extend completely across the diameter of the specimen. The twins obtained in the first few crystals tested were extremely fine in size and did not extend very far below the surface. Data were obtained, however, on several succeeding crystals for which the volumes of the twins produced could be measured to an accuracy of approximately 25 percent. The results are compiled in Table I.

TABLE I. Energy absorbed per unit volume of twins. ϕ = angle between specimen axis and the normal to the basal plane.

Temp.	Crystal	ϕ	Energy absorbed per unit volume of twins, in ergs/cc
20°C	*FF*-1	$15\frac{1}{2}°$	38×10^6
20°C	*FF*-2	$15\frac{1}{2}°$	27×10^6
−180°C	*GG*-3	7°	38×10^6
20°C	*GG*-1	7°	5×10^6
20°C	*GG*-2	7°	2×10^6
200°C	*GG*-4	7°	$<1\times10^6$

The first two specimens were cut from the same single crystal, while the last four were cut from another. The tests were run at the temperatures indicated. At 200°C, unfortunately, an extremely large number of fine twins were produced whose volume could not be measured. Nevertheless, the indication was that less energy per unit volume of twin was absorbed at this temperature.

The data taken on crystals *FF*-1 and *FF*-2 at 20°C agree well within an order of magnitude; the same is true for crystals *GG*-1 and *GG*-2. It is therefore believed that the differences in the values of energy absorbed per unit volume of twins for the two orientations are significant and the following conclusions may be drawn:

(1) At room temperature the energy absorbed in twins produced by impact is less, the closer the basal plane approaches being normal to the specimen axis.

(2) As the temperature is decreased the energy absorbed seems to increase. This would agree with the work of Davidenkov *et al.*,[4] who showed that the resistance to twinning under tension increased with decreasing temperature. Obviously there are insufficient data to indicate the exact relationship.

I wish to thank Mr. F. W. VonBatchelder for determining the orientations of the above crystals.

* The opinions expressed in this paper are those of the author, and not necessarily the Navy Department.

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Zeeman Effect and Hyperfine Splitting of Positronium*

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THE effect of a magnetic field on the ground state doublet of positronium may be calculated from the Breit-Rabi formula. The result, first published by Berestetskii,[1] is illustrated in Fig. 1. The hyperfine splitting ΔW, here of the order of the fine structure, can be obtained from the frequencies of transitions between the magnetic levels as in the case of the other hydrogen isotopes.[2] Because of the high rate of annihilation the lines are wide and rf fields of several gauss are required to obtain observable transition rates. Therefore, the transitions with $\Delta F=1$ which occur near 200,000 Mc/sec are beyond the power of established techniques. We have observed the line $(1, \pm1)\rightarrow(1, 0)$ in a field of about 9000 gauss at a frequency of 3000 Mc/sec. According to Fig. 1 this frequency is given by $\nu=(\Delta W/2h)((1+x^2)^{\frac{1}{2}}-1)$, where $x=4\mu_0 H/\Delta W$.

The transition was detected by the increase, at resonance, of two-photon annihilation relative to the three-photon process.

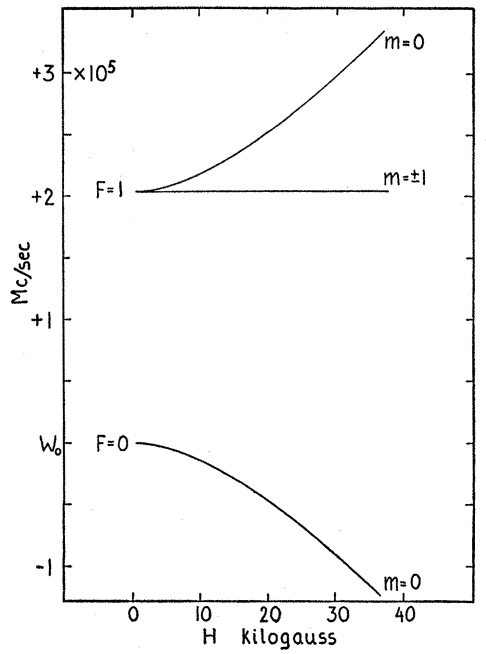

FIG. 1. Positronium levels in a magnetic field. The energies of the levels with respect to the unperturbed singlet state are given by: $W-W_0=(\Delta W/2)\,[1+mx\pm(1-2mx+x^2)^{1/2}]$; where $x=4\mu_0 H/\Delta W$.

