ments, using 30-cycle modulation. Measurements were made with a dual system, excited by a single oscillator at 27.2 Mc, and incorporating two samples in separate probes in the field. The difference in resonance magnetic fields for the two samples was obtained by measuring alternately the dc field-biasing current necessary to center first one resonance on an oscilloscope and then the other. The small difference in the applied fields at the two samples, due to residual field in homogeneities, was cancelled in the case of H_2O *versus* mineral oil by interchanging samples.

The effects of bulk diamagnetism are appreciable. The field, H_i, in the sample will differ from the applied field H_0, by an amount[4]

$$H_i - H_0 = (\tfrac{4}{3}\pi - \alpha)\kappa H_i = (\tfrac{4}{3}\pi - \alpha)\kappa H_0.$$

Here κ is the volume susceptibility of the sample, and α is the demagnetization factor which is 2π for an infinite cylinder and $4\pi/3$ for a sphere. Spherical samples are indicated but experimental difficulties prevented their use. Instead, "infinite cylinders" 8 in. long and $\frac{3}{8}$ in. in diameter were used for H_2O and mineral oil. Diamagnetic corrections were made using an α of 2π and κ's of -0.70 and $-0.65\pm0.05\times10^{-6}$ cgs units for H_2O and mineral oil respectively. The mineral oil κ was estimated from hydrocarbon data. κ for H_2 may be neglected.

H_2 was observed at 30 atmos in the pressure probe shown in Fig. 1. A photograph of its resonance and that of mineral oil is reproduced in Fig. 2. The phasing of the 30-cycle voltage on the x-axis of the oscilloscope is adjusted to superimpose the first relaxation wiggle; this provides a sharper setting point than the resonance line itself. The pressure and reference probes were mounted rigidly in the gap. A length of $\frac{3}{32}$-in. copper tubing connected to the bottom inlet of the pressure probe was used to introduce, or remove hexane from the sample cavity. By comparing its resonance field with that of a hexane sample of the same shape in the reference probe, the difference in applied fields at the two positions was obtained. In all experiments with H_2 the sample in the reference probe was contained in the same Pyrex tube, 8 mm internal diameter and 8 in. long, with a thin glass barrier at the middle, and placed in the same position with the glass film below the bottom of the rf coil. For "infinite cylinders" the whole tube was filled.

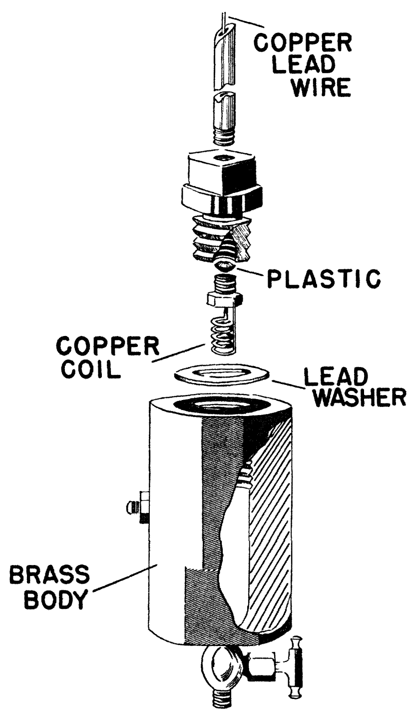

FIG. 1. Pressure probe for nuclear magnetic resonance experiments with gases. A null-T rf bridge was used with this assembly.

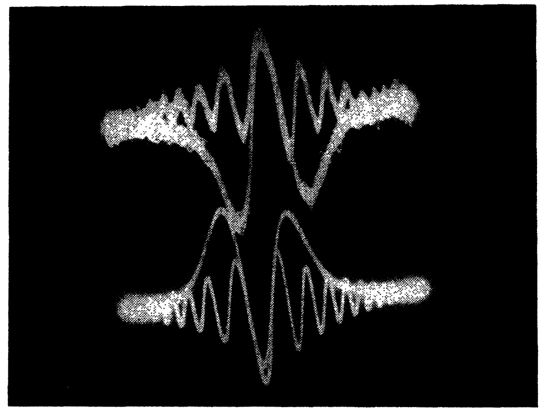

FIG. 2. Proton magnetic resonance lines in H_2 gas at 30 atmos (top) and mineral oil (bottom). The phasing of the 30-cycle reference voltage on the oscilloscope x-axis is adjusted to superimpose the first relaxation wiggles to provide a sharper setting point. Total modulation sweep is about 0.75 gauss.

