Gamma-Rays Emitted During the Radioactive Transitions $Sb^{124} \rightarrow Te^{124}$ and $Na^{24} \rightarrow Mg^{24}$

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Pair electrons observed in a cloud chamber provide the most accurate means of measuring gamma-ray energies, provided suitably rigid criteria of the selection of valid pairs are followed. The gamma-ray energies here reported were deduced from stereoscopic photographs of pair electrons formed in the gas of a cloud chamber. The magnetic field was known in absolute value to 1 percent or less and in relative value was constant to 0.2 percent or less. The radius of the electron tracks was measured by a special measuring engine. Careful collimation between the source and the cloud chamber was found necessary.

$Sb^{124} \rightarrow Te^{124}$

An examination of the gamma-rays emitted during the nuclear transition $Sb^{124} \rightarrow Te^{124}$ reveals a single monochromatic gamma-ray of energy 1.70 ± 0.02 Mev. This agrees with the beta-ray spectra observed by other experimenters. The pair production method of measuring gamma-ray energies is found to be accurate to ± 0.02 Mev provided care is taken in the selection of pairs.

$Na^{24} \rightarrow Mg^{24}$

Eleven thousand pictures yielded 56 pairs which satisfied the selection rules. Twelve of these pairs showed no observable scattering and indicate four gamma-ray lines at 2.56, 2.68, 2.76 and 2.89 Mev. Another pair indicates a weak line at 3.24 ± 0.1 Mev. These data are correlated with data on the beta-ray spectra and allow a term scheme for the nuclear transition $Na^{24} \rightarrow Mg^{24}$ to be proposed. The relative intensities of beta-ray and gamma-ray spectra are not incompatible, and the mass difference between the ground states of Na^{24} and Mg^{24} is in good agreement with the proposed term scheme.

THEORETICALLY the pair production method of measuring gamma-ray energies is ideal because of the high resolution which may be expected and the small number of observed pairs necessary to give a gamma-ray energy to within a few hundredths of a million electron volts. The method has been used in this laboratory[2] and has been tested by Groshev,[3] but it was thought worth while to do further work along these lines and to search for a radioactive source which emits a single monochromatic gamma-ray. From an examination of the literature it seemed that radioactive Sb and Na would be suitable sources to examine.

I. THE EXPERIMENTAL METHOD

The Wilson cloud chamber used in these experiments was eight inches in diameter and about one and one-half inches deep. It was constructed by W. E. Shoupp after the design of Crane.[4] The chamber was filled with air and a mixture of alcohol and water vapors, at atmospheric pressure. The ratio of alcohol to water was 3.5 to 1, and 27 cubic centimeters of liquid was used.

The field current was turned on eight seconds before expansion. In the runs on sodium it reached 74.8 amperes in about five seconds, and was held constant by an automatic regulator until about two seconds after the expansion. The regulator kept the current constant to ± 0.1 ampere. The ammeter used was calibrated by means of a standard resistance and a Wolff potentiometer and was found to read 75 when the current was 74.8 amperes. During the runs on antimony the current was kept at 49.9 amperes, which corresponds to a 50 amp. reading on the ammeter.

Stereoscopic pictures of the tracks were taken by a mirror system previously described.[5] An air-operated camera built by the University of Illinois physics department shop, and having an $f/2$ lens was used. The exposure time was between $\frac{1}{5}$ and $\frac{1}{10}$ of a second.

A G.E. high pressure mercury arc type H-6 was used as a source of illumination. The arc was run continuously, and a solenoid operated shutter was used to illuminate the chamber just before the expansion.

[1] Now engaged in military research.
[2] Kruger, Stallmann, and Shoupp, Phys. Rev. **56**, 297 (1939).
[3] Groshev, J. Phys. Acad. Sci. U.S.S.R. **5**, 135 (1941).
[4] Crane, Rev. Sci. Inst. **8**, 440 (1937).
[5] Kruger, Shoupp, and Stallmann, Phys. Rev. **52**, 678 (1937).