In a magnetic field of the magnitude used, there is sufficient admixture of singlet component to the (1, 0) level to make two-quantum decay predominant. The states (1, 1) and (1, −1) always decay into three photons. This quenching by the magnetic field was discussed in an earlier communication.[3] Induced transitions from $(1, \pm1)$ to (1, 0) will result in additional quenching. To an accuracy sufficient for our purpose, the fraction ϕ of the $(1, \pm1)$ atoms quenched at resonance by an rf field of amplitude H' perpendicular to H is given by $\phi\cong(\mu_0 H'/\pi h)^2\lambda_0/\lambda_p$, where λ_0 and λ_p are the unperturbed decay rates of the ortho- and para-states, respectively. For $H'=5$ gauss, $\phi\cong0.1$. The fractional width of the line due to the annihilation process is $\gamma/\nu\simeq\lambda_p h/2\pi\Delta W=6.2\times10^{-3}$. In our experiments H is varied rather than ν. The observed width should then be $\Delta H/H=\gamma/2\nu=3.1\times10^{-3}$. These expressions for ϕ and γ are also valid for the transitions with $\Delta F=1$. More exact expressions will be given in a more extensive later communication. There we shall also discuss reasons for believing that other causes of line width should be small compared with the annihilation width.

A source of a few millicuries of Cu^{64} was electroplated at the center of one of the end plates of a cylindrical high Q cavity driven in the $TM(110)$ mode. The cavity was placed with its axis parallel to the magnetic field which confined the positrons to a beam of about 3 cm diameter. Extensive lead collimation assured that the gamma-ray detector used counted only radiation from annihilations occurring in the gas near the center of the cavity. In this region the magnetic field deviated no more than ±10 gauss from its value at the center. Most of the rf transitions probably occurred near the middle of this region where the field is very uniform. The quenching was observed by measuring the gamma-ray scintillation spectrum as in the experiments of Deutsch and Dulit,[3] and in one run also by the gamma-ray coincidence rate at 180°. Under our experimental conditions the former method proved more sensitive. A statistically significant run could be obtained in about two hours. An unexpected complication arose from the fact that the high rf fields (about 1000 v/cm) used increase the amount of positronium formed, probably by accelerating some slow positrons to the energy required for electron capture. In argon, where the energy required for inelastic scatter-

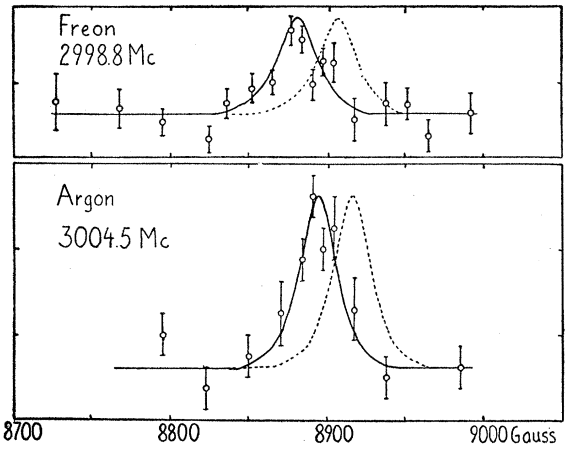

FIG. 2. Radiofrequency quenching of three-quantum annihilation. The dotted curves indicate the theoretical position of the line without radiative corrections.

ing is above that required for positronium formation, the amount of positronium was doubled by the rf field.

Figure 2 shows the results of two typical runs obtained under different experimental conditions. The ordinates represent a parameter extracted from the data roughly proportional to the amount of two-quantum annihilation. The solid curves are drawn with the theoretical width with the location and height of the peak fitted to the data. The height, corresponding to $\phi=0.06$, is slightly less than expected but within the uncertainty of the estimate; the observed width, although very uncertain, does not seem to be much larger than the theoretical value. From the average of five runs like those shown in Fig. 2 we calculate the hyperfine splitting $\Delta W/h=2.032\pm0.003\times10^5$ Mc/sec. This compares with the value 2.044×10^5 Mc/sec calculated from the expression $\Delta W=7\mu_0^2/3a_0^3$ given by Pirenne[4] and Berestetskii.[1] The dotted curves in Fig. 2 show the expected location of the line for this value of ΔW. First results of a new and fairly complex experiment may always be affected by unsuspected systematic errors but it seems very probable that the observed shift of -1200 ± 300 Mc/sec is at least partly real. Both ΔW and the magnetic energy are subject to corrections of the order of α/π. Ferrell[5] has calculated some of the corrections to ΔW and the interaction with the field must be corrected at least by multiplying μ_0 in the expression for x above by $(1+\alpha/2\pi)$. When all known corrections are thus considered the line is shifted by about -4 gauss compared with an observed shift of -27 ± 7 gauss. Other corrections of comparable magnitude still remain to be calculated, however.