The results are summarized in Table I. The stated errors are probable errors, which include the calibration of the field-biasing current, uncertainties in the diamagnetic corrections, and the probable error of the measured field-biasing currents themselves. The H_2O *versus* mineral oil results are in good agreement with those of Lindström,[5] whose data are equivalent to the applied field for H_2O being less than that for paraffin oil by the fractional amount $4.1\pm3.0\times10^{-6}$. The absolute value of the proton magnetic moment is virtually unaffected[6] by the results reported herein, because differences in magnetic shielding constitute only about five percent of the stated error in the most recent determination.[7]

TABLE I. Magnetic shielding of the proton resonance in H_2, H_2O, and mineral oil at 27.1 Mc (6365 gauss). The applied field for mineral oil is higher than for H_2. Field differences are in gauss.

Sample	Difference in applied field corrected for diamagnetism	Fractional effect corrected for diamagnetism	Difference in applied field for "infinite cylinders"	Fractional effect for "infinite cylinders"
Mineral oil (Nujol)	0.0235 ± 0.0020	$(3.7\pm0.3)\times10^{-6}$	0.0150 ± 0.0010	$(2.3\pm0.15)\times10^{-6}$
H_2O (distilled)	0.0020 ± 0.0020	(0.3 ± 0.3)	-0.0075 ± 0.0010	(-1.2 ± 0.15)
H_2 (g, 30 atmos)	0.0000 ± 0.0020	(0.0 ± 0.3)	0.0000 ± 0.0020	(0.0 ± 0.3)

We wish to thank C. J. Hoffman for his assistance with several of the measurements. Equipment was provided by a Grant-in-Aid from Research Corporation.

* Supported in part by the ONR.
[1] N. F. Ramsey, Phys. Rev. **78**, 699 (1950).
[2] G. F. Newell, Phys. Rev. **80**, 476 (1950).
[3] H. S. Gutowsky and C. J. Hoffman, Phys. Rev. **80**, 110 (1950).
[4] W. C. Dickinson, Ph.D. thesis, MIT, Cambridge, Massachusetts (1950).
[5] G. Lindström, Phys. Rev. **78**, 817 (1950).
[6] The value obtained in reference 7 cannot be compared directly with these data as their water sample contained ferric ions.
[7] Thomas, Driscoll, and Hipple, Phys. Rev. **78**, 787 (1950).

The Production of π-Mesons in Proton-Proton Collisions

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RECENT measurements[1] on the production of π-mesons in 345-Mev $p-p$ collisions have shown that the spectrum of the mesons has a strong maximum near the upper energy limit. This has been attributed to the interaction between the resulting proton and neutron and to the possible formation of a deuteron.[2] The cross section in the laboratory system was estimated to be 20×10^{-30} cm^2/sterad-Mev in the forward direction.[3]

We have carried out calculations which confirm this interpretation. A phenomenological interaction between nucleons has been assumed, following Foldy and Marshak.[4] It proves to be important, however, to give a more accurate account of the nuclear wave functions. The method employed is similar to that used by various authors[5] for the discussion of bremsstrahlung. The interaction Hamiltonian

$$H'=\int \psi^{+}(x)Q\phi(x)\psi(x)dx$$

between the nucleon and the meson field is written as

$$H'=\int\int [\psi_f{}^{*} \sum_{i=1}^{2} Q_i\phi(x_i)\psi_0]dx_1dx_2$$

in terms of the two-particle wave functions ψ_0 and ψ_f of the initial and final state. For nonrelativistic nucleons the 8-component spinor functions can be reduced to 4-component Pauli functions by a procedure in which a certain allowance is made for negative energy contributions. For the nonrelativistic approximation solutions of the appropriate Schrödinger-Pauli equation with empirical potentials V_0 and V_f can be taken. Serber's suggestion for zero interaction in odd states was adopted, but recent refinements in the $p-p$ interaction were not included.