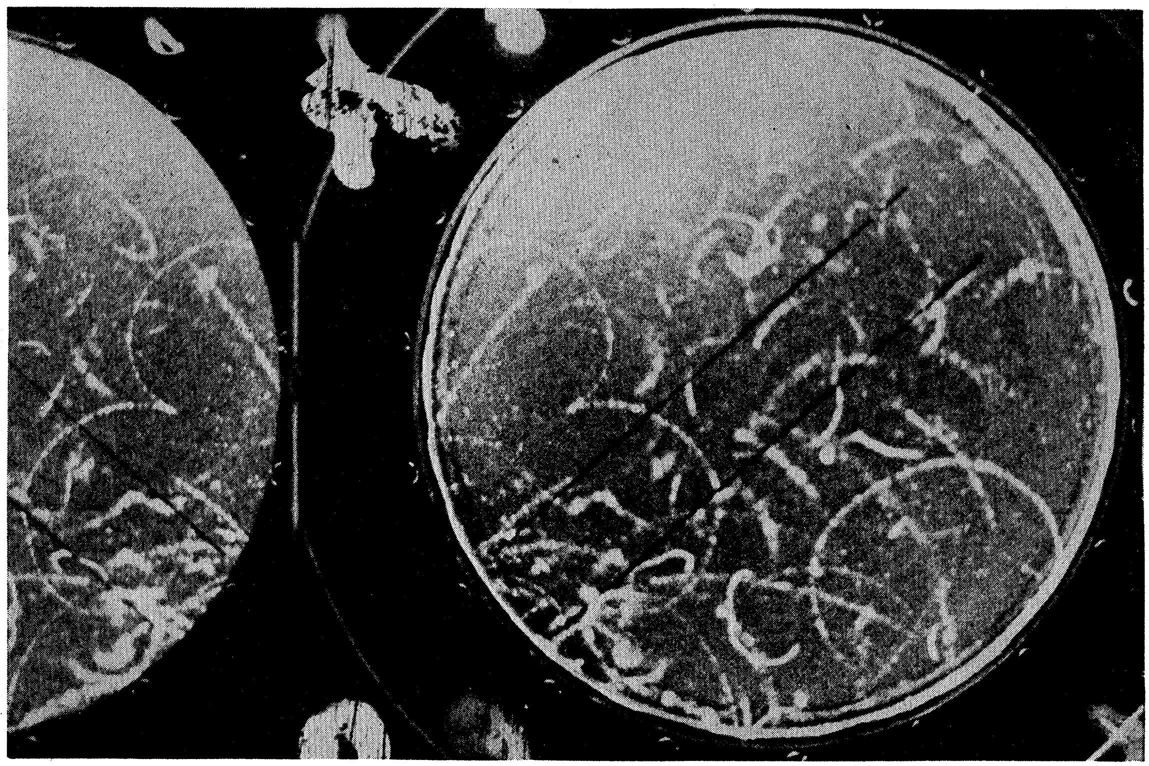


FIG. 1. Electron pair (No. 1 in Table I) produced by gamma-rays from radio-antimony. The magnetic field is 703 oersteds. The gamma-rays are collimated in the direction of the ruled lines which cross the picture and enter from the lower left side.

The Super XX film used was developed seven minutes in Kodak D-11, fixed 20 minutes in F-5, washed 30 minutes, wiped with viscose sponges and allowed to dry.

The gamma-rays were collimated perpendicular to the magnetic field and in the median plane of the cloud chamber by means of a slit 1″ wide, $\frac{1}{2}$″ high, and 44″ long through a lead block. The region in which unscattered gamma-rays could form pairs in the chamber was outlined on the glass top of the chamber in ink so that it appeared in the pictures (Figs. 1 and 2). Pairs were readily located, since it was easy to see the positron track coming out of this region into a clear space relatively free of Compton electron tracks. There were a few Compton electrons, owing to scattered gammas from the wall of the chamber formed in the clear region to one side of the collimated beam, but this did not cause any confusion.

The pictures were examined first by means of a Spencer Delineascope and any possible pairs picked out. These pictures were marked. Then they were projected through the same optical system of camera and mirrors with which the pictures were taken. The pictures were brought into focus on a ground glass screen and a careful examination of each pair was made.

The criteria used to select a pair as valid data are as follows:

1. Both tracks must be in the same plane, and that plane must lie within 10° of a plane through the median plane of the cloud chamber and perpendicular to the magnetic field.
2. Both tracks must lie within a 20° solid cone of the forward direction.
3. The initial angle between the paths of the pair electrons must be less than 25° unless the electron has so much more energy than the positron that large angle scattering can be ruled out.
4. Both tracks shall start at the same point and be of the same age as determined by the diffuseness of the track.
5. There can be no obvious scattering in the track over the region in which the radius of curvature is measured.

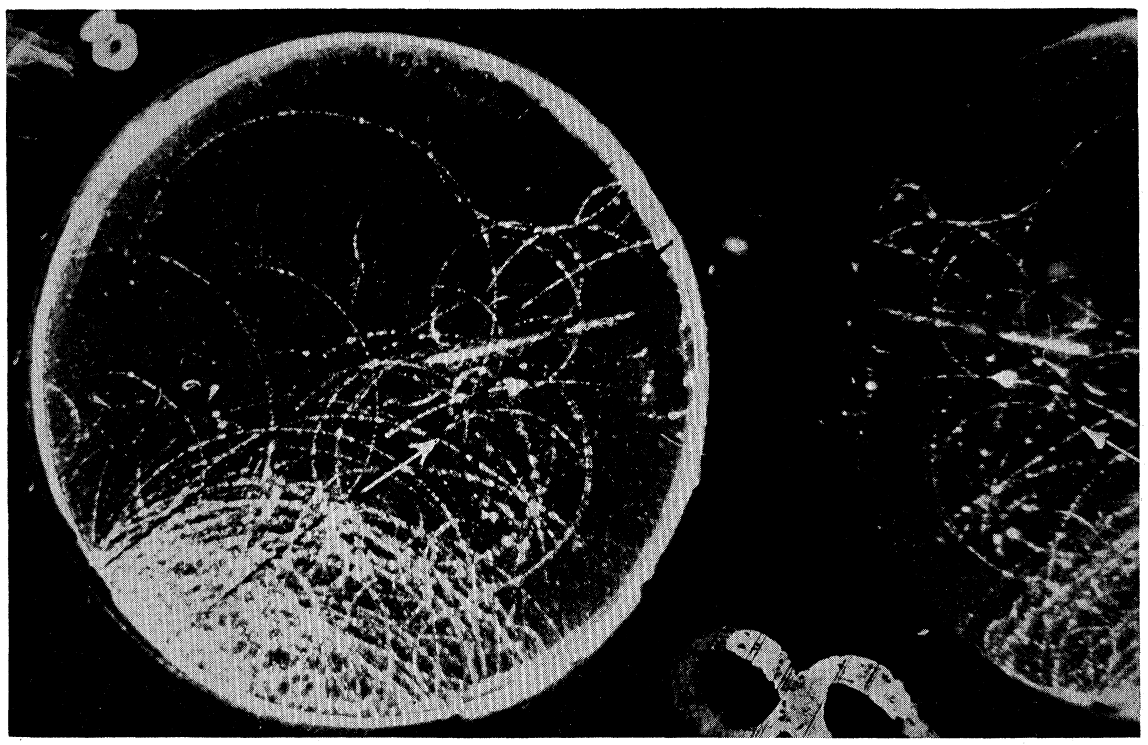


FIG. 2. Electron pair (No. 89 Class AA, Table III) produced by gamma-ray from radium-sodium. The magnetic field is 1055 oersteds. Other conditions are the same as those in Fig. 1. The effect of collimation is clearly evident.

