source was deposited on an aluminum-coated Nylon film <0.08 mg/cm² in thickness, in the form of sodium fluoride solution. This solution was spread out over a circular area 1.2 cm in diameter, and, when dried, left a deposit of 4.5 mg of sodium fluoride. The effective thickness of the source, as derived from the Fermi plot of the beta-spectrum (see below), was indicated to be from 6–10 mg/cm². This was due to clumping of the NaF crystals. Because of this effect sources of larger area produced no significant decrease in effective thickness while sources of smaller area tended to pile the crystals on top of each other and increase the effective thickness.

The Nylon film backing was stretched on a light Bakelite frame[7] two inches in diameter and was made conducting by evaporating an aluminum layer on to it <0.02 mg/cm² in thickness. The edge of the foil was then grounded to the machine through a layer of Aquadag painted on one of the thin Bakelite columns supporting the frame.

Both the Cs^{137} and Co^{60} sources were made so as to be exact duplicates of the Na^{24} source in size and location, and were deposited on a similar backing. The shape of the Ba^{137} K-conversion peak is shown in Fig. 4. The resolution is 10.23 percent and $H\rho = 105.2I$, where

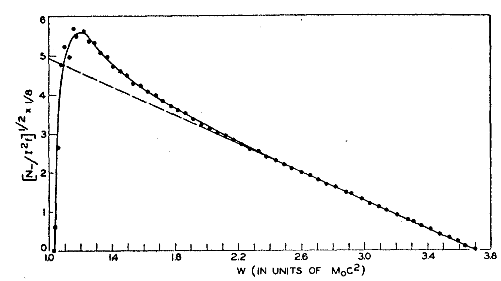

FIG. 7. Fermi plot of Na^{24} β^- spectrum.

I is the current in amperes. The formula for $H\rho$ is based on the assignment of the K-conversion kinetic energy[16] to the position of the peak at 34 amperes.

The activity of the Na^{24} at the beginning of the experiment was 2.5 millicuries and the activity of the Cs^{137} source was about 1.5 microcuries.

EXPERIMENTAL PROCEDURE

The experimental procedure used here consisted of a series of spectrometer current surveys of the radioactive emanations from Na^{24} and Mg^{24}. The first survey was that of the positron spectrum emitted by the excited states of Mg^{24}, the positron decay of Na^{24} being energetically impossible.[10] The second survey was that of the current dependent γ-produced background, conducted with both iris diaphragms closed down (see Fig. 1). The iris diaphragms were then reopened to their original aperature and the third survey was made on the negatron spectrum of Na^{24}. This last survey was conducted after a few days lapse, to allow the source to decay to an activity practicably observable. The observed spectra were then converted to momentum spectra (see Figs. 2 and 5), and procedures were intro-

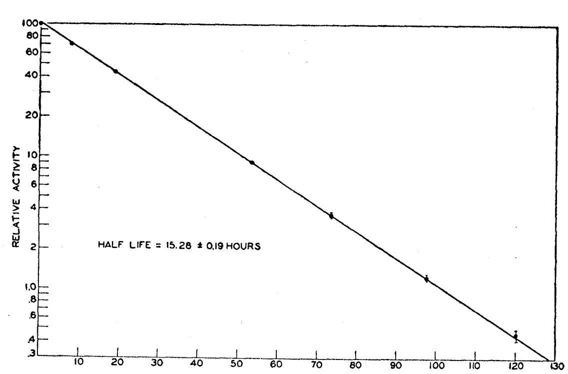

FIG. 6. Semilog plot of decay curve.

[16] L. M. Langer and R. D. Moffat, Phys. Rev. 78, 75 (1950).

duced (see below) to remove distortions due to source and window thickness and finite resolution. After a separation of the two overlaid positron spectra due to γ_1 and γ_2 (see below), a comparison of the areas of each of these spectra with the total area of the negatron spectrum gave numerical values for I_1 and I_2 (see Table I).

