Gamma-Rays from $Be^9(\alpha,n)$ *

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(Received August 4, 1950)

The gamma-ray spectrum produced by bombarding Be^9 with polonium alpha-particles has been analyzed by means of a 180° focusing pair spectrometer. The spectrum shows a single gamma-ray of energy 4.45±0.09 Mev. The 6.7-Mev gamma-ray reported by earlier observers is not detected: no gamma-rays are present in the range 6 to 11 Mev to the extent of one-half percent of the 4.45-Mev intensity. Although no gamma-rays were detected below 4.45 Mev, the sensitivity of the spectrometer is much smaller in this low energy region, and the 2.7-Mev gamma-ray reported by Bothe and Dzelepov would probably not be detected if present. The ThC″ gamma-radiation, investigated as a check on the operation of the spectrometer, is measured as 2.62±0.06 Mev; no gamma-radiation is detectable in the vicinity of 3.2 Mev with intensity as great as one-half percent of that of the 2.62-Mev gamma-ray.

I. INTRODUCTION

THE nuclear reaction $Be^9(\alpha, n)C^{12}$, C^{12}*, produced by bombarding beryllium with the 5.3-Mev alpha-particles of polonium, has long been a well-known source of neutrons. However, the gamma-ray spectrum of this source has never been determined unambiguously. The earlier investigators were unable to obtain strong polonium-beryllium sources; furthermore, the presence of the neutrons is a complicating factor.

Bothe,[1] investigating this gamma-ray spectrum with a 180° focusing electron spectrometer, found three gamma-rays, of energies 2.7, 4.2, and 6.7 Mev, and of roughly equal intensities. Maier-Leibnitz[2] reported neutron-gamma- and gamma-gamma-coincidences due to this source, and concluded that the two lower energy gamma-rays are the product of a cascade transition from a 6.7-Mev level in C^{12}, which is also the source of the highest energy gamma-ray. A second investigation of the gamma-ray spectrum was performed by Dzelepov[3] by means of a 180° focusing pair spectrometer. Dzelepov found gamma-rays of energy 2.7, 4.7, and 7.0 Mev, with the middle line 14 times as intense as the high energy line. The intensity of the lowest line was not estimated because of the unfavorable conditions for detecting it. Unfortunately, all of these early determinations of the gamma-ray spectrum were limited in accuracy by statistical factors owing to the relative weakness of the sources.

The neutron spectrum from polonium-beryllium has not been examined with precision; however, Bradford and Bennett,[4] using 1.4-Mev alpha-particles to bombard beryllium, found two well-resolved neutron groups, from the ground level of C^{12} and from an excited level at 4.45 Mev. A level at 7 Mev would not have been excited at this bombarding energy.

II. DESCRIPTION OF THE APPARATUS

The pair production spectrometer used in this work is similar to that used by Walker and McDaniel,[5] but has been designed for high intensity, with some necessary loss of resolution. A uniform magnetic field is used to produce 180° focusing of the pairs produced in a thin radiator by collimated gamma-radiation from the source (Fig. 1). The electrons and positrons are counted by four Geiger-Müller counters on either side of the radiator. Coincidences between the counters, in all 16 possible combinations, can be measured as a function

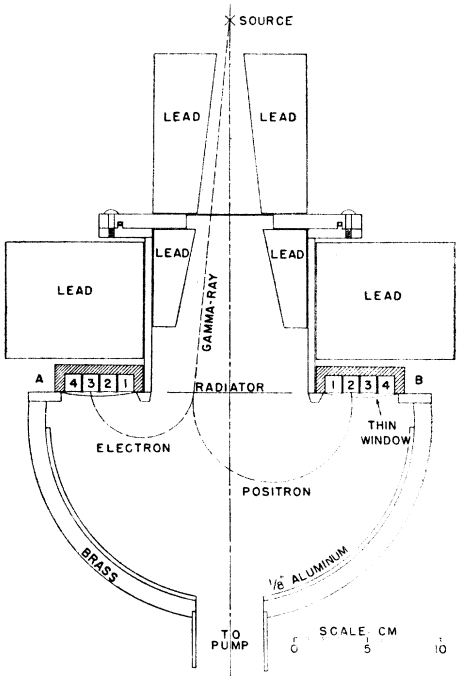

FIG. 1. Pair spectrometer for gamma-rays, in cross section.