A measuring engine which determined the chord and the sagitta of the arc of the track was used to find the radius of curvature of each track. The engine was calibrated by means of a comparator. The radius of curvature of an electron track is given by

$$r=(c^2/4+s^2)/2s,$$

where c is the length of the chord and s is the corresponding sagitta length.

Several (two or more) independent sets of measurements on each pair were taken and the probable error in measurement for each pair was calculated from these data. The pairs were then ranked inversely as their probable error, and weighed accordingly.

The energy of the gamma-ray is then given by

$$E=mc^2[(B_1{}^2+1)^{\frac{1}{2}}+(B_2{}^2+1)^{\frac{1}{2}}],$$

where

$$B=Hre/mc^2,$$

and the subscript 1 refers to the electron and 2 to the positron. Here Hr is the product of the radius of curvature of the track and the magnetic field strength, e is the charge on the electron, and mc^2 is the self-energy of the electron. In these calculations the following values were used:

$$mc^2=81.83\cdot 10^{-8}\text{ ergs}=0.5108\text{ Mev.}$$
$$e=4.8025\cdot 10^{-10}\text{ e.s.u.}$$

The magnetic field caused by the cloud chamber coils was measured by a method involving the use of a flip coil, 6″ in diameter, connected in series with a standard mutual inductance and a ballistic galvanometer whose period was long compared to the time necessary to flip the coil. The breaking of a known current in the primary of the mutual inductance produced a deflection of the galvanometer that could be compared to the deflection produced by flipping the coil in the magnetic field. From these data the field intensity was calculated. The area of the flip coil was known with an error of less than 0.1 percent. The standard mutual inductance was calibrated by the National Bureau of

TABLE I. Pairs produced by gamma-rays from the nuclear transition $Sb^{124} \rightarrow Te^{124}$.

Pair number	Pair class	Hr^+	Hr^-	E^+ Mev	E^- Mev	E Mev
1	*C*	1974	2527	0.271	0.403	1.70±0.03
2	*B*	1959	2570	0.267	0.414	1.70±0.02
3	*AA*	1355	3046	0.142	0.535	1.699±0.002
4	*A*	2383	2289	0.367	0.345	1.73±0.01
5	*D*	1915	2345	0.258	0.359	1.64±0.05

Standards. Magnetic field measurements were made at 74.8 amp. before the pictures were taken and were checked at 74.8 amp. and 49.9 amp. at the end of the experiment. These measurements gave field values of 1055±0.4 percent oersteds at 74.8 amp. and 703±0.4 percent oersteds at 49.9 amp. Thus, the absolute value of magnetic field should be accurate to 1 percent.

II. THE GAMMA-RAY SPECTRUM OF $Sb^{124} \rightarrow Te^{124}$

The gamma-rays from $Sb^{124} \rightarrow Te^{124}$ have been examined by Mitchell, Langer, and McDaniel,[6] and by Klaiber and Scharff-Goldhaber[7] who reported 1.82 Mev and 1.75 Mev respectively for the gamma-ray energy. The beta-ray spectrum has been examined by Mitchell, Langer, and McDaniel,[6] and by Hales and Jordan,[8] the latter reporting beta-rays of 0.74 Mev and 2.45 Mev, so that a single gamma-ray of energy 1.71 might be expected.[9] The establishment of a standard monochromatic gamma-ray source would be valuable in many nuclear physics experiments.

The radioactive Sb was prepared in this laboratory by bombarding chemically pure Sb powder with 10-Mev deuterons. The estimated bombardment was 600±200 μamp. hours. In such a bombardment the following nuclear reactions may take place:

$$Sb^{123}(d, p)Sb^{124};\ Sb^{123}(d, n)Te^{124};\ Sb^{121}(d, p)Sb^{122};\ Sb^{121}(d, n)Te^{122};\ Sb^{121}(d, 2n)Te^{121}.$$

Thus, after bombardment, it was necessary to separate chemically the radioactive Te from the radioactive Sb. After separation the Sb source was aged for 2 weeks to reduce the Sb^{122} (2.8 day half life) to less than 1/50 of its original activity. A measurement of the activity of the Sb source after ageing showed that about 1 mC of radio antimony was obtained.

Twelve thousand pictures taken with the Sb source in the Pb collimator and 50-cm distance from the cloud chamber, yielded the five pairs listed in Table I. The magnetic field was 703 oersteds.

The error given is the probable error, calculated from several measurements on the same pair made along different parts of the positron and electron tracks. That is, the radius of curvature was measured close to the vertex, further along close to the center, and at the end of the track. Thus, the probable error, as given, is a measure of the error introduced by small angle scattering. These probable errors are in agreement with that which would be expected from the theory of small angle scattering. The weighted (see weights in the sodium data) average value of E_γ from the data in Table I is 1.70±0.01 Mev. Since the magnetic field has a probable error of one percent, the absolute value of E_γ is 1.70±0.02 Mev.

Of the pairs reported in Table I, numbers 1, 2, and 3 satisfy all of the criteria set forth above. Pair No. 4 satisfies all criteria except criterium No. 2, i.e., pair No. 4 was formed in the backward direction. Pair No. 5 satisfies all criteria except criterium No. 5. Because of the relatively large probable error it is clear that serious small angle scattering has occurred. The pair classification in Column 2 of Table I is made on the basis of the probable error for each track.

From these data it is clear that with careful selection of tracks following the criteria stated above, the spread of pair energies from a monochromatic gamma-ray is small, in this case 0.01 Mev so that it is possible to resolve gamma-ray lines as close as 0.05 Mev apart.

