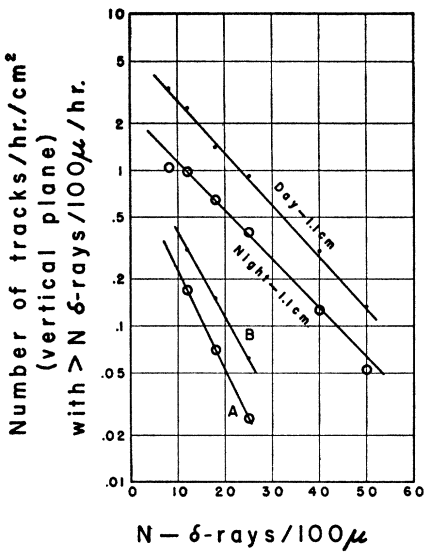

FIG. 1. Number of tracks/cm²/hr. having more than n delta-rays per 100μ. Note that the cm² is in the vertical plane.

per hundred microns. In order to show that temperature variations during the balloon flight could not affect the delta-ray intensities, measurements of the temperature sensitivity of the photographic plates were made which showed that all grain densities of tracks changed less than five percent in the interval of -15 to $+28$°C. At a temperature of -50°C the grain density of tracks of ionization energy loss 15 times the minimum value was reduced by 30 percent from the value at 20°C, while the tracks of minimum ionization were reduced by less than 10 percent in the same temperature interval. Thus the relatively small temperature change (20°C) occurring during the entire balloon flight could have no effect on the delta-ray intensity. This is substantiated further by the fact that the delta-ray intensity of primary nuclei of $Z\cong 26$ (iron nuclei) is the same on both the day and night portions of this balloon flight.

The flux of heavy nuclei having more than n delta-rays per hundred microns as a function of n is given in Fig. 1. In the interval from $n=10$ to $n=55$ the atomic number changes from $Z\cong 10$ to $Z\cong 26$. The upper two curves give the results of the measurements described in this paper. The ratio of the flux of heavy nuclei during the day to that at night is 2.55 ± 0.26, and within experimental error is the same for all atomic numbers from $Z\cong 10$ to $Z\cong 26$. As given previously[2] the two curves marked A and B (Fig. 1) give, respectively, the corresponding intensities during the night and during the day at an elevation of approximately 70,000 ft. The steeper slope of the curves, A and B, at 70,000 feet is the result of the increase of the absorption cross section of heavy nuclei with Z (atomic number).

The effect to be expected at sea level due to this observed diurnal variation of heavy nuclei can be estimated. Such an estimate is based on the known altitude variation of the rate of production of relativistic particles by nuclear interactions produced by the primary heavy nuclei, which will be published shortly. If approximately one-half of the relativistic particles produced are assumed to be mesons of high energy, then a change of the order of 0.1 percent would be produced in the total meson component at sea level by the observed diurnal variation of heavy nuclei. This is in agreement with the magnitude (0.3 percent) of the well-established diurnal variation of the total intensity of cosmic rays at sea level.[4,5] This diurnal variation of heavy nuclei would also account for the observed absence of any change with altitude in the time variation of the total cosmic-ray intensity.[6,7]

Measurements will need to be made at geomagnetic latitudes of less than about 40° in order to determine whether or not only low energy heavy nuclei are responsible for the observed diurnal effect. The evidence given above suggests strongly that the origin of the heavy nuclei is closely related to the sun.

Further experiments are now in progress in which two emulsions in contact are moved at a uniform rate with respect to each other, so that the time at which each heavy nucleus passes through the plates can be determined. This will make it possible to carry out a much more detailed study of the diurnal variation. In addition, the measurements are now being extended to include particles with $Z=6$ to $Z=10$.

The efforts of Mr. C. B. Moore of the General Mills Company in making possible such an excellent balloon flight and in arranging for highly accurate altitude determinations is gratefully acknowledged. We would also like to thank Mr. J. Litwin for his assistance in the measurements.