* This paper is condensed from part of a Ph.D. thesis presented to the faculty of the Rice Institute in May, 1950. A preliminary report of this work was presented at the April, 1950, meeting of the American Physical Society [Phys. Rev. **79**, 239 (1950)]. This work was supported by the joint program of the ONR and AEC.

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[1] W. Bothe, Zeits. f. Physik **100**, 273 (1936).

[2] H. Maier-Leibnitz, Zeits. f. Physik **101**, 478 (1936).

[3] B. S. Dzelepov, Comptes Rendus U.R.S.S. **23**, No. 1, 24 (1939).

[4] C. E. Bradford and W. E. Bennett, Phys. Rev. **78**, 302 (1950).

[5] R. L. Walker and B. D. McDaniel, Phys. Rev. **74**, 315 (1948).

of magnetic field. The use of the large radiator and banks of counters is made possible by the fact that the total momentum of a pair (algebraic sum) is nearly independent of the manner in which the energy of the gamma-ray is divided between the two particles.

The vacuum box, counters, and lead shielding are shown in cross section in Fig. 1, in a plane perpendicular to the magnetic field. The brass box, 4 in. deep in the direction of the field, is lined with $\frac{1}{8}$-in. aluminum to reduce scattering effects; with this in place the distance between interior walls is $3\frac{1}{4}$ in. The radiator is 8.7 cm square, but the area effective for pair production is smaller, approximately 8.1×5.4 cm, the short dimension being parallel to the magnetic field. The distance from source to radiator is 25.5 cm. The thin windows soldered to the vacuum box and to the counter blocks are brass shim stock, 0.004 and 0.002 in. thick, respectively. The counters are milled out of Muntz metal, four in each block, separated by 0.05-cm walls. Each counter is 1.14 cm wide and 1.20 cm deep; the average distance from the radiator center is 8.86 cm. The counter wires are 5-mil tungsten, with an effective length, between Kovar seals, of 9.0 cm ($3\frac{1}{2}$ in.); the filling mixture is argon-alcohol at 23 cm pressure (22 cm of argon and 1 cm of alcohol).

The circular pole pieces are $10\frac{1}{2}$ in. in diameter, the center of the pole pieces nearly coinciding with the center of the cylindrical part of the magnet box. Slots are cut into the pole faces to receive the ends of the counters. The magnetic field is found to be sufficiently uniform in the region of the desired electron paths; it is uniform within one percent for most of this region, dropping off by two percent from its maximum value for portions of the outermost paths. In the region between the vacuum wall of the spectrometer and the radiator, the magnetic field serves as a clearing field, removing secondary particles produced in the vacuum wall. The electronically regulated magnet current, furnished by a 25-kw generator, does not fluctuate more than one percent for the smallest currents used, and is constant to better than one-half percent for larger current values. The magnetic field has been measured with flip coils and fluxmeter to a relative accuracy considerably better than one percent; the absolute value of the field is thought to be known within approximately two percent. Hysteresis effects are small, and are found to be entirely negligible when a standard cycle of current settings is followed.

The amplification and coincidence circuits are such that each counter is placed in coincidence with each of the four counters in the other block; the outputs of the 16 coincidence circuits are grouped according to the distance between counters, in order to simplify the taking of data. There are thus seven channels, with statistical weights of 1, 2, 3, 4, 3, 2, 1 (number of pairs of counters) in order of increasing distance of separation. The circuits are arranged such that the individual counting rates of the counters can also be determined, both to check the operation of the counters and to allow the calculation of accidental coincidence rates. The resolving time of the coincidence circuits is 0.5 μsec., small enough to make the accidental correction a minor and sometimes negligible factor.