In conclusion, from the data of Hales and Jordan[8] and from these data, it appears that Sb^{124} decays with two beta-rays, one to the ground state of Te^{124} and one to an excited state of Te^{124} which is 1.70 Mev above the ground state. The

[6] Mitchell, Langer, and McDaniel, Phys. Rev. **57**, 1107 (1940).
[7] Klaiber and Scharff-Goldhaber, Phys. Rev. **61**, 733 (1942).
[8] Hales and Jordan, Phys. Rev. **62**, 553 (1942).
[9] Because of the 0.069 Mev gamma-ray reported by Mitchell, *et al.*, there is the possibility of a gamma-ray at 1.78 Mev, which from our data, if it exists, must be less than $\frac{1}{5}$ as intense as the 1.71 Mev line.

observed gamma-ray of 1.70 Mev results from a transition from the excited state of Te^{124} to the ground state of Te^{124}. The gamma-ray apparently is monochromatic.

The energy of the Sb gamma-ray here reported is also in agreement with that reported by Scharff-Goldhaber and Klaiber.[10] They deduced the gamma-ray energy from energy measurement on recoil protons, produced by photo-neutrons which were ejected from beryllium by gamma-rays from radio-antimony. The value they obtained was 1.75 ± 0.04 Mev.[11]

Fig. 1 shows a picture of a pair produced by Sb gamma-rays.

III. THE GAMMA-RAY SPECTRUM OF $Na^{24} \rightarrow Mg^{24}$

The gamma-rays of Na^{24} have been studied by many investigators[12–18] who have reported various gamma-ray energies between 0.8 Mev and 3.0 Mev. Only recently have the reported γ-ray energies come into near agreement. For this reason it was considered advisable to make another study, employing the pair production method, to determine the gamma-ray energy more accurately and to see if the gamma-ray lines were single or complex.

The Na^{24} used in these experiments was produced by bombarding c.p. NaF with 10-Mev deuterons in this laboratory. Each bombardment yielded about 200 mC of Na^{24}. Radioactive F^{20} was produced at the same time by the d, p reaction. The source was aged about an hour before pictures were taken, and it was used until it decayed to about 30 mC. The half-life of radioactive fluorine is about 13 seconds, so no contamination should be introduced by the fluorine.

With the sodium source placed in the lead collimator at an average distance of 1 meter from the cloud chamber, 11,000 pictures were taken. These yielded about 200 pairs, of which 56 satisfied the selection rules and were accepted

TABLE II. Experimental data on positron-electron pairs (Mg^{24} gamma-rays).

E^+ is the kinetic energy of the positron in Mev.
E^- is the kinetic energy of the electron in Mev.
E_γ is the energy of the gamma-ray from E^+ and E^-.

Pair number	E^+	E^-	$E^+/(E^++E^-)$	E_γ
15	0.749	0.994	0.45	2.76
17*T*	0.425	0.978 0.259		2.68
18	0.816	1.017	0.445	2.85
19	0.523	1.158	0.31	2.70
21	0.979	0.535	0.64	2.54
22	1.758	0.101	0.95	2.88
23	0.941	0.691	0.58	2.65
24	0.520	1.161	0.31	2.70
25	0.488	1.007	0.32	2.52
26	1.348	0.519	0.72	2.89
29	0.806	0.671	0.54	2.50
30	0.526	0.854	0.382	2.40
31	1.446	0.205	0.88	2.67
33	0.607	1.145	0.35	2.77
34	1.056	0.512	0.68	2.58
35	1.256	0.507	0.71	2.78
38	1.206	0.453	0.73	2.68
42	0.633	0.930	0.40	2.58
43	1.170	1.048	0.53	3.24
44*T*	0.674	0.900 0.067		2.66
45	0.871	0.660	0.57	2.55
49	0.767	0.808	0.49	2.60
51	0.849	0.804	0.51	2.68
53	0.391	1.318	0.23	2.73
54	1.285	0.459	0.73	2.77
56	0.803	0.913	0.47	2.74
57	0.152	1.714	0.08	2.89
58	0.627	0.899	0.41	2.55
61	0.412	1.120	0.27	2.55
62	0.498	1.013	0.33	2.53
63	0.436	1.129	0.28	2.59
66	1.432	0.150	0.904	2.60
67	0.511	0.998	0.34	2.53
69	0.290	1.238	0.19	2.55
70	1.439	0.260	0.85	2.72
71	0.703	0.985	0.42	2.71
73	0.787	0.972	0.45	2.78
74	1.450	0.094	0.94	2.57
77	0.554	1.164	0.32	2.74
78	1.335	0.325	0.81	2.68
79	0.902	1.040	0.47	2.96
80	0.933	0.712	0.57	2.67
83	1.357	0.400	0.79	2.78
84	1.104	0.340	0.76	2.47
85	0.735	0.829	0.47	2.59
86	0.857	0.941	0.48	2.79
87	0.394	1.328	0.23	2.74
89	1.435	0.476	0.75	2.93
90	1.424	0.282	0.83	2.73
91	1.472	0.351	0.81	2.85
92	0.985	0.520	0.65	2.53
94	0.502	1.241	0.29	2.77
97	0.605	0.954	0.39	2.58
99	0.678	0.930	0.42	2.63
100	0.269	1.586	0.145	2.88

[10] Scharff-Goldhaber and Klaiber, Phys. Rev. **61**, 733A (1942).
[11] The probable error given by Goldhaber in private communications.
[12] Richardson and Kurie, Phys. Rev. **50**, 1004 (1936). Richardson, Phys. Rev. **53**, 124 (1938).
[13] J. Itoh, Proc. Phys. Math. Soc. Japan **23**, 605 (1941).
[14] Curran, Dee, and Strothers, Proc. Roy. Soc. **A174**, 546 (1940).
[15] Mandeville, Phys. Rev. **62**, 309 (1942); Phys. Rev. **62**, 555 (1942); Phys. Rev. **63**, 91 (1943); Phys. Rev. **63**, 387L (1943).
[16] Elliot, Deutsch, and Roberts, Phys. Rev. **63**, 386L (1943).
[17] M. Goldhaber, Klaiber, and G. Scharff-Goldhaber, Phys. Rev. **65**, 61A (1944).
[18] A preliminary report on the data in this paper was given previously. W. E. Ogle and P. G. Kruger, Phys. Rev. **65**, 61A (1944).