* Assisted by the joint program of the ONR and AEC.

[1] J. J. Lord and Marcel Schein, Phys. Rev. **78**, 321 (1950).
[2] J. J. Lord and Marcel Schein, Phys. Rev. **78**, 484 (1950).
[3] Freier, Ney, Naugle, and Anderson, Phys. Rev. **79**, 206 (1950).
[4] V. F. Hess and H. Th. Graziade, Terr. Mag. **41**, 9 (1936). W. Kolhorster, Physik. Zeits. **42**, 55 (1941). H. Alfven and K. G. Malmfors, Arkiv. f. Mat. Astr. Phys. **29**, A, No. 24 (1943).
[5] H. Elliot and D. W. N. Dolbear, Proc. Roy. Soc. **A63**, 137 (1950).
[6] D. W. N. Dolbear and H. Elliot, Nature **165**, 353 (1950).
[7] T. A. Bergstralh and C. A. Schroeder, Phys. Rev. **80**, 134(A) (1950).

A Direct Determination of the Magnetic Moment of the Proton in Nuclear Magnetons*

F. BLOCH AND C. D. JEFFRIES
Department of Physics, Stanford University, Stanford, California
September 5, 1950

THE method of Alvarez and Bloch[1] for reducing the measurement of a magnetic moment in units of the nuclear magneton μ_n to that of a frequency ratio has been applied to the magnetic moment μ_P of the proton. If ν_N and ν_R are the frequencies of nuclear resonance and orbital rotation, respectively, of a proton, both measured in the same homogeneous magnetic field H, one has

$$\nu_N=2H\mu_P/h, \quad (1)$$

$$\nu_R=eH/2\pi Mc \quad (2)$$

(h = Planck's constant, e = elementary charge, c = velocity of light, M = mass of proton), and therefore

$$\mu_P/\mu_N=\mu_P/(eh/4\pi Mc)=\nu_N/\nu_R. \quad (3)$$

By means of relation (3) we have determined μ_P/μ_n with a relative accuracy better than 1/10,000; since nuclear induction makes it easily possible within a few parts in 100,000, both to measure ν_N and to ascertain the homogeneity of the magnetic field, the problem consisted essentially in an accurate determination of ν_R. This has been achieved by the arrangement schematically indicated in Fig. 1. A proton beam of 20,000 ev, originating from the arc source A passes through a tube T of 4 ft. length with three differential pumping stages before entering into the gap of the electromagnet M and the dee cavity of a very small decelerating cyclotron; the diameter of the dees is 8.5 cm and their width is 1.7 cm. Up to the injection region R, the path is held approximately straight by nine compensating electrodes C and the last injection

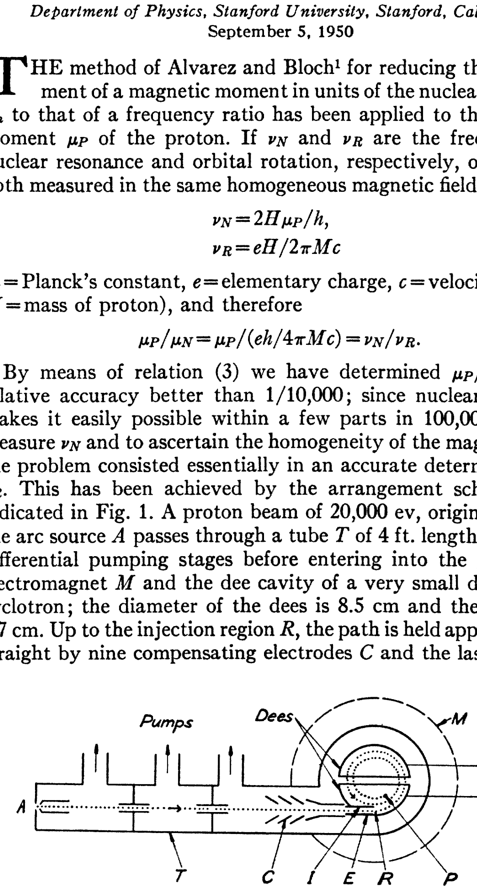

FIG. 1. Schematic arrangement of apparatus.