RESULTS

The experimental results are contained in Figs. 2 and 5. Figure 2 is a plot of the actual counts obtained as a function of current from the positron run, for the two conditions of the iris diaphragms open and closed. Figure 5 is a plot of the observed positron and negatron momenta spectra, the positron spectrum having first been corrected for γ-background in the manner described above. The data of both Figs. 2 and 5 are corrected for the counter background, which amounted to 10.3 counts per minute, and for radioactive decay back to a time about an hour before the actual beginning of the experiment. The half-life used in the decay correction was the latest published value, 15.06 hours.[17] The half-life of the source (checked after the spectrometer runs) was found to be 15.28±0.19 hours (see Fig. 6). The error is within range of Sreb's measurement.

The positron and negatron spectra in Fig. 5 are also corrected for the effect of resolution. This was done by

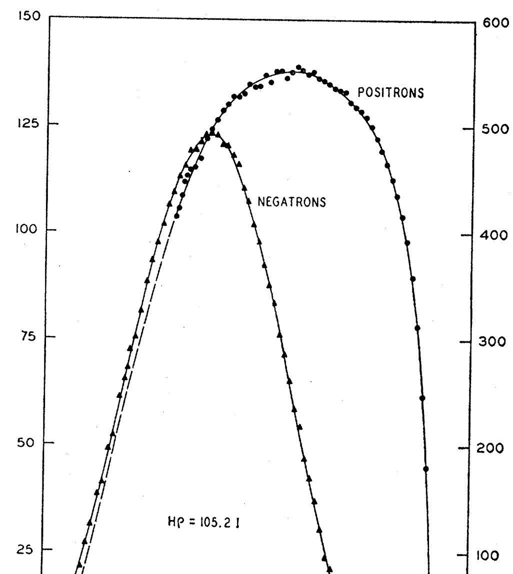

FIG. 8. Negatron and γ_1 positron momentum spectra of Na^{24}. Both spectra are corrected for source and window thickness distortion and resolution distortion. The extrapolation of the γ_1 positron spectrum below 24 amperes (0.36 Mev) is based on the method described under "Positron Spectra."

[17] J. H. Sreb, Phys. Rev. **81**, 469 (1951); he finds the half-life to be 15.060±0.039 hours.

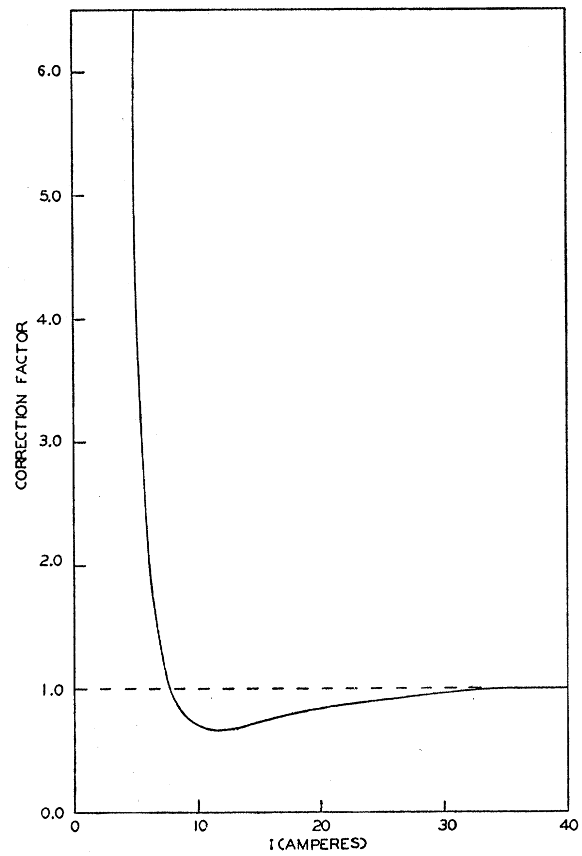

FIG. 9. Correction curve as derived from Na^{24} Fermi plot.

assuming a perfect-resolution shape for each spectrum and then folding it into the resolution curve (see Fig. 4). The resulting curve (i.e., the fold of the resolution curve and the assumed spectrum) should reproduce the observed spectrum in each case. This process was iterated until the actual spectrum and the derived one agreed to within about 1 percent, except in the vicinity of the end point where the agreement is necessarily more uncertain.