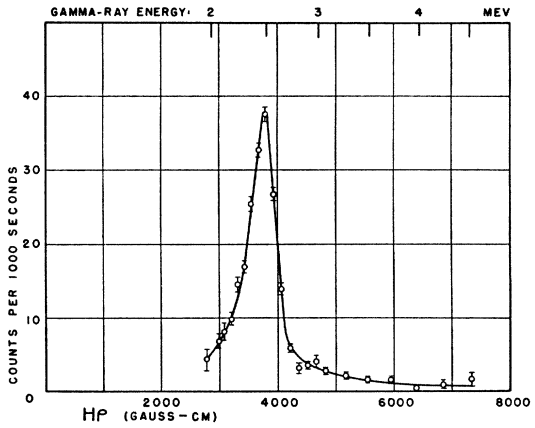

FIG. 2. Pair spectrum from ThC″, using 20.7-mg/cm² tin radiator. The ordinate scale is the counting rate for a single pair of counters.

III. RESOLUTION AND YIELD

The most important of the factors affecting the resolution are the width of the counters and the angular distribution of the pairs leaving the radiator. The counters, with an effective width of 1.19 cm, are at an average distance of 8.86 cm from the radiator center. In the idealized case of particles leaving the radiator in the direction normal to the surface, the counting rate for pairs as a function of $H\rho$ is a triangular curve of 6.7 percent width at half-height, with the peak of the triangle corresponding to the true momentum of the pairs. The effect of an angular distribution differing from this ideal is to broaden and round the triangular shape and to shift the peak toward lower momentum values.

The angular distribution of electrons and positrons leaving the radiator is determined by two independent factors in addition to the initial directions of the gamma-rays: the pair production process, and multiple scattering in the radiator. For the radiators used in this work the angular effects due to multiple scattering are more important than those due to pair production. No accurate theory exists for either effect, for the large average angles involved at these energies of a few Mev. Thus the peak shift and half-width due to angular effects cannot be calculated directly with any precision.

However, the yield of pairs as a function of $H\rho$ has been calculated by numerical integration for several assumed Gaussian angular distributions, and it is found that the peak shift is approximately equal to half of the width at half-height due to angular effects, this width in excess of 6.7 percent being calculated by the difference of squares. Calculation of the peak shift from the

width should give an approximate correction for angular effects, as well as for the less important effects of radiator energy loss and the dependence of the sum of positron and electron momenta on the division of energy between them. It is found that more elaborate corrections do not give results appreciably different from this simple process. However, this correction could not be expected to be valid for the asymmetrical line shapes obtained for thick radiators, nor for line breadth due to several unresolved lines.

Factors other than the counter width and angular effects do not have large effects on the resolution. The positrons and electrons lose about one percent of their energy, on the average, in passing through the radiator. The effect of scattering in the thin windows between the magnet box and the counters is minimized by making the distance between box window and counter as small as possible; in the present case the average distance is about $\frac{1}{16}$ in. The effects on the resolution of slight inhomogeneities and fluctuations in the magnetic field should be very small, considerably less than one percent.

The numerical integrations used in the calculation of peak shifts also give the spectrometer efficiency (fraction of pairs formed in the radiator which are counted) for an assumed angular distribution. This efficiency is of the order of 6.7 percent per pair of counters when angular effects are negligible, at high energies; for energies of several Mev the efficiency is much lower and must be found experimentally.

The coincidence rate for a pair of counters depends on the distance between them as well as on the value of $H\rho$; counter pairs which are farther apart than the average have somewhat better resolution and lower counting rates than the average. This has been taken into account by modifying the channel weights somewhat empirically by a $1/\rho^2$ factor, taken as unity for the central channel, which is found to give good agreement between the channels. In the most important regions of the gamma-ray spectra the magnetic field settings are taken at 3.5 percent intervals, overlapping all four channels used for each value of $H\rho$. Since these four counting rates are simply added, and the sum divided by the total channel weight, the shape of the curve is unaffected by the choice of weights. Weighting factors would be unnecessary were it not that some points of the data do not represent the overlap of all four channels.

