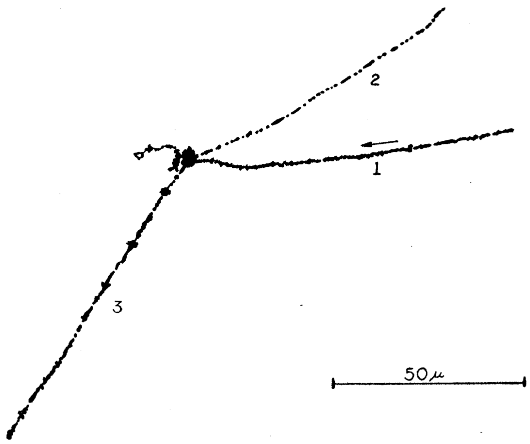

FIG. 2. Trace of projection of heavy meson star. Short curly track is typical of an Auger electron.

heavy mesons and overlap the values given for τ and K mesons[2-4] and also the larger masses found by Daniel *et al.*[5]

The target-to-star path corresponds to 1.2×10^{-8} sec for the heavy meson in its rest system. If the mean life of such mesons were as low as 1 millimicrosecond, it can easily be shown (using cosmic ray evidence that the ratio R of heavy mesons to pions created is less than 0.1) that the probability of observing 1 heavy meson in our experimental arrangement would be less than 0.01. If, on the other hand, the mean life of 8 millimicroseconds indicated for cosmic ray heavy mesons[6] is adopted, the observed proportion of 1 heavy meson star to 2000 pion stars (a proportion that may, of course, change markedly with more observations) would correspond to a value of about 10^{-4} for R.

The creation process of this meson cannot be analyzed unambiguously because of the thickness of the target; the heavy meson could have lost as much as 100 Mev in the beryllium and, besides, could have been made by a fast secondary (pion or proton).

We are particularly indebted to Dr. William H. Moore for his essential share in setting up the experiment, and to Dr. Morton F. Kaplon for initiating us in the gap-length determinations. We take great pleasure in acknowledging the invaluable aid given by our scanning and processing staff, R. Mildred Bracker, Margaret D. Carter, Barbara M. Cozine, Jeanne C. Dennison, Mary C. Hall, Alice C. Lea, and Jacqueline D. Leek.

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1 L. LePrince-Ringuet, Revs. Modern Phys. **21**, 42 (1949); W. F. Fry and J. J. Lord, Phys. Rev. **87**, 533 (1952).
2 Lal, Pal, and Peters, Phys. Rev. **92**, 438 (1953).
3 D. M. Ritson, Phys. Rev. **91**, 1572 (1953).
4 Crussard, LePrince-Ringuet, Morellet, Orkin-Lecourtois, and Trembley, Phys. Rev. **90**, 1127 (1953).
5 Daniel, Davies, Mulvey, and Perkins, Phil. Mag. **43**, 753 (1952).
6 J. W. Keuffel and L. Mezzetti, Bull. Am. Phys. Soc. **29**, No. 1, 60 (1954); Astbury, Buchanan, Chippindale, Millar, Newth, Page, Rytz, and Sahiar, Phil. Mag. **44**, 242 (1953).

Radiative Corrections in Positronium

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ALL corrections of order α^5 to the $n=2$ energy levels of positronium have been evaluated using the relativistic two-body equation[1,2] with techniques recently proposed by several authors.[3,4] The corrections arise from three sources:

(1) The self-energy and vacuum polarization effects analogous to those which yield the main part of the Lamb shift in hydrogen.

(2) Recoil and retardation corrections to the Breit interaction. Similar contributions have been calculated by Salpeter[5] for hydrogen. In hydrogen such terms account for less than 0.05 percent of the Lamb shift. The effect is much larger in positronium since the mass dependence is of the form $m_1^2m_2^2/(m_1+m_2)^3$.

(3) Corrections to the α^4 virtual annihilation interaction[6-8] and α^5 annihilation processes.[9] These are of course peculiar to a particle-antiparticle system.