THE POSITRON SPECTRA

The observed positron spectrum is distorted by the effects of source and window thickness. This distortion has been corrected to some extent by studying suitable negatron spectra whose effective source thickness was made identical with that of the positron source and whose true shape is that given by the allowed Fermi distribution. The γ_1 positron spectrum was corrected with a correction function derived from the β^- spectrum of Na^{24}, which is emanated along with the γ_1 positrons from the same NaF source. The γ_2 positron spectrum was corrected with a function similarly derived from the β^- spectrum of Co^{60}.

The Fermi plot of the observed negatron spectrum (see Figs. 5 and 7) starts to depart from linearity at

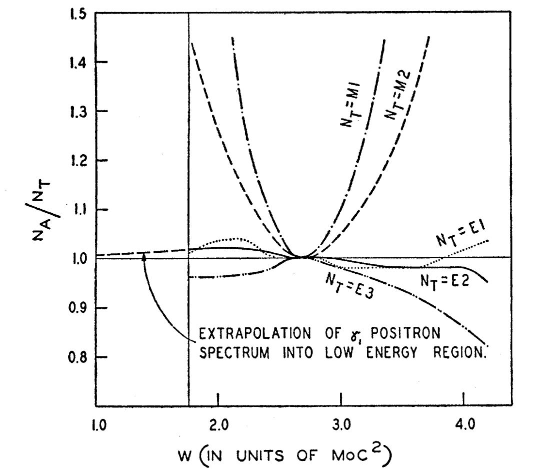

FIG. 10. Comparison of observed γ_1 spectrum and various theoretical spectra (see "Discussion" section).

about 0.7 Mev, whereas Siegbahn[18] showed with a thin source that the Fermi plot is linear down to energies at least as low as 0.2 Mev. This distortion is produced by the finite source thickness and is a combination of absorption and scattering effects. The correction function necessary to remove it should be approximately correct also for the γ_1 spectrum, since both these spectra have end points considerably beyond 0.7 Mev and, as will be shown, their shapes below this energy are roughly similar (see Fig. 8). Thus a correction function was derived from a comparison of the extrapolation of the straight line portion of the negatron Fermi plot and the observed Fermi plot (see Figs. 8 and 9), and applied to both the negatron spectrum and the γ_1-positron spectrum. In the case of the γ_1 positron spectrum this correction could not be applied below 0.36 Mev because of the presence of the γ_2 spectrum in this range, which made it necessary to separate the

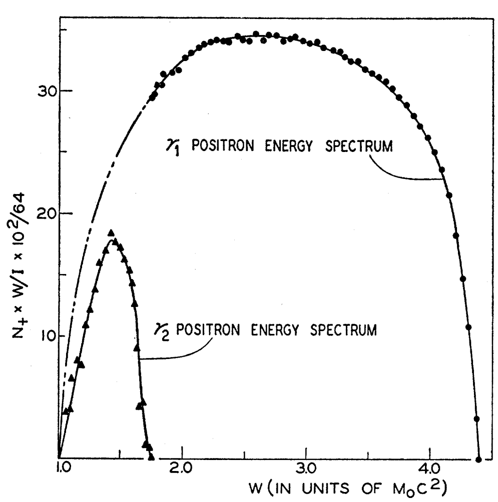

FIG. 11. Energy spectra of γ_1 and γ_2 positrons.

[18] Kai Siegbahn, Phys. Rev. **70**, 127 (1946).

spectra in order to calculate I_1 and I_2. To this end, the corrected γ_1-positron spectrum was referred to an appropriate theoretical spectrum and an extrapolation of the curve of this comparison was made from 0.36 Mev down to zero energy (see Fig. 10). The theoretical spectrum chosen was based on the $E2$ spectrum for a γ-ray energy of 2.76 Mev as predicted by Rose.[4,19] The appropriateness of this choice was well borne out by the results and is further discussed later in this report. The results of all these corrections are given in Figs. 8 and 11.

After the source and window thickness distortion correction and the extrapolation into the low energy region had been applied to the observed γ_1 spectrum, the inverse of the source and window correction function was applied to the corrected spectrum in order to gain an idea as to how much of an effect was involved. The uncorrected spectrum gave 5 percent more positrons than the corrected spectrum. Since the shape of the corrected negatron spectrum corresponds closely to the shape of the γ_1 positron spectrum, as extrapolated in its corrected form, in the region where the correction is necessary (see Fig. 8), it is felt that a 50 percent uncertainty in the correction of the γ_1 positron spectrum area is a liberal estimate, which means a probable error of 2.5 percent in the deduced value of I_1.

