Measurement on the *I*, *F*, and *A* Lines of Thorium by a New Method

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A NEW method for the measurement of β-ray energies has been used with the deposit from radioactive thorium. It is an adaptation suggested by R. E. Siday of the lens type spectrometer and is capable of very high accuracy in both the absolute and comparative measurements of the specific momenta of β-ray lines.

The method consists in the recording on a photographic plate of the line image of a line source. The angular rotation of the image with respect to the object can be found by producing a second image on the plate with the lens current reversed. For the absolute determination of the specific momentum, only this angle, the lens current, and the effective number of turns need be known, and in this respect Dietrich[1] has demonstrated the possibilities of the method in a pilot experiment, in which he obtained an accuracy of 1 in 700. For comparative determinations of momentum, only the angle and the lens current are required. Further details will be published shortly.

Comparison has been made between the *I* and *F* lines of thorium-*C*. The ratio between their $(H\rho)$'s was found to be 1.26317 $\pm$0.00012, where the estimated probable error of 1 part in 10,000 is very conservative. This ratio agrees exactly with that found by Lindström[2] with a semicircular focuser. The absolute energies can be found, as pointed out by Siegbahn,[3] by making use of the difference in binding energy between the *K* and L_1 shells of element 83. Assuming this difference to be 74,128$\pm$10 electron volts,[4] the velocity of light to be 299,793.1$\pm$0.25 km per second,[5] and the ratio e/m to be 1.75890$\pm$0.00005 abs. emu per g,[6] one obtains the specific momenta of *F* and *I* lines as 1388.5$\pm$0.3 and 1753.9 $\pm$0.4 gauss cm, respectively. The $(H\rho)$ value of the *A* line, by ratio to the *F* line, has been found to be 533.66$\pm$0.12 gauss cm.

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[1] C. F. Dietrich, thesis, London (1951).
[2] G. Lindström, Phys. Rev. **83**, 465 (1951).
[3] K. Siegbahn, Arkiv Mat. Astron. Fysik **28B**, No. 6 (1941).
[4] Private communication from Mlle. Y. Cauchois.
[5] E. Bergstrand, Nature **163**, 338 (1949); Arkiv Fysik **2**, 119 (1950).
[6] Thomas, Driscoll, and Hipple, Phys. Rev. **78**, 787 (1950).

Use of HD for Experiments on the Proton-Deuteron Magnetic Moment Ratio

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IN the recent high precision experiments by Lindström,[1] Smaller,[2,3] Yasaitis,[2] and Anderson[2] on the ratio of the proton magnetic moment to that of the deuteron, a dominant limitation to the final accuracy of the experiment has been the uncertainty[3] as to the difference of the magnetic shielding correction for molecules containing hydrogen and deuterium. As discussed by Smaller[2,3] and Newell,[4] the large difference in the masses of hydrogen and deuterium gives rise to a difference in the zero-point vibration amplitude and consequently to a difference in the magnetic shielding even in molecules which are identical except for the interchange of deuterium and hydrogen. Since no one has yet been able to calculate the dependence of the shielding upon internuclear spacing, it has been impossible to determine with sufficient precision the dependence of the shielding upon the zero-point vibration amplitudes.

It is the purpose of this note merely to point out that this uncertainty can be overcome in future experiments on the proton-deuteron magnetic moment ratio by observing both the proton and the deuteron resonance in the molecule HD. In this molecule the modification of the magnetic shielding by the zero-point vibration is the same for both the proton and deuteron measurements. Experiments with HD should not be appreciably more difficult than some of the past experiments. HD can be obtained in high purity.[5] Furthermore HD is as convenient to handle as either H_2 or D_2, and some of the most accurate of the past experiments[3] have been with these gaseous molecules.

[1] G. Lindström, Phys. Rev. **78**, 817 (1950).
[2] Smaller, Yasaitis, and Anderson, Phys. Rev. **81**, 896 (1951).
[3] B. Smaller, Phys. Rev. **83**, 812 (1951).
[4] G. F. Newell, Phys. Rev. **80**, 476 (1950).
[5] Fookson, Pomerantz, and Rich, Science **112**, 748 (1950).

A Determination of the Nuclear Magnetic Moment of Co^{60}, Using the Method of Nuclear Alignment

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WE have in an earlier publication[1] described preliminary results of an experiment to align Co^{60} nuclei. The alignment was detected and measured by observation of the anisotropic polar diagram of γ-radiation from a 70-μcurie source, which was a single crystal with the composition (1% Co, 12% Cu, 87% Zn) $SO_4 \cdot Rb_2SO_4 \cdot 6H_2O$. This was cooled by adiabatic demagnetization to approximately 0.010°K when, as explained by Bleaney,[2] the crystalline interactions cause an alignment of the cobalt nuclei relative to the crystal axes. The alignment effect found by us has recently been confirmed by Gorter, Poppema, Steenland, and Beun,[3] who now also use the Bleaney method applied to a diluted cobalt Tutton salt. No conclusive results were obtained in previous Leiden attempts[4,5] relying on the Gorter-Rose[6,7] method or on the antiferromagnetism of a concentrated cobalt Tutton salt, an experiment announced by Gorter at the Oxford Conference on Low Temperature Physics (1951),[5] and since carried out in Leiden.