TABLE III. Positron-electron pairs arranged according to energy and probable error (Mg^{24} gamma-rays).

Class AA—Very best pairs. No observable scattering.
Class A—Probable error 0.01 Mev.
Class B—Probable error 0.02 Mev.
Class C—Probable error 0.03 Mev.
Class D—Probable error 0.04 Mev or greater.
T indicates "Triplets."
Values given in million electron volts.
( ) Give pair number.

Class AA		(69) 2.55 (21) 2.54 (67) 2.53		(19) 2.70 (31) 2.67 (17) 2.68*T* (44) 2.66*T*	(83) 2.78 (77) 2.74 (73) 2.78	(89) 2.93 (57) 2.89	
Class A		(42) 2.58 (45) 2.55 (49) 2.60		(24) 2.70 (38) 2.68	(33) 2.77		
Class B	(30) 2.40 (84) 2.47	(62) 2.53 (66) 2.60 (58) 2.55 (97) 2.58	(99) 2.63	(51) 2.68 (78) 2.68 (70) 2.72	(15) 2.76	(18) 2.85 (26) 2.89	
Class C		(61) 2.55 (85) 2.59 (74) 2.57 (63) 2.59 (92) 2.53		(71) 2.71	(35) 2.78 (53) 2.73 (86) 2.79 (54) 2.77 (87) 2.74 (90) 2.73	(22) 2.88	
Class D		(29) 2.50 (34) 2.58 (25) 2.52		(23) 2.65 (80) 2.67	(56) 2.74 (94) 2.77	(79) 2.96 (91) 2.85 (100) 2.88	(43) 3.24±0.1

as valid data. Figure 2 shows a typical pair produced by Na gamma-rays. Data on these pairs are shown in Tables II and III. Table II gives the energy of the electron (E^-) in million electron volts, the energy of the positron (E^+) of the same pair, the ratio $E^+/(E^++E^-)$, and the gamma-ray energy calculated from those data. The *T* indicates that numbers 17 and 44 are triplets; i.e., pairs produced in the field of an electron.

It is of interest to compare the experimental distribution of $E^+/(E^++E^-)$ with the theoretical distribution calculated by Heitler.[19] E^+ is the kinetic energy of the positron of a pair, and E^- is the kinetic energy of the electron of the same pair. The theoretical curve of number of pairs *vs.* $E^+/(E^+-E^-)$ is shown by the solid curve in Fig. 3 for a gamma-ray in the energy region of 2.7 Mev. The curve is normalized to the number of pairs observed. The experimental points are plotted on the same graph, and the probable error ($\sqrt{N}$) is shown by the length of the vertical line going through the experimental point. The observed distribution of $E^+/(E^++E^-)$ is not in disagreement with the theoretical distribution as given by Heitler.

The pair energies, as calculated from the observed data, spread over the region from 2.4 to 3.24 Mev. From the theory of pair production one would expect to obtain the true energy of the gamma-ray from the measurements on a single ideal pair; i.e., a pair that has suffered no scattering. The pair energies obtained during the measurements of the gamma-ray from the decay of Sb^{124} were all within 0.03 Mev of each other, with the exception of one pair (No. 5, Table I) that was very badly scattered.

Since the scattering of the electrons is a multiple process, with just as much chance of scattering to one side as to the other side, one should sometimes be able to find tracks that are scattered just as much to one side as to the other, so that the effective scattering is zero. Then if one measures the radius of curvature of that electron track in a magnetic field one should be able to calculate the energy very accurately. A

[19] Heitler, *The Quantum Theory of Radiation* (Oxford University Press, New York, 1936), p. 199.

track that would satisfy the above criteria then would be one that was long enough so that one could make several measurements of the radius of curvature along the length of the track, and such that those measurements would all show the same radius of curvature. From the data on Sb^{124} it appears that such tracks are possible. The 56 pairs due to the Na^{24} gamma-rays were very carefully inspected and 12 satisfied the above criteria. Those 12 are listed in the top (AA) section of Table III. They seem to fall into four groups of pairs. The four groups have average energies of 2.54, 2.68, 2.77, and 2.91 Mev. Thus, it seems that the gamma-ray spectrum of $Na^{24} \rightarrow Mg^{24}$ is complex and that there are four gamma-ray lines in the region from 2.4 to 3.0 Mev.

The rest of the pairs are arranged in Table III in columns corresponding to that energy group with which they are in closest agreement. They are also arranged in rows according to their probable error in measurement as indicated by the general appearance of the pair (length of track, evidence of scattering) and by the spread in energy measurements made on different parts of the tracks. The second or A section of Table III gives those pairs such that the probable error from several measurements is about ± 0.01 Mev, B section lists those such that the probable error is about ± 0.02 Mev, C section lists those with a probable error of ± 0.03 Mev, and D section lists those with a probable error of ± 0.04 Mev or greater. The pairs in sections B and D probably do not improve the value of the energy of the group, but their number is useful in estimating the intensity of the gamma-ray line. The energies of the pairs in each group were averaged weighing the AA pairs five times, the A pairs four times, the B pairs three times, and the C pairs twice as much as the D pairs.

It is possible that pairs numbers 30 and 84 indicate a lower energy gamma-ray line, but since they are not really first class pairs no particular importance is attached to them. Number 99 was right between two energy groups, so it was not assigned to either one of them. It is not a really first class pair so no importance is attached to the fact that it lies right between two of the energy groups indicated by the AA pairs. Possibly numbers 30, 84, and 99 are among the 5 or 6 percent of the pairs that one would expect to be formed by gamma-rays that are scattered by the glass wall of the cloud chamber in such a manner that they still get into the cloud chamber. Pair number 43 indicates the possibility of a very weak gamma-ray at about three and a quarter million electron volts.