In order to obtain the positron spectrum due to γ_2, the extrapolated part of the γ_1 positron spectrum, uncorrected for source and window thickness distortion, was subtracted from the observed positron spectrum, uncorrected. In order to obtain some correction for the effect of source and window thickness, a source of Co^{60} was made up, of identical distribution and location as the Na^{24} source. A survey of the negatron spectrum was made at the original thickness, which was <0.1 mg/cm^2. Four and five-tenths mg of inactive NaF in aqueous solution was then added and, after the artificially thickened source was dry, a second survey was made. A comparison of the Fermi plots of these two surveys (see Fig. 12), identical with the type of comparison described above for the Na^{24} negatron spectrum, then produced a correction function (see Fig. 13) for the effect of source and window thickness, which was applied to the γ_2 positron spectrum. The corrected γ_2 momentum spectrum is shown in Fig. 14. It gave 7 percent more positrons than the uncorrected spectrum. Since the γ_2 positron spectrum and the Co^{60} β^- spectrum not only have different shapes but different end points, it can hardly be expected that the correction function is an entirely reliable one; however, it can be expected that the correction is in the right direction and of the proper order of magnitude, as far as the

[19] Rose's calculation uses the Born approximation ($Z=0$), whereas in the present case the emitted nucleus (Mg) has a positive coulombic charge of $12e$. The Z-dependence was inserted by multiplying his formula by the factor

$$f(\xi_+, \xi_-) = \frac{(2\pi\xi_+)(2\pi\xi_-)}{(e^{2\pi\xi_+}-1)(1-e^{2\pi\xi_-})},$$

where $\xi_+ \equiv Ze^2/\hbar v_+$ (see reference 15).

calculation of I_2 is concerned. The energy spectrum with the correction included is given in Fig. 11.

The shape of the derived γ_2 spectrum and its total integrated value is also affected by the degree of accuracy of the extrapolation of the γ_1 positron spectrum. This statement applies to the γ_1 spectrum as well, but to a different degree, the γ_2 positron spectrum being about ten times as sensitive to extrapolation inaccuracy as the γ_1 spectrum. Also, the two are oppositely affected, a too high answer in I_1 giving a too low answer in I_2, and vice versa. In order to ascertain how much of a change a different extrapolation would cause in the values of I_1 and I_2, it was assumed that below 0.8 Mev the shape of the observed γ_1 spectrum should correspond exactly to the theoretical $E2$ spectrum (see Fig. 10). On the basis of this extrapolation the deduced value of I_1 was decreased 1 percent and that of I_2 was increased 12 percent, which magnitudes give a reasonable estimate as to the uncertainties in I_1 and I_2 due to this correction.

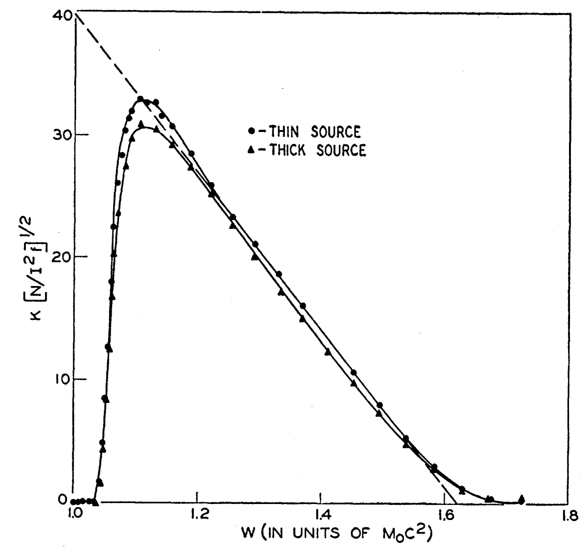

FIG. 12. Fermi plot of thin and thick Co^{60} sources.