In the past two months we have performed further experiments, and the statistical accuracy of the results has been increased. Also the determination of temperatures was improved; first by correcting for a spurious magnetic effect caused by the cryostat (which made the T^* values quoted in our previous publication too high), and secondly, by accounting theoretically for the deviations from Curie's law. The observed temperatures reached after demagnetization now agree with those calculated from the known splittings of the ground state of the Co^{++} and Cu^{++} ions. The shape of the polar diagram as a function of temperature is in very close agreement with that predicted by Steenberg,[8] except at the lowest temperatures where, however, the theoretical $T-T^*$ relationship used is of doubtful validity. If $F(K_1)$ and $F(K_2)$ are respectively the γ-ray intensities along the K_1 and K_2 axes of the Co^{++} ions, a parameter of anisotropy can be defined as $F(K_2)/F(K_1)$. We observed, for example, that at 0.020$\pm$0.002°K the value of this parameter is 1.25$\pm$0.02; the value observed at the lowest temperatures was 1.45.

The anisotropy of the γ-radiation depends on temperature through the Boltzmann factor $\exp(\mu H/kTI)$, where μ and *I* are respectively the magnetic moment and spin of Co^{60}. *H* is the effective magnetic field acting on the nucleus; its magnitude can be calculated from measurements of the hyperfine splitting of the paramagnetic resonance spectrum of Co^{59} in this salt,[9] and from the known magnetic moment of Co^{59}. Thus, it is possible to deduce from the experimental data a value for the magnetic moment of Co^{60}, provided that the spin is known. Assuming that $I=5$, which Deutsch and Scharff-Goldhaber[10] suggest is the probable value, we obtain for the magnetic moment of Co^{60} the value 3.0$\pm$0.5 nuclear magnetons. The sign of the magnetic moment

cannot be obtained from this experiment. We hope, however, to carry out experiments on the polarization of γ-rays emitted from polarized (as opposed to aligned) nuclei, which, among other things, should give the sign of the magnetic moment.

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[1] Daniels, Grace, and Robinson, Nature **168**, 780 (1951).
[2] B. Bleaney, Proc. Phys. Soc. (London) **A64**, 315 (1951); Phil. Mag. **42**, 441 (1951).
[3] Gorter, Poppema, Steenland, and Beun, Leiden Communications **287b** (1951).
[4] Gorter, de Klerk, Poppema, Steenland, and de Vries, Physica **15**, 679 (1949); O. J. Poppema, Helv. Phys. Acta **23**, Suppl. III, 187 (1950).
[5] C. J. Gorter, Proceedings of the International Conference on Low Temperature Physics, Oxford, 1951, p. 158.
[6] C. J. Gorter, Ceremonies Langevin-Perrin, Les Phenomenes Cryomagnetiques, Paris, 1948; Physica **14**, 504 (1948).
[7] M. E. Rose, Phys. Rev. **75**, 213 (1949).
[8] N. R. Steenberg, unpublished.
[9] K. D. Bowers, unpublished.
[10] M. Deutsch and G. Scharff-Goldhaber, Phys. Rev. **83**, 1059 (1951).

Comparison of Total Photoneutron Yield from 160- and 320-Mev Bremsstrahlung

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THAT an appreciable fraction of the photoneutrons produced by a high energy (320-Mev) bremsstrahlung might be the result of quanta of energy greater than 150 Mev was pointed out by Eyges[1] on analysis of high energy[2,3] and lower energy[4] absolute photoneutron production cross sections and of transition curves.[2,5,6] Eyges proposes that the nuclear absorption cross section for photons has a resonance maximum in the region of 15 to 20 Mev, then falls almost to zero and rises once again somewhere above 100 Mev. The results of the present experiment bear out the essential validity of this theory.

In this experiment, the total photoneutron yield measurements previously reported[2] for the 320-Mev bremsstrahlung from the Berkeley synchrotron were repeated at 160 Mev maximum energy for nine elements. Full energy (320-Mev) measurements were also made on these nine elements at the same time as a check. The experimental arrangement used was very similar to that previously described.[2] Neutrons were counted at 90° to the beam direction with a boron trifluoride proportional counter in a "long counter" geometry of paraffin. The pulses from the counter were clipped to 0.5-microseconds pulse length.

The ionization chamber beam monitor was calibrated at both energies for equivalent numbers of low energy quanta by two methods. The first was the induced 10-minute half-life β^+ activity in copper foils because of the $Cu^{63}(\gamma, n)Cu^{62}$ reaction as used by Sagane.[7] The second was the photodisintegration of deuterium as determined by direct neutron counting from water and heavy water targets. Both of these reactions are presumably sensitive only to quanta below 50 Mev. The deuterium yield was 6.5 percent higher from 160-Mev bremsstrahlung than the copper yield for equal copper and deuterium yields at 320 Mev. The average of the deuterium and copper results was used.