Items (1) and (2) above have been calculated with arbitrary masses m_1 and m_2 so as to determine the mass dependence in general. In the limit m_1 small and m_2 large, we confirm Salpeter's numerical result[5] and Arnowitt's hyperfine structure calculation.[10] In the limit $m_1=m_2$ we confirm the results of Karplus and Klein.[9] We also agree with them on item (3). The energy shift due to items (1) and (2) is given by the expression below:

For the $2S$ state:

$$\Delta E_1=\frac{\alpha^5\mu^2}{m_1+m_2}\frac{1}{8\pi}\Big\{-\frac{4}{3}+\frac{8}{3}\Big[\frac{25}{12}+\ln\frac{2Ry_\infty}{\alpha k_0(2,0)}\Big] +2\Big[\ln\alpha+\frac{7}{4}+\frac{4}{3}(1-\ln 2) -(m_1^2-m_2^2)^{-1}(m_2^2\ln\eta_2-m_1^2\ln\eta_1)\Big] -2\langle 2S^2-3\rangle m_1m_2(m_1^2-m_2^2)^{-1}\ln\frac{m_1}{m_2}\Big\}, \quad (1)$$

$$\Delta E_2=\frac{\alpha^5\mu^2}{m_1+m_2}\frac{1}{6\pi}\Big\{\frac{m_1^2+m_2^2}{m_1m_2}\Big(\frac{5}{6}-\frac{1}{5}^{\dagger}-\ln\frac{\alpha^2k_0(2,0)}{Ry_\infty}\Big) -\frac{m_2}{m_1}\ln\eta_2-\frac{m_1}{m_2}\ln\eta_1+\frac{1}{2}\langle 2S^2-3\rangle\Big\}. \quad (2)$$

For the $2P$ state:

$$\Delta E_1=-\frac{\alpha^5\mu^2}{m_1+m_2}\frac{1}{8\pi}\Big(\frac{7}{18}-\frac{8}{3}\ln\frac{Ry_\infty}{k_0(2,1)}\Big), \quad (3)$$

$$\Delta E_2=\frac{\alpha^5\mu^2}{m_1+m_2}\Big\{\frac{-1}{6\pi}\Big(\frac{m_1^2+m_2^2}{m_1m_2}\Big)\ln\frac{k_0(2,1)}{Ry_\infty}\Big\} +\frac{\alpha^2}{m_1m_2}\Big\{\frac{1}{4\pi}\Big\langle\Big(\frac{m_2}{m_1}\boldsymbol{\sigma}_1+\frac{m_1}{m_2}\boldsymbol{\sigma}_2\Big)\cdot\frac{\mathbf{L}}{r^3}\Big\rangle +\frac{1}{2\pi}\Big\langle\frac{\mathbf{S}\cdot\mathbf{L}}{r^3}-\frac{1}{2}\Big[\frac{\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2}{r^3}-\frac{3\boldsymbol{\sigma}_1\cdot\mathbf{r}\boldsymbol{\sigma}_2\cdot\mathbf{r}}{r^5}\Big]\Big\rangle\Big\}, \quad (4)$$

where

$$\mu=\frac{m_1m_2}{m_1+m_2},\quad \eta_1=\frac{m_1}{m_1+m_2},\quad \eta_2=\frac{m_2}{m_1+m_2},\quad \mathbf{S}=\tfrac{1}{2}(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2),$$

and $k_0(2,0)$ and $k_0(2,1)$ are given by Bethe, Brown, and Stehn.[11] $\langle A\rangle$ denotes the expectation value of A. The dagger in Eq. (2) signifies that in positronium, this vacuum polarization term is 1/10.

In positronium, there is no accidental α^4 degeneracy. Hence, the α^5 shifts must be added to the much larger α^4 fs and hfs in order to obtain the corrected level spacing. Table I gives the α^4 corrections determined by Ferrell[8] and the α^5 contributions we have found.

TABLE I. Additions to the nonrelativistic $n=2$ level of positronium, Mc/sec.