EXTERNAL PAIR-PRODUCTION

The errors due to external pair-production (within the source itself) amounts to less than 0.1 percent for both I_1 and I_2. This estimate is based on the values of the cross section for pair-production as calculated from the Bethe-Heitler formula[15] and an assumed effective thickness of 8 mg/cm^2 for the NaF source. The effective source thickness was estimated by comparing the Fermi plot obtained here (see Fig. 7) with Fermi plots obtained with similar sources of known uniform thickness. The energy at which deviation from the straight line Fermi plot began was assumed to be proportional to the effective source thickness, and a value was calculated for the effective source thickness of the NaF source used in this experiment. This is a very rough approach, but for the purposes involved here it was quite adequate. It generally gave values far in excess of the average thickness (3.9 mg/cm^2), although these values were quite scattered. Two criteria used in selection were (1) that the sources should be of the same order of magnitude thickness as the average thickness of the NaF source used in this experiment; (2) that the energy end point of the spectrum should be greater than 1 Mev. With reference to criterion (2) it should be pointed out that it was felt that electrons or positrons whose energies were greater than 1 Mev contributed little to distortions in the Fermi plot beginning at energies equal to or less than 0.7 Mev, as was the case here (see Fig. 7). For this reason it could be expected that the results of this method should be fairly insensitive to the energy end point of the Fermi plot used for comparison, and this was found to be the case. The figure obtained by this method was 8 ± 2 mg/cm^2.

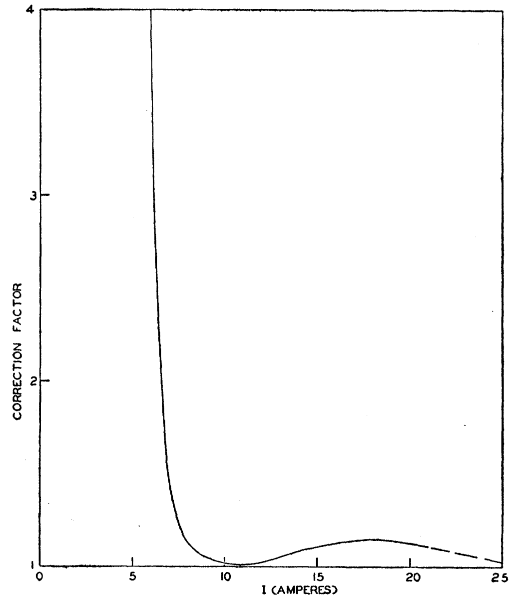

FIG. 13. Correction curve as derived from Co^{60} Fermi plot.

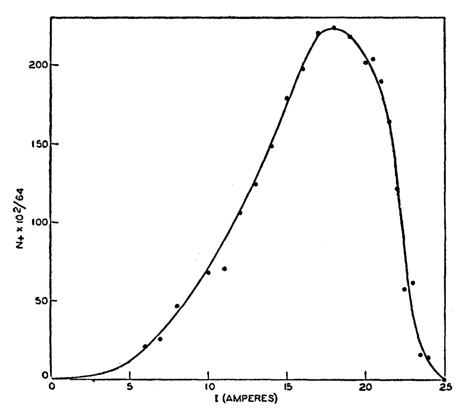

FIG. 14. γ_2 positron momentum spectrum.

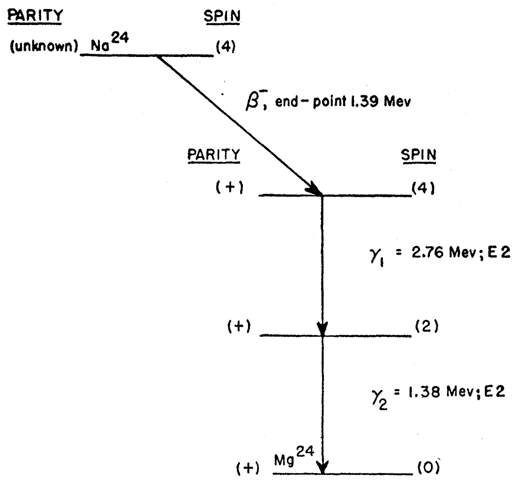

FIG. 15. Energy level diagram for decay of Na^{24}.