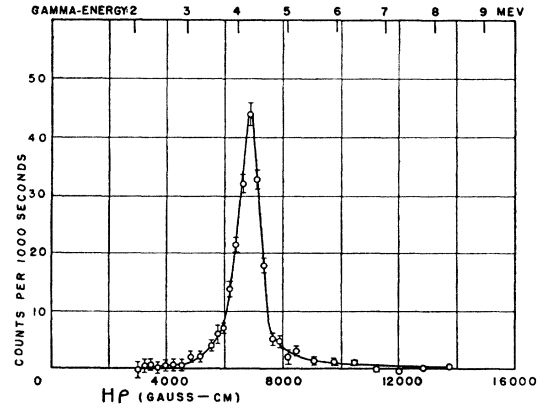

FIG. 3. Pair spectrum from polonium-beryllium source, using 31.0-mg/cm² tin radiator. The ordinate scale is the counting rate for a single pair of counters.

IV. EXPERIMENTAL RESULTS

A. Mesothorium Source

As a check on the operation of the spectrometer, pairs were observed from the 2.62-Mev gamma-ray of ThC″. The source was a MsThI salt, with gamma-radiation equivalent to about 9 mg of radium. The pair counting rate obtained in the most carefully done of several runs using a 20.7-mg/cm² tin radiator is plotted as a function of $H\rho$ (value for one particle) in Fig. 2. Standard statistical errors are indicated for all the points. The counting rates have been divided by channel weights to reduce the data to the counting rate for a single pair of counters, and have been corrected for accidental counts (about four percent of the peak counting rate) and for a small background (also about four percent) independent of the presence of the radiator, which was measured as a function of $H\rho$. The pair yield curve shows a single peak, with a long low tail at high energy. The long tail is probably due in part to pairs, one member of which has been scattered from an interior wall of the spectrometer; another probable source is coincidences between Compton electrons produced in the radiator and the scattered quanta. The peak is located at $H\rho=3800$ gauss-cm, and has a height of 34.4 counts per 1000 sec. above the low background tail. The width at half-height is 13.8 percent of 3800 gauss-cm; the high energy edge is somewhat steeper than the low energy edge. Allowing for 6.7 percent counter resolution, we find a width of 12.0 percent due to angular distribution effects and to energy loss in the radiator (about 28 kev average for the pair). Applying a peak shift correction of 6.0 percent, we obtain 2.62 Mev as the energy of the gamma-ray from ThC″. The fact that this is accurately known to be the energy[6] indicates that no correction is necessary to the measured value of the magnetic field. The order of magnitude of the error involved in this energy measurement is probably not less than two percent; thus we write the energy of the ThC″ gamma-ray as 2.62 ± 0.06 Mev, as determined in this pair spectrometer. This serves more as a calibration for the spectrometer than as an absolute measurement of the gamma-ray energy.

There is no evidence in Fig. 2 for any gamma-ray in the neighborhood of 3.2 Mev, which has been suspected on the basis of the disintegration scheme. Statistical fluctuations here are of the order of two

[6] G. D. Latyshev, Rev. Mod. Phys. 19, 132 (1947); J. L. Wolfson, Phys. Rev. 78, 176 (1950).

percent of the peak counting rate, and, allowing for increased spectrometer efficiency and higher pair cross section at this energy, we may be reasonably sure that no gamma-ray exists in this region with intensity greater than about one-half percent of the intensity at 2.62 Mev. This is in agreement with the data of Bell and Elliott,[7] who set a maximum of 0.2 percent for any possible gamma-radiation at 3.2 Mev.

A ThC'' source of 9-mC strength should emit about 3.4×10^8 gamma-rays/sec.; comparing this with the observed counting rate of 0.034 pair/sec./pair of counters, we find that the spectrometer counts one pair for each 10^{10} gamma-rays emitted, per pair of counters, using a 20.7-mg/cm^2 tin radiator. This sensitivity is 340 times lower than that calculated on the basis of no angular distribution losses, giving a loss factor of about 18 for each side of the spectrometer due to this angular distribution; the spectrometer is very insensitive at this low energy.

The ThC'' gamma-ray was also observed, less carefully, using a tin radiator twice as thick as in the work just described. The width (14.9 percent) was slightly larger, and the yield of pairs was increased by 33 percent. The small increase in pair yield is undoubtedly due to the poorer angular distribution from the source side of the radiator, causing the added thickness to be relatively ineffective in producing pair counts. The high energy tail was just twice as high as for the thinner radiator.