Order	$^1S_0$	$^3S_1$	$^1P_1$	$^3P_2$	$^3P_1$	$^3P_0$
α^4	−18135	7413	−3536	−981	−5360	−10835
α^5	357	232	−3	1	−5	−16
Total	−17778	7645	−3539	−980	−5365	−10851

The α^5 correction to the 2^1S_0 (2^3S_1) level may be broken down as follows: 112 (61) Mc/sec arise from recoil effects; 261 (295) Mc/sec come from vertex parts; -16 (-124) Mc/sec are due to the annihilation interaction. All these effects are much smaller in P states.

It is hoped that work now in progress elsewhere will provide experimental level shifts sufficiently accurate to compare with those predicted theoretically. The details of this calculation will be published later. We wish to thank Professor R. Karplus, Professor J. Schwinger, and Dr. A. Klein for helpful discussions.

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† National Science Foundation Predoctoral Fellow.

1 J. Schwinger, Proc. Natl. Acad. Sci. U. S. **37**, 452, 455 (1951).
2 E. E. Salpeter and H. A. Bethe, Phys. Rev. **84**, 1232 (1951).
3 R. J. Eden, Proc. Roy. Soc. (London) **219**, 519 (1953).
4 T. Fulton and R. Karplus, Phys. Rev. **93**, 257 (1954).
5 E. E. Salpeter, Phys. Rev. **87**, 328 (1952).
6 V. B. Berestetskii and L. D. Landau, J. Exptl. Theoret. Phys. (U. S. S. R.) **19**, 673 (1949).
7 J. Pirenne, Arch. sci. phys. et nat. **29**, 207 (1947).
8 R. A. Ferrell, Phys. Rev. **84**, 858 (1951) and PhD thesis, Princeton, 1951 (unpublished).
9 R. Karplus and A. Klein, Phys. Rev. **87**, 848 (1952).
10 R. Arnowitt, PhD thesis, Harvard, 1952 (unpublished).
11 Bethe, Brown, and Stehn, Phys. Rev. **77**, 370 (1950).

The Nuclear Magnetic Moments of Xe^{129} and Xe^{131}

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THE nuclear magnetic resonances of Xe^{129} and Xe^{131} in pure Xe gas at a pressure of approximately 50 atmos have been detected with a nuclear induction spectrometer similar to the one described by Weaver.[1] A sample of ordinary Xe gas at 50 atmos without any catalyst was used. The signal of Xe^{131}, abundance 21.17 percent which from hfs is known to have a spin $I=\frac{3}{2}$, and a quadrupole moment $Q\approx -0.15$, appeared as a slow-passage signal with a signal-to-noise ratio of about 40:1. The nature of the signal caused by Xe^{129} ($I=\frac{1}{2}$; abundance $f=26.23$ percent) in the same sample, indicated that the experimental conditions for this isotope were not these of slow passage, the relaxation time T_1 being at least several minutes. Comparison of the proton resonance frequency in water containing 0.1-molar $MnSO_4$ with the resonance frequencies of Xe^{129} and Xe^{131} in the same magnetic field yielded the following results:

$$\nu_{129}/\nu_p=0.276633\pm0.000005, \quad \nu_{131}/\nu_p=0.081976\pm0.000001.$$

Using the value of the proton moment of Sommer, Thomas, and Hipple[2] ($\mu_p=2.79268\pm0.00006$ nm) the above frequency ratios lead to the following magnetic moments for Xe^{129} and Xe^{131}:

$$\mu_{129}=-0.77255\pm0.00002 \text{ nm}, \quad \mu_{131}=+0.68680\pm0.00002 \text{ nm}.$$

Both values are given without diamagnetic corrections. From these values the ratio of the magnetic moments is obtained as

$$\mu_{129}/\mu_{131}=-1.12485\pm0.00002.$$

The value of μ_{129} agrees within the experimental error with that obtained by Proctor and Yu[3] ($\mu_{129}=-0.7726\pm0.0001$ nm) in a sample of Xe gas at 12 atmos and containing Fe_2O_3 powder as paramagnetic catalyst. The ratio of the magnetic moments is also in fair agreement with the value of Bohr, Koch, and Rasmussen[4] ($\mu_{129}/\mu_{131}=-1.131\pm0.005$) obtained by hfs measurements.