SOURCE CONTAMINATION

Since the half-life determination was carried out over a period of thirteen days after the beginning of the spectrometer runs and since, in that time, the source did not exhibit a half-life significantly different from the expected one (see Fig. 4), the contamination level of long-lived positron emitters (such as Na^{22}) must have been of the order 10^{-6}, during the time of the positron run. Such contamination could cause at most an error of the order of 0.1 percent in the value of I_1 or 1 percent in the value of I_2. Since these errors are insignificant compared to the actual uncertainties, they have been ignored.

2.758-Mev γ-Ray (γ_1)

The internal pair conversion coefficient of γ_1 was computed by taking the ratio of the area of the γ_1-positron spectrum to the area of the negatron spectrum, both spectra being corrected for source and window thickness distortion and resolution distortion (see Fig. 8). The result was

$$I_1 = (7.1 \pm 0.2) \times 10^{-4}.$$

The error given is that due to uncertainty in the correction for source and window thickness distortion, and errors in the low energy extrapolation of the γ_1 positron spectrum, both of which have been estimated above.

The observed momentum and energy spectra, after corrections for source and window thickness spectral distortion and resolution distortion, are given in Figs. 8 and 11.

The end point of the γ_1 positron spectrum, after resolution distortion correction, was found to be 1.73 ± 0.02 Mev. This is in good agreement with what is to be expected from the γ-ray energy,[18] 2.758 Mev, after subtracting $2m_0c^2$.

1.380-Mev γ-RAY (γ_2)

By taking the ratio of the corrected γ_2 spectrum area (Fig. 14) to the corrected negatron spectrum area (Fig. 8), the internal pair conversion coefficient for γ_2 was found to be

$$I_2 = (0.6 \pm 0.1) \times 10^{-4}.$$

The error given is much larger than that for I_1 because of the much greater uncertainties in the correction for source and window thickness and in the extrapolation of the high energy spectrum. For the same reasons the localization of the end point of the γ_2 spectrum is less certain than for the γ_1 spectrum. The measured end point was (0.35 ± 0.02) Mev. The error includes the end-point energy to be expected from the γ-ray energy,[18] 1.380 Mev, after subtracting $2\ m_0c^2$.

DISCUSSION

A comparison of the measured values of I_1 and I_2 with the theoretical values to be expected for various pure multipolar transitions, as shown in Table I, and the fact that only odd electric and even magnetic transitions may occur between states of different parity, while even electric and odd magnetic transitions may occur only between states of the same parity, limits the possibilities for γ_1 to the following two: 1. Pure $E2$. 2. Mixture of $E1$, $E3$, and $M2$. The experimental observations of Brady and Deutsch,[8] who found the $\gamma_1 - \gamma_2$ angular correlation consistent with two electric quadrupole transitions, indicate that the radiations should be pure $E2$ for both γ-rays. The conclusion that γ_1 is an $E2$ transition is a result also of a comparison of the γ_1 positron energy spectrum, as measured in this experiment, with various theoretical energy spectra of pure multipolar transitions as predicted by Rose,[4] with an added correction for the effect of the Coulomb field of the Mg^{24} nucleus (see above). The results of this comparison are shown in Fig. 10, which is the plot of the ratio of the observed energy spectrum (N_A) to various theoretically predicted energy spectra (N_T) as a function of energy, for all energies from 0.36 Mev to close to 1.73 Mev. This plot shows that only two theoretical spectra, those for $E1$ and $E2$, have a close resemblance to the observed shape. However, any mixture of $E1$, $E3$, and $M2$ arranged to yield the observed value of I_1 will produce a theoretical spectrum differing far more from the observed spectrum than the pure $E2$ spectrum, aside from deviations near the end-point, which are relatively large in all cases. Thus we see that the pure $E2$ spectrum provides the best fit to the data of all possible combinations.

In the case of γ_2 the value of I_2 seems to limit the possibilities to pure $E2$ radiation alone. However, we cannot substantiate this by a comparison with theoretical spectra because of distortions affecting the entire observed spectrum. Nevertheless, the evidence for pure $E2$ radiation as against other alternatives is very persuasive, since the $\gamma_1 - \gamma_2$ angular correlation is also characteristic of an $E2$ transition. Thus we make the assignment of pure $E2$ radiation in the case of γ_2 as well as γ_1. This conclusion is very much in line with the recently published work of Goldhaber and Sunyar,[20] who find that the first excited state of about 30 even-even nuclei has spin 2 and + parity (all spin 0 and + parity in the ground state).