Detailed calculations have been carried out for the case of a pseudoscalar charged meson with pseudovector coupling. The potentials were assumed to be of the Hulthén form

$$V=J^{(s)}e^{-\kappa r}/(1-e^{-\kappa r})$$

for even triplet ($s=3$) and even singlet ($s=1$) states, with $V=0$ for odd states. The result for the cross section corresponding to the formation of a deuteron is approximately

$$\frac{d\sigma}{d\Omega}=\frac{f^2}{v\mu^2}\cdot\frac{b^3(b^2-1)}{\{1+[(b+1)\kappa/2p_0]^2\}^2}\cdot\frac{k^3\kappa^5}{p_0{}^8}\cdot\left[2\left(\frac{\omega p_0}{kM}\right)^2+\left(\frac{\Delta J}{J^{(3)}}\right)^2-\frac{8\omega}{M}\cos^2\theta\right].$$

Here v is the relative velocity of the protons; $b=MJ^{(3)}/\kappa^2$; $\Delta J=J^{(3)}-J^{(1)}$; k and ω are the momentum and energy of the meson, and p_0 is the initial proton momentum. Inserting values corresponding to Peterson's experiments and taking $1/\kappa=1.17\times10^{-13}$ cm one finds that

$$d\sigma/d\Omega=19f^2(1-0.7\cos^2\theta)\times10^{-30}\ \text{cm}^2.$$

The isotropic term dominates near the threshold; both terms are of the same order of magnitude for 345-Mev protons. It will be seen that after transformation to the laboratory system the magnitude of the cross section at 30° is of the observed order (if an experimental energy resolution of 6 Mev is assumed). At 0° the agreement does not appear to be as good. The angular distribution depends on the type of meson theory assumed; the magnitude of the cross section is strongly dependent on the internucleon potential. Singular potentials give large values for the cross section; a square well leads to a reduction by a factor of 50. This is in contradiction with the earlier results of Foldy and Marshak and illustrates the importance of using a reasonably accurate wave function for small separations of the nucleons.

The transitions to the continuous spectrum of the proton-neutron system can be treated in a similar manner. The virtual ^1S-state of the deuteron tends to produce a peak near the upper end of the meson spectrum. This peak, however, is completely masked by the dominating transitions to a final continuous ^3S-state. The differential cross section is approximately

$$\frac{d\sigma}{d\omega d\Omega}=\frac{2f^2}{v\mu^2}\cdot\frac{b^3}{\{1+[(b+1)\kappa/2p_0]^2\}^2}\cdot\frac{kM\kappa^3}{p_0{}^6}\cdot\left[\frac{2\mu^2}{M^2}-\frac{8\mu k^2}{Mp_0{}^2}\cos^2\theta\right].$$

In the zero momentum system the continuous spectrum consists of an isotropic part proportional to the meson momentum, k, and a $\cos^2\theta$ term proportional to k^3. One finds by integration that the numbers of mesons produced in the discrete and continuous spectra are of the same order. This is consistent with the observations.

The calculations here reported will be presented more fully elsewhere. They are capable of immediate extension to other meson fields and to more complicated nuclear systems.

[1] V. Z. Peterson, Phys. Rev. **79**, 407 (1950).
[2] W. Barkas, Phys. Rev. **75**, 1109 (1949).
[3] L. W. Alvarez, Harwell Conference, September, 1950.
[4] L. L. Foldy and R. E. Marshak, Phys. Rev. **75**, 1493 (1949).
[5] N. F. Mott, Proc. Camb. Phil. Soc. **27**, 255 (1931).

Nuclear Audiofrequency Spectroscopy by Resonant Heating of the Nuclear Spin System

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In nuclear magnetic induction and resonance absorption experiments, the sensitivity decreases rapidly with decreasing frequency[1] if the size of the sample being tested is kept constant. This decrease in sensitivity is due to various causes including the reduction in the difference in the Boltzmann factor for the states