B. Polonium-Beryllium Source

After this preliminary work with ThC'', the pair spectrometer was used to observe the gamma-rays from a strong polonium-beryllium source loaned by Los Alamos Scientific Laboratory. The source emitted $4.86\pm0.40\times10^6$ neutrons/sec. on November 26, 1949, according to a calibration performed at Los Alamos. Since the source decayed with a half-life of 140 days, the data obtained have been corrected to the value which would have been obtained on the calibration date. The pair counting rates observed from this source have been plotted in Fig. 3, as obtained from a 31.0-mg/cm^2 tin radiator. The data has been corrected for accidental counts with a rate about three percent of the maximum counting rate, and for a no-radiator background which is about 13 percent of the maximum pair counting rate in the vicinity of the peak, and rises to about 40 percent of the maximum pair rate in the vicinity of 3000 gauss-cm. The observed maximum counting rate for pairs was 41.8 counts/1000 sec./pair of counters, at 6880 gauss-cm, and the width at half-height was observed to be 11.9 percent. The peak shift may be calculated to be 4.9 percent, giving a gamma-ray energy of 4.45 ± 0.09 Mev. No other gamma-rays are apparent in the spectrum, but the sensitivity is very much lower below the 4.45-Mev peak, so that gamma-rays in this region are not ruled out. Statistical deviations in the region between 6 and 8 Mev are of the order of one percent of the peak yield, and a consideration of the increase in efficiency and pair cross section cuts the maximum intensity which might not be detected to about one-half percent of the 4.45-Mev gamma-ray strength.

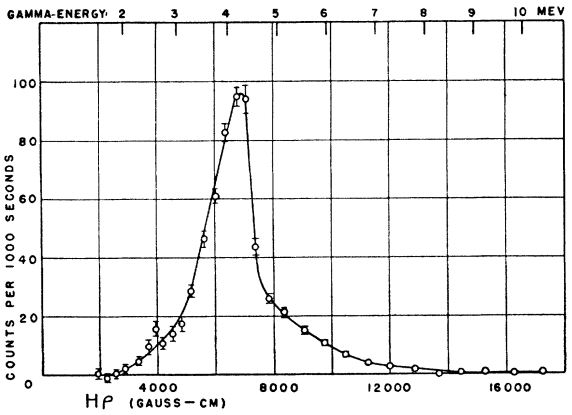

FIG. 4. Pair spectrum from polonium-beryllium source, using 273-mg/cm^2 tungsten radiator. The ordinate scale is the counting rate for a single pair of counters.

Estimating the number of 4.45-Mev gamma-rays emitted by the source as 3×10^6 quanta/sec., we calculate that this pair spectrometer counts one pair (per unit channel weight) for 7×10^7 gamma-quanta emitted, when a 31.0-mg/cm^2 tin radiator is used. This figure is of course only roughly determined. If we take the value for 2.62 Mev as 8×10^9 gamma-quanta/pair count for the same radiator thickness, we find the sensitivity to be about 110 times higher at the higher energy. Thus a 2.7-Mev gamma-ray would probably not be detected even if present with intensity several times larger than that of the 4.45-Mev gamma-ray (statistical fluctuations in the region of 2.7 Mev are of the order of three percent of the maximum counting rate).

The polonium-beryllium gamma-rays have also been observed with a much thicker radiator, partly to observe the effect of such a radiator. The results obtained with a 273-mg/cm^2 tungsten radiator are plotted in Fig. 4. Such a radiator is about 340 kev thick for the pairs, as compared to 42 kev for the 31-mg/cm^2 tin radiator, and should yield 12.4 times as many pairs. The actual peak intensity observed was only 77 percent higher than for the tin radiator, or 74 counts/1000 sec. above a wide, low background. This background, which is due to the radiator, is proportionately higher than for the tin target by the ratio of radiator weights (8.8). The width at half-height of the peak is 18.7 percent; the peak cannot be located accurately, but does not appear to be shifted from the location observed with the tin radiator. The curve is markedly asymmetrical, so that the peak shift cannot be estimated from the width. This thick-radiator data gives information as to the absence of gamma-radiation in the region be-

[7] R. E. Bell and L. G. Elliott, Can. J. Research **26A**, 379 (1948).

tween 8 and 11 Mev; any gamma-rays in this region could not have intensities as large as one-half percent of the 4.45-Mev intensity.