The mechanism of relaxation is apparently caused by strong van der Waals forces since pure nuclear dipole-dipole interaction would lead to enormous relaxation times ($\sim10^6$ sec). This explanation is corroborated by the work of Proctor and Yu, who were unable to detect signals of either odd isotope in pure Xe at a pressure of 12 atmos without catalyst. In our experiment, the van der Waals forces are appreciable since at a pressure of 50 atmos the density of the gas is roughly 1.6 times that to be expected for an ideal gas. It is also worth noting that the relaxation time for Xe^{131} is several orders of magnitude smaller than that of Xe^{129}, indicating that strong electric interaction takes place with the quadrupole moment of Xe^{131}. Further studies of these processes are in progress.

1 H. E. Weaver, Phys. Rev. **89**, 923 (1953).
2 Sommer, Thomas, and Hipple, Phys. Rev. **82**, 697 (1951).
3 W. G. Proctor and F. C. Yu, Phys. Rev. **81**, 20 (1951).
4 Bohr, Koch, and Rasmussen, Arkiv Fysik **4**, 455 (1952).

Electric Excitation of Low-Lying Levels in Separated Wolfram Isotopes*

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ELECTRIC excitation of heavy nuclei was first observed simultaneously by two groups.[1,2] Subsequently, this has been confirmed by a number of others[3] and a major improvement in the technique for determination of the energy of the excited state has been achieved by Huus and Bjerregaard[4] using magnetic analysis of the internal conversion electrons. These investigators established that the broad peak observed[1] at 105–125 kev (see Fig. 1)[5] is composed of three separate peaks at 102, 113, and 124 kev. The Bohr-Mottelson theory[6] predicts that each even-even isotope of wolfram has a 2+ low-lying rotational level above the 0+ ground state, that these levels should have nearly the same energy, and that in this element the energy of the level in a given isotope should increase with atomic weight. It is known that W^{186} has a 2+ level at about 123 kev.[7] Accordingly Huus and Bjerregaard tentatively assigned the above three levels to the

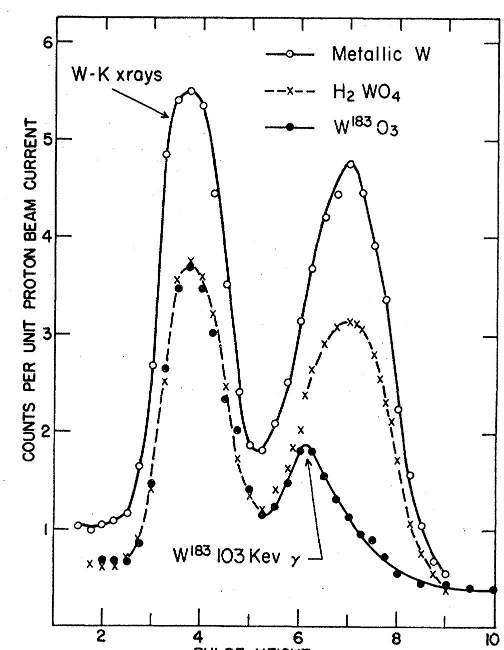

FIG. 1. NaI(Tl) scintillation spectrometer pulse spectra from three wolfram targets during bombardment with 2.5-Mev protons. The broad gamma photopeak shown for metallic wolfram and H_2WO_4 is produced by unresolved gammas from all wolfram isotopes. The pulse spectrum from W^{183} is shown for comparison. Spectra from even-even wolfram isotopes are displayed in Fig. 2. The energy of the W^{183} gamma is given to an accuracy of ±8 kev. The breadth of this peak on the high-energy side results from the appreciable concentrations of the heavier isotopes as impurities (see Table I). In each case a 0.1-inch copper absorber was used to reduce the intensity of the K x-ray background. The intensity of the W^{183} gamma has not been corrected for absorption in copper.