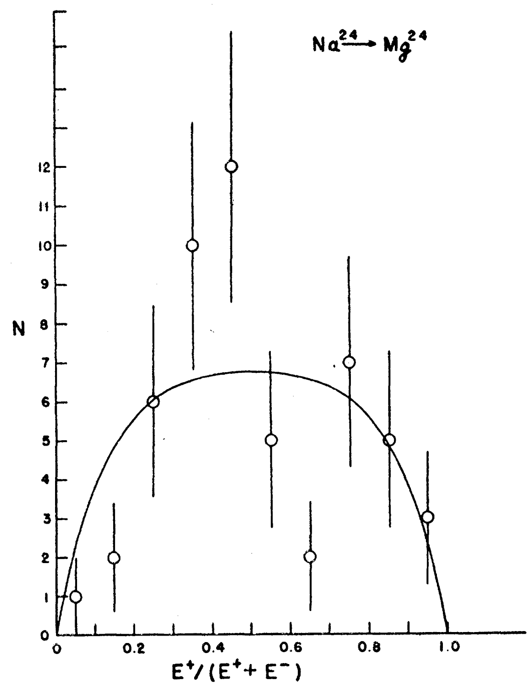


FIG. 3. The number of pairs having a given value of $E^+/(E^+ + E^-)$ is plotted against the value of $E^+/(E^+ + E^-)$. The solid curve represents the theoretically predicted distribution. These data represent the pairs produced by radio-sodium gamma-rays.

In order to estimate the intensities of the gamma-ray lines observed by the method of pair production one must take into account the variation of pair production probability with the energy of the incident gamma-ray. The number of pairs produced per unit time by a monochromatic gamma-ray of intensity I will be proportional to the product of the intensity and the pair production probability at that energy. So if one divides the number of pairs observed for each gamma-ray line by the pair production probability at that energy (taken from Heitler)[20] one obtains a number that is proportional to the intensity of that gamma-ray line. These data for Na^{24} are given in Table IV.

[20] Heitler, p. 201 (see reference 19).

Thus, these data indicate the existence of four gamma-ray lines due to the radioactive decay of Na^{24}, with the possibility of a weak fifth line. Their energies are 2.56±0.02 Mev, 2.68±0.02, 2.76±0.02, 2.89±0.03, and 3.24 ±0.1 Mev; of relative intensities 26, 15, 16, 9.0, 0.9, respectively.

Other investigators[15,16] report, in addition to a gamma-ray of about 2.8 Mev, a line at 1.38 Mev. Because of the decrease of pair production probability with decreasing gamma-ray energy, the pair production method probably would not show such a gamma-ray line unless it were very intense as compared to higher energy lines. The 1.38 Mev line is reported to be about the same intensity as the line at 2.80±0.1 Mev. The pair production probability at 1.38 Mev is about 1/16 that at 2.8 Mev. The present investigation would thus expect to find three pairs of that energy. None was observed, possibly because such pairs would have electron tracks with very small radii of curvature, and might easily be mistaken for scattering, since probably the whole pair would be in the gamma-ray beam.

The gamma-ray energies reported here are not incompatible with the results of other recent investigations. Elliott, Deutsch and Roberts[16] report two lines at 1.38 and 2.76±0.01 Mev. The 2.76 Mev line is in agreement with the 2.76 Mev line of this paper. That measurement was made by means of observing the end point of a Compton electron distribution and also the photoelectron peak with a magnetic spectrograph. The half-width of the photoelectron peak was 3.5 percent. The photoelectron peak would probably show up the strong line at 2.76 Mev, and the weaker line at 2.89 Mev would possibly not be noticed. Mandeville[15] reports two lines at 1.38 and 2.94±0.05 Mev. The 2.94 Mev value is the end point of a Compton electron distribution as measured with a magnetic spectrograph. That value is in essential agreement with the 2.89 Mev line of this paper. The close lines of about the same intensity would possibly not be resolved by the spectrograph.

TABLE IV.

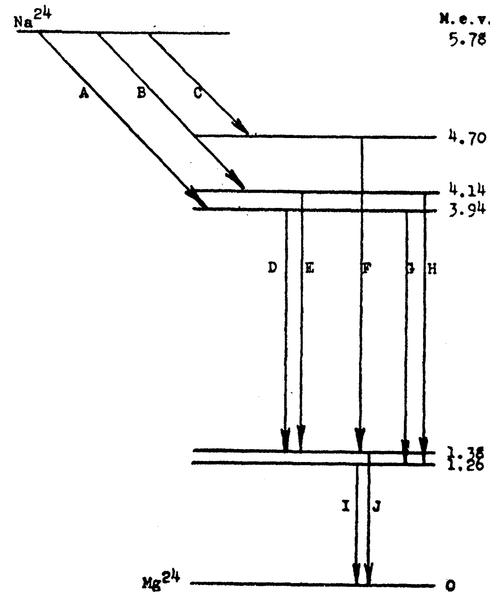
Gamma-ray energy (Mev)	Relative pair production probability	Number of pairs observed	Relative gamma-ray intensity
2.56	0.70	18	26
2.68	0.78	12	15
2.76	0.82	13	16
2.89	0.88	8	9.0
3.24	1.07	1	0.9

Goldhaber, Klaiber, and Scharff-Goldhaber[17] have reported a line at 2.87±0.05 Mev agreeing with the 2.89 Mev line of the present paper, and measured by observing the end point of the distribution of recoil protons in an ionization chamber. The recoil protons are produced by neutrons from the photo-disintegration of beryllium and deuterium.