Table I gives the ratios of total photoneutron yields for equivalent $Cu^{63}(\gamma, n)$ and $D(\gamma, n)$ reaction yields (i.e., for the same number of quanta below 30 Mev) from 320-Mev bremsstrahlung and 160-Mev bremsstrahlung. The probable counting errors of these ratios are less than 3 percent in every case except carbon (error 4 percent). The relative yields at 320 Mev checked within statistics the previously reported values.[2] Although the beam-pulse length at half-energy was only 20 microseconds, no neutron pile-up occurred in the counter because of the long average diffusion time (about 200 microseconds) of neutrons in the paraffin of the "long counter." Neutron pile-up and counts resulting from scattered gamma-rays or electrons were checked for, both by increasing the counter voltage by 100 volts and by reducing the beam intensity by a factor of four. In both cases the counts per unit beam were the same within statistics, indicating negligible contribution from either effect.

TABLE I. Ratios of total photoneutron yields.

Element	Be	C	Al	Fe	Cu	Mo	Ta	W	Pb
Yield at 320 Mev / Yield at 160 Mev	1.21	1.18	1.48	1.23	1.28	1.30	1.28	1.33	1.30

If the calibration methods described can be assumed to normalize the beam to equal numbers of quanta between 0 and 30 Mev for full and half energy beams, the shapes of the bremsstrahlung spectra at these energies indicate that only quanta of greater than 140 Mev energy could account for the 30 percent increase in yield actually observed.

[1] L. Eyges, Bull. Am. Phys. Soc. **26**, No. 8, 5 (1951).
[2] Terwilliger, Jones, and Jarmie, Phys. Rev. **82**, 820 (1951).
[3] D. W. Kerst and G. A. Price, Phys. Rev. **79**, 725 (1950).
[4] G. A. Price and D. W. Kerst, Phys. Rev. **77**, 806 (1950).
[5] Karl Strauch, Phys. Rev. **81**, 973 (1951).
[6] L. Eyges, Phys. Rev. **81**, 981 (1951).
[7] R. Sagane, Phys. Rev. **83**, 174 (1951).

Effect of Intrinsic Moment of Electron on Spectroscopic Isotope Shift*

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IT is pointed out below that the intrinsic moment of the electron[1-3] has a non-negligible effect on the spectroscopic isotope shift. In a central electric field, according to the third paper listed in reference 1 the first order effect of the magnetic moment μ_e on the energy of an s electron is

$$\langle H'''\rangle = -\langle \mu_e \rho_2 (\mathcal{E}\boldsymbol{\sigma})\rangle = 2\mu_e \int_0^\infty fg\mathcal{E}_r r^2 dr, \quad (1)$$

where $\mathcal{E}$ is the electric field, $\mathcal{E}_r$ its radial component, ρ_2, $\boldsymbol{\sigma}$ the usual Dirac matrices and f, g are the radial functions defined in reference 1; r is the distance from the center of the nucleus. Calculations were made for a model in which the charge Ze is distributed with density proportional to r^{n-2} in $r<a$. The change in the electrostatic potential energy caused by the finiteness of the nucleus is referred to as δV, changes in $\langle \delta V\rangle$, $\langle H'''\rangle$ caused by change $\delta' a$ for fixed n by $\delta'\langle \delta V\rangle$, $\delta'\langle H'''\rangle$, respectively. The ratio to the volume effect[4] is

$$\mathfrak{R} = \delta'\langle H'''\rangle/\delta'\langle \delta V\rangle = -\gamma(2\rho+1)(2\rho+n+1)(e^2/mc^2)/[4\pi a(2\rho+n)], \quad (2)$$

where

$$\gamma = Z\alpha, \quad \rho = (1-\gamma^2)^{\frac{1}{2}}, \quad (3)$$

and α is the fine structure constant. In Eq. (2) the electronic wave function is approximated by the first nonvanishing power of r in f and g for a Coulomb field and[3] $\mu_e \cong -(\alpha/2\pi)(e\hbar/2mc)$. For Pb^{208}, with $a = 0.5A^{\frac{1}{3}}10^{-13}$ cm,

$$\mathfrak{R} = -0.050. \quad (4)$$

The interaction of Eq. (1) is related to that invoked by Foldy[5] for the electron-neutron force.[6] It may be noted that in the non-relativistic approximation,

$$H''' \cong -(\hbar\mu_e/2mc)\,\mathrm{div}\,\mathcal{E}, \quad (5)$$

and for this, values about 10 times those of Eq. (4) result if one calculates with relativistic wave functions. The parameter $2\mu_e/(ea) = -e^2/(2\pi amc^2) \cong -1/20$. The ratio $f/g \cong -\gamma/2$ is ~ -0.3 for