V. CONCLUSIONS

The polonium-beryllium gamma-ray spectrum has been found to consist of a single gamma-ray of energy 4.45±0.09 Mev, with the possibility of radiation at lower energy remaining because of the decrease in sensitivity of the spectrometer below this energy. Since no gamma-radiation is observed at 7 Mev, one of the important bits of evidence for the 7-Mev level in C^{12} appears to be removed. However, since there is good evidence that there are no levels in C^{12} below 4.45 Mev, the 2.7-Mev gamma-ray found by early observers cannot be accounted for except by postulating the 7-Mev level. Thus it seems possible that this low energy gamma-ray may also not exist, the evidence for it being of the same statistical accuracy as the evidence for the 7-Mev gamma-ray. Further doubt is cast on the existence of this level by recent experimental results[8] on the inelastic scattering of protons by carbon nuclei, which indicate levels in C^{12} only at 4.8 and 10.1 Mev.

The author wishes to thank Professor T. W. Bonner for guidance and assistance in all phases of this work, and to express his indebtedness to the Los Alamos Scientific Laboratory for the loan of the polonium-beryllium source.

[8] Levinthal, Martinelli, and Silverman, Phys. Rev. 78, 199 (1950).

PHYSICAL REVIEW VOLUME 80, NUMBER 6 DECEMBER 15, 1950

On the Deep Configurations of V I and Cr II

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(Received July 5, 9950)

The theoretical formulas for d^3s^2, d^4s, and d^5 are compared with the experimental data of V I and Cr II; the Cr II terms are assigned to configurations. The agreement remains practically unimproved by taking into account the interactions between configurations.

I. INTRODUCTION

THIS study constitutes a direct continuation of Many's work[1] on 3- and 4-electron spectra in the iron group, applied to 5-electron spectra. The procedure adopted is essentially the same in our case, and the reader is referred to Many's article for abbreviations, designations, etc., In both spectra, we may still presume that we are confronted with *LS* coupling.

Following Many's example, we first compared the theoretical formulas with the experimental term values, not taking into account any configuration interactions. Thereafter we repeated our calculations allowing for interactions between configurations. In either case, we calculated the Slater-Condon *F*'s and *G*'s by means of least squares, evaluated the terms, and, finally, compared the agreements in both cases.

All theoretical formulas are taken from Racah.[2]

II. V I

This spectrum is well known for its clean *LS* coupling. The experimental term values are taken from Meggers and Russell.[3] The two lowest configurations d^3s^2 and d^4s are moderately well mixed up. Of their 32 terms 17 are found experimentally; besides a high lying ^6S term, a still higher ^4F assigned to d^5 is given in the new tables of Moore.[4] Both are excluded from our calculations and dealt with separately afterward.

At first, separate calculations for d^4s and d^3s^2 were carried out, although there is but little theoretical justification for such a procedure, and then the calculations for d^4s and d^3s^2 combined were made. Finally, the configuration interactions were taken into account. It is seen from Table I that, on the one hand, the small lowering of the mean deviation and the rise of the mean error in the case of d^3s^2, when taking separate parameters *B* and *C* in d^4s and d^3s^2 (see column 1) do not warrant this procedure; on the other hand, the mean error rises also when taking into account the electrostatic interactions between d^4s and d^3s^2 (see column 3). Therefore, the best result is obtained by calculating with the same *B* and *C* in both configurations and neglecting the interactions between configurations (see column 2). As regards d^3s^2 and d^4s, there is no possibility of interchanging the assignments of any two terms.

Concerning the two d^5 terms, there can be no doubt about the identity of the ^6S. Computing $A(d^5)$ from this latter term and taking the values of *B* and *C* from our previous calculation, we can compute the theoretical

[1] A. Many, Phys. Rev. **70**, 511 (1946).
[2] G. Racah, Phys. Rev. **62**, 438 (1942); **63**, 367 (1943).
[3] H. N. Russell and W. F. Meggers, J. Research Nat. Bur. Stand. **17**, 125 (1936).
[4] C. E. Moore, *Atomic Energy Levels* (National Bureau of Standards, 1949), Vol. I.