The beta-ray spectrum of Na^{24} has been investigated by several workers. Feather and Dunworth[21] investigated the spectrum by absorption methods, and reported one beta-ray at 1.4±0.05 Mev. From coincidence measurements they think there is more than one gamma-ray per beta-ray. Amaki and Sugimoto[22] using a Wilson cloud chamber, report two beta-rays at 1.24 and 0.29 Mev.[23] The relative intensities were given as 4.9 to 1 respectively. Kurie, Richardson, and Paxton[24] reported a beta-ray between 1.43 and 1.18 Mev,[23] and also suggested the possibility of a lower energy beta-ray. Lawson,[25] using a magnetic spectrograph, found evidence of a single beta-ray at 1.4 Mev.[23] Kikuchi, *et al.*[26] measured the beta-ray spectrum with a magnetic spectrograph and found an upper limit of the spectrum at 1.37 Mev.[24] However, the Fermi plot of their data, which should be a straight line if there is only one beta-ray, is kinked, indicating beta-rays at 1.84, 1.63, and 1.07 Mev (including the rest mass), of relative intensities 515:160:40, respectively. Konopinski and Uhlenbeck[27] find that the Na^{24} beta-ray spectrum may be complex. The coincidence measurements of Langer, Mitchell, and McDaniel,[28] and of Watase[29] indicate that at least two quanta are successively emitted after each beta-disintegration.

[21] Feather and Dunworth, Proc. Camb. Phil. Soc. **34**, 442 (1938).
[22] Amaki and Sugimoto, Sci. Pap. Inst. Phys. and Chem. Res. (Tokyo) **34**, 1650 (1938).
[23] Beta-ray value does not include rest mass.
[24] Kurie, Richardson, and Paxton, Phys. Rev. **49**, 375 (1936).
[25] J. L. Lawson, Phys. Rev. **56**, 131 (1939).
[26] Kikuchi *et al.*, Physico Math. Soc. Japan **21**, 381 (1939).
[27] Konopinski and Uhlenbeck, Phys. Rev. **60**, 308 (1941).
[28] Langer, Mitchell, and McDaniel, Phys. Rev. **56**, 962 (1941).
[29] Watase, Physico Math. Soc. Japan, **23**, 618 (1941).

The results of the last three papers above and of the present work suggest the term scheme for the decay of Na^{24} to Mg^{24} shown in Fig. 4. It is proposed that Na^{24} decays with the emission of three beta-rays of energies (including mc^2) of 1.84, 1.63 and 1.07 Mev to three excited levels of Mg^{24} at 3.94, 4.14, and about 4.70 Mev, respectively. These levels in turn decay by gamma-emission to two levels at 1.38 and 1.26 Mev. That is, the level at 4.70 Mev, which has a very weak population according to Kikuchi, decays with the emission of a weak gamma-ray of about 3.24 ± 0.1 Mev to the level at 1.38 Mev. The Mg^{24} level at 4.14 Mev above ground decays with the emission of two gamma-rays of energies 2.89 and 2.76 Mev to levels at 1.26 and 1.38 Mev respectively. Likewise, the level at 3.94 Mev decays with the emission of two gamma-rays of energy 2.56 and 2.68 Mev to the levels at 1.38 and 1.26 Mev. The levels at 1.38 and 1.26 Mev then decay by gamma-emission to the ground state of Mg^{24}. The gamma-ray of energy 1.26 Mev has not been reported by other investigators, and would not be observed in the course of the present investigation. However, from the above data that line would be about as intense as the line at 1.38 Mev, and only 0.12 Mev away from it, and hence might not have been resolved.



Line	Beta-Ray Spectra Energy Mev	Relative intensity
A	1.84	515
B	1.63	160
C	1.07	40
	Gamm-Ray Spectra	
D	2.56	26
E	2.76	15
F	3.24	0.9
G	2.68	16
H	2.89	9
I	(1.26)	(25)
J	1.38	42

FIG. 4. Proposed term scheme for the nuclear transition $Na^{24} \rightarrow Mg^{24}$. Lines I and J have been observed as a single line by other investigators and no data on these lines are reported in this paper.

In order for the term scheme of Fig. 4 to be reasonable the intensities of the various gamma-rays should correlate with the populations of the levels expected from beta- and gamma-ray measurements. Other investigators report that the gamma-ray of energy 1.38 Mev is of about the same intensity as the line they observe at about 2.8 Mev. If that line is actually complex as indicated by the present work, and is made up of gamma-rays as indicated by Fig. 4, the sum of the individual intensities of the high energy gamma-rays would add up to the sum of the low energy gamma-ray intensities, as reported. The populations of the Mg^{24} levels at 3.94, 4.14, and 4.71 Mev from the beta-ray spectrum observed by Kikuchi are about 13:4:1, respectively. The populations of the same levels estimated using the gamma-ray intensities given in Table IV are in the ratio of $42 \pm 11 : 24 \pm 8 : 0.9 \pm 1$. By assuming the most favorable limits of error the ratios can be written 53:16:0.2; which is 13.4:0.5 and which is not incompatible with Kikuchi's results. The proposed term schene would place the ground state of Na^{24} 5.78 Mev above the ground state of Mg^{24}.

The theoretical work of Barkas[30] predicts atomic masses of Na^{24} and Mg^{24} of 23.9974 and 23.9920 atomic mass units, respectively. The difference between these two values is 0.0054 mass unit, or 5.03 Mev. Thus the energy difference between the nuclear ground levels should be 5.03 Mev. The present work gives 5.78 Mev but this value includes mc^2 for the beta-ray. Therefore, the value to be compared with 5.03 Mev is 5.78 Mev minus mc^2, which equals 5.27 Mev. This is in good agreement with the value obtained from the mass difference.

[30] Barkas, Phys. Rev. **55**, 691 (1939).