electrode E, which compensate the Lorentz force due to the motion of the protons in the magnetic field. Beyond R, the path becomes a slowly shrinking spiral with the dee voltage chosen slightly above the minimum of about 100 v, necessary to allow clearance of the injection plate I of 0.25 mm thickness after the first revolution. ν_R is determined from the dee frequency ν at which protons reach the inner probe P, protruding into the dee cavity. Since the magnetic field has to be shimmed to very great homogeneity and, therefore, could not provide magnetic focusing, we relied principally upon phase focusing to hold the protons within the dee cavity; it proved, indeed, sufficient to give probe currents of the order of 10^{-12} amp. after about 500 revolutions. This arrangement has the following advantages.

(1) Independently of the arc pressure, the pressure in the dee chamber can be made low enough so that gas collisions and ionization do not affect the measurement.

(2) Contrary to accelerating operation, the decelerating cyclotron can be operated not only at a dee frequency in the vicinity of $\nu=\nu_R$, but also of $\nu=n\nu_R$, where n is an odd integer. For a given number of revolutions, the higher multiples provide a correspondingly more accurate timing of the protons and the resonance band width is thereby reduced by $1/n$. A further reduction of the band width is due to the circumstance that the energy change of the protons per revolution becomes appreciably less when they have reached a radius sufficiently small so that the transit time between the dees becomes comparable to the period of the dee oscillation. Consequently, with the dee voltage still high enough to allow clearance of the injection plate, the number of revolutions which are necessary to reach the probe at a given position increases with increasing n, so that additional gain in resolution is obtained.

The measurements were carried out at a field $H\cong 5300$ gauss where the frequency of rotation is $\nu_R\cong 8.1$ Mc, and we have successfully operated the dees near all odd multiples of ν_R from the first to the eleventh. The consistency of the results obtained for the higher multiples gave a gratifying confirmation of our accuracy. Observations were made by applying a slight modulation with a period of 4 sec. to the dee frequency and by photographing the trace on an oscillograph whose vertical deflection gave a measure of the instantaneous probe current. Figure 2 shows a typical trace, taken around $\nu=9\nu_R$ with the same frequency interval covered twice as the small modulating condenser goes through a full revolution. The shape of the traces has been qualitatively understood in terms of the focusing action and its variation with ν. The relative half-width has been found to be about 1/200 for $n=1$; the expected gain in resolution was confirmed by the corresponding values 1/4000 and 1/10,000 found for $n=5$ and $n=11$, respectively. A marker was produced on each trace by the beat with a frequency meter, thus providing a highly precise record of the dee frequency. A small nuclear induction head, movable within the dee chamber, gave the nuclear resonance frequency ν_N of protons in water; the signal from this head was also used to hold H constant during runs and to ascertain homogeneity between the monitoring position and the inner region of the dees.

To insure an accurate result we have searched carefully for systematic errors: analysis showed that relativistic corrections were negligible; both by analysis and by experiment it was further shown that space-charge effects, collisions of the protons, fringing fields from the injection electrode, and distortions of the oscillating dee field by the probe likewise did not affect the accuracy of the result. Taking all errors into account, we can at present state our result to be

$$\mu_P=(2.79245\pm 0.0002)\mu_n. \quad (4)$$

The performance of our apparatus indicates that considerably higher accuracy, valuable also for relative mass determinations of the light atoms, will be attainable through some modifications; operation with very large values of n seems here particularly promising.

While this work was in progress, Hipple, Sommer, and Thomas[2] reported a new determination of the Faraday, based upon a similar principle for measuring ν_R by their accelerating "omegatron"; the value for μ_P derived from their measurement agrees with (4). We shall not enter into a discussion here of the connections between our result, the value of the Faraday, the ratio of the masses of proton and electron through the experiment of Purcell and Gardner,[3] and other fundamental constants.