Improvements in field homogeneity, higher rf power and provision for circular polarization will be used to extend our results and to search for the structure of excited states. We wish to thank Professor F. Bitter for permission to use the large magnet.

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Multiple Gamma-Ray Scattering in Lead

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SPENCER and Fano[1] have published solutions of the general transport equation for the propagation of gamma-rays through an infinite medium. Their method of solution depends upon the fact that the moments $b_{ln}(\lambda)$ of the photon distribution can be found by a chainwise solution of a set of integral equations, which for a point isotropic source are

$$(2l+1)^{-1}[(l+1)(l-n)b_{l+1,\,n-1}(\lambda)-l(l+n+1)b_{l-1,\,n-1}(\lambda)] = -\mu(\lambda)b_{ln}(\lambda)+\int_0^\lambda d\lambda' k(\lambda',\lambda)P_l(1-\lambda+\lambda')b_{ln}(\lambda') +\text{source term.} \quad (1)$$

A knowledge of the $b_{ln}(\lambda)$ enables one to calculate the energy distribution of photons as a function of the distance from the source.

This approach was used with success by Spencer and Fano[2] to explain the data of White[3] for the case of a point isotropic Co^{60} source in water.

In the present work, calculations have been made by this method to obtain the distribution function in lead in order to check the consistency of the theoretical predictions with experimental build-up factors measured in lead. A cylindrical pellet (1 cm in diameter and 1 cm in length) containing 2.74 curies of Co^{60} was used as a source in the experiment. The scattering medium was composed of antimony-hardened lead bricks; chemical analysis of the bricks showed an average of 2.89 percent antimony present. Du Pont 552 x-ray film was used as a detector; the blackening of this film per roentgen is known[4,5] to be the same for all photon energies from the Co^{60} primary energies down to approximately 0.2 Mev. The experimental build-up factor, defined as the ratio of the total film blackening to that expected from narrow-beam absorption coefficient calculations, was measured at various distances from the source; the results of two such runs are shown in Fig. 1.

To simplify the source term for the numerical integrations required in Eq. (1), the photons were separated into two classes in the following manner:

$$N(r,u_r,\lambda)=N'(r,u_r,\lambda)+\sum_i \frac{e^{-\mu(\lambda)r}}{4\pi r^2}\frac{\delta(1-u_r)}{2\pi}\delta(\lambda-\lambda_i), \quad (2)$$

where $N'(r,u_r,\lambda)$ represents those photons which have been scattered at least once and the remaining term is the direct beam. This separation leads to

$$(2l+1)^{-1}\{(l+1)(l-n)b_{l+1,\,n-1}'(\lambda)-l(l+n+1)b_{l-1,\,n-1}'(\lambda)\} = -\mu(\lambda)b_{ln}'(\lambda)+\int_0^\lambda d\lambda' k(\lambda,\lambda')P_l(1-\lambda+\lambda')b_{ln}(\lambda') +\sum_i \frac{n!}{\mu^{n+1}(\lambda_i)}k(\lambda,\lambda_i)P_l(1-\lambda+\lambda_i), \quad (3)$$

where the $b_{ln}'(\lambda)$ now represent the moments of the photons scattered at least once.

For the present experiment the distribution function for scattered photons at a distance r, including photons arriving in all directions, was computed using the first four moments $b_{0n}'(\lambda)$.

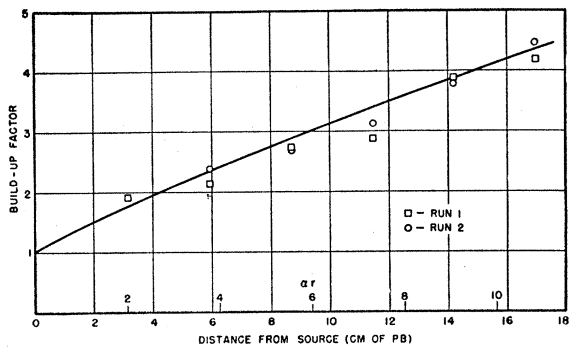

FIG. 1. Build-up factor in lead for a Co^{60} point isotropic source as measured by duPont 552 photographic film. The solid curve represents the calculated build-up factor.