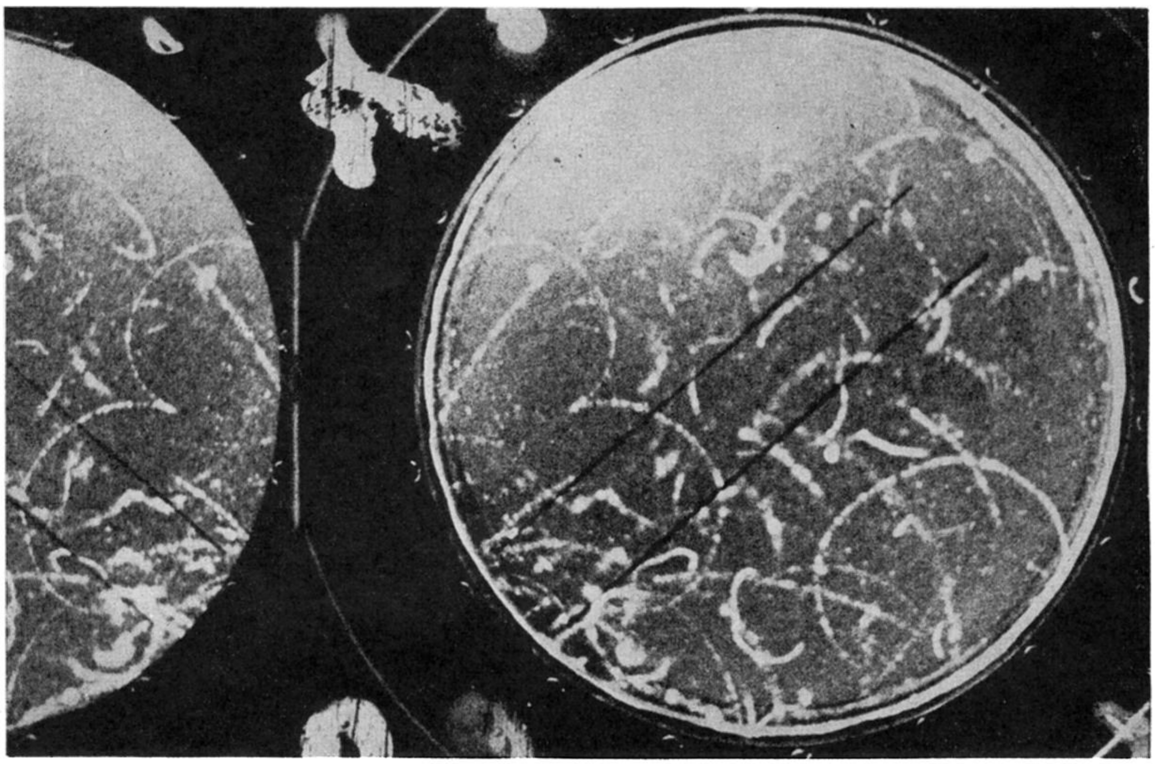


FIG. 1. Electron pair (No. 1 in Table I) produced by gamma-rays from radio-antimony. The magnetic field is 703 oersteds. The gamma-rays are collimated in the direction of the ruled lines which cross the picture and enter from the lower left side.

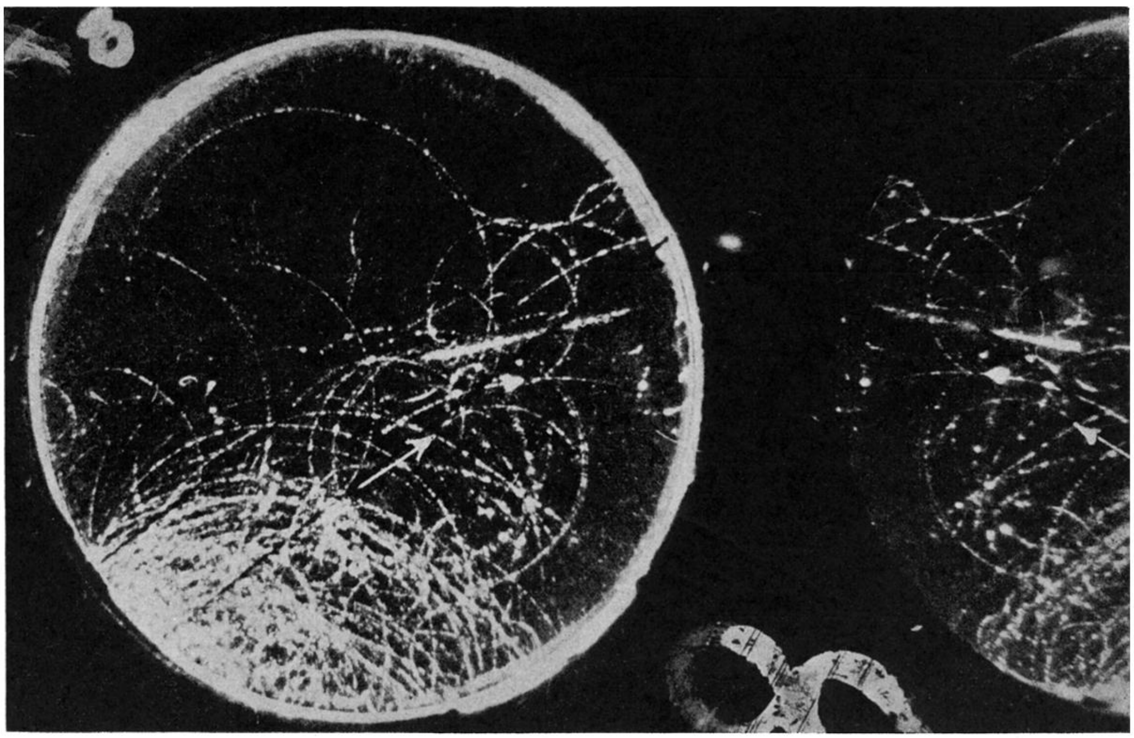


FIG. 2. Electron pair (No. 89 Class AA, Table III) produced by gamma-ray from radium-sodium. The magnetic field is 1055 oersteds. Other conditions are the same as those in Fig. 1. The effect of collimation is clearly evident.