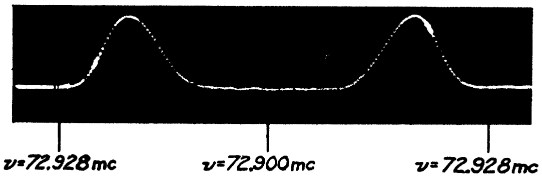

FIG. 2. Oscillogram of detector probe current *versus* dee frequency near the ninth multiple of ν_R.

* Assisted by the joint program of the AEC and ONR.

[1] L. W. Alvarez and F. Bloch, Phys. Rev. **57**, 111 (1940).
[2] Hipple, Sommer, and Thomas, Phys. Rev. **76**, 1877 (1949).
[3] J. H. Gardner and E. M. Purcell, Phys. Rev. **76**, 1262 (1949).

Calculation of the Absorption and Emission Spectra of the Thallium-Activated Potassium Chloride Phosphor

FERD E. WILLIAMS
General Electric Research Laboratory, Schenectady, New York
August 25, 1950

PREVIOUS interpretations of solid-state luminescent phenomena have been either qualitative or phenomenological.[1] Therefore, it is important to calculate quantitatively the properties of a simple phosphor from first principles. The calculation of the peak absorption and emission energies for KCl:Tl has already been reported.[2] Improvements in the theory have permitted the determination of the absorption and emission spectra and their temperature dependence.

It is first recognized that the KCl:Tl phosphor is an ionic crystal[3] and that the luminescence arises from transitions characteristic of Tl^+ substituted in dilute concentration for K^+ ions.[4] The radial charge densities of free Tl^+ in the ground $^1S_0$ state and in the excited $^3P_1{}^0$ state are evaluated using the Sommerfeld modification[5] of the Fermi-Thomas method for the core and the Hartree self-consistent field method[6] for the two outer shell electrons. From these wave functions and from the known ionic radius r_0, polarizability α, and repulsion energy constant ρ for the ground state,[3] these parameters are evaluated for the Tl^+ in the excited state interacting with Cl^-. The method of Kirkwood[7] is used to determine α. The variation of repulsion energy with interatomic distance a is shown to be equal to the variation of S^2/a with a, where S is the overlap integral: $\int\Psi_{Tl^+}\Psi_{Cl^-}dV$. The Tl^+ in the $^1S_0$ and the $^3P_1{}^0$ states are substituted in dilute concentrations for the K^+ in the KCl, and the change in total energy of the system is calculated as a function of the change in the $Tl^+(000)$ nearest $Cl^-(100)$ distance Δr with the condition that the remainder of the lattice rearranges to minimize the total energy. A good approximation to this condition requires only displacement $\Delta r'$ of the $K^+(200)$ radially from the Tl^+ to the position $\Delta r_m'$ of minimum energy. Only symmetric displacements in Δr and $\Delta r'$ are considered. Madelung, exchange repulsion, van der Waals, and ion-dipole interactions are included. For the $^3P_1{}^0Tl^+$, the Coulomb overlap interactions determined from the free ion wave functions are included. After transformation to the $\Delta r_m'$ plane, the total energy *versus* the configuration coordinate Δr is plotted in Fig. 1 for the $^1S_0$ and $^3P_1{}^0$ states. It should be noted that the equilibrium Tl^+ nearest Cl^- distance is less for the excited than for the ground state. The energies are fitted to the plotted parabolas by mini-

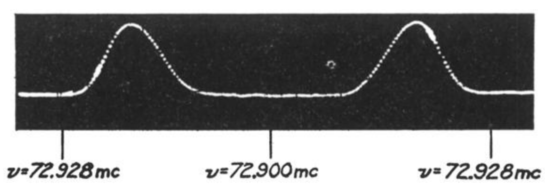

FIG. 2. Oscillogram of detector probe current *versus* dee frequency near the ninth multiple of ν_R.