Figure 15[21] summarizes the conclusions of this section.

[20] M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).

[21] D. E. Alburger and E. M. Hafner, Revs. Modern Phys. **22**, 373 (1950).

No conclusions from the data in this experiment can be derived as to the parity of Na^{24}. The spin assignment of Na^{24} comes from the recent work of Smith.[22]

I should like to express my profound gratitude to my sponsor, Professor H. L. Anderson, whose interest and encouragement made possible this work.

I would also like to express my thanks to C. Y. Fan, David Saxon, M. Goldberger, and M. Friedman for their generous help.

[22] K. F. Smith, Nature **167**, 942 (1951).

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Rocket Determination of the Ionization Spectrum of Charged Cosmic Rays at $\lambda=41°$N

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In a V-2 rocket measurement at $\lambda=41°$N an analysis has been made of the various components of the charged particle radiation on the basis of ionization and absorption in lead. The ionization was determined by two proportional counters, the particle paths through which were defined by Geiger counters. With increasing zenith angle toward the north, the intensity is found to be substantially constant until the earth ceases to cover the under side of the telescope. The intensity of all particles with range ≥ 7 g/cm² is 0.079 ± 0.005 (cm² sec steradian)$^{-1}$. Of this an intensity 0.012 ± 0.002 is absorbed in the next 14 g/cm². The ionization measurement is consistent with $\frac{3}{4}$ of these soft particles being electrons of $<\sim 60$ Mev, the remainder being slow protons and alpha-particles. For the particles with greater range an ionization histogram is plotted, the smaller of the two ionization measurements for a single event being used to improve the resolution. The particles divide into protons, alpha-particles, and one carbon nucleus, with $N_p/N_\alpha=5.3\pm1.0$. Their absorption is exponential with mean free path 440 ± 70 g/cm² Pb. Extrapolating to zero thickness, the total primary intensity is 0.070 ± 0.005 (cm² sec steradian)$^{-1}$ with 0.058 ± 0.005 as protons, 0.011 ± 0.002 as alpha-particles, and 0.001 ± 0.001 as $Z>2$.

INTRODUCTION

THIS paper reports on some measurements made on February 17, 1950, by apparatus flown in a V-2 rocket. The launching occured at White Sands, New Mexico (geomagnetic latitude 41°N). The purpose was to distinguish among and count the various components of the charged particle cosmic radiation above the atmosphere. For each particle which entered the solid angle of a Geiger tube telescope, the ionization was measured twice, using proportional counters for the purpose. The subsequent history of each particle in traversing lead absorbers was then recorded. In this way the poor statistics of a rocket flight were somewhat compensated by detailed knowledge of each recorded event.

THE EXPERIMENTAL METHOD

Figure 1 shows the telescope schematically. The rocket nose in which it was mounted was a conical shell of $\frac{1}{16}$-inch Al joining at the wide end and about halfway down the telescope to an Al cylinder $\frac{1}{8}$-inch thick. The coincidence ABC (which we shall abbreviate as T) defined a beam of particles which traversed the proportional counters P_1 and P_2. No event of any sort was registered unless the threefold T occured coincidently. The discharge of either group S_1 or S_2 indicated a "side" shower, as did the discharge of both counters A_1, A_2 comprising tray A or C_1, C_2 of tray C. The side showers were presumably undesired events but were registered for information. Counter trays D, E, and F beneath their respective lead absorbers covered the solid angle of T with some overlap. Thus, each selected particle was interrogated as to its range in lead within certain limits. Trays D and E were further subdivided into threefold sets and tray F into a fourfold set. In this way showers produced in the absorbers could be detected, provided of course that T was tripped.

The proportional counters contained argon with 2 percent of CO_2 and were filled to atmospheric pressure. Figure 2 is a plot of multiplication *vs* voltage obtained by irradiating the active region with γ-radiation and measuring the current with a vibrating reed electrometer. The counters behaved identically, although this was actually not essential to the reduction of flight data. The counters were operated finally at a multiplication $\sim$2000. The stability of voltage was not a problem at any time.

The electronic coincidence circuits were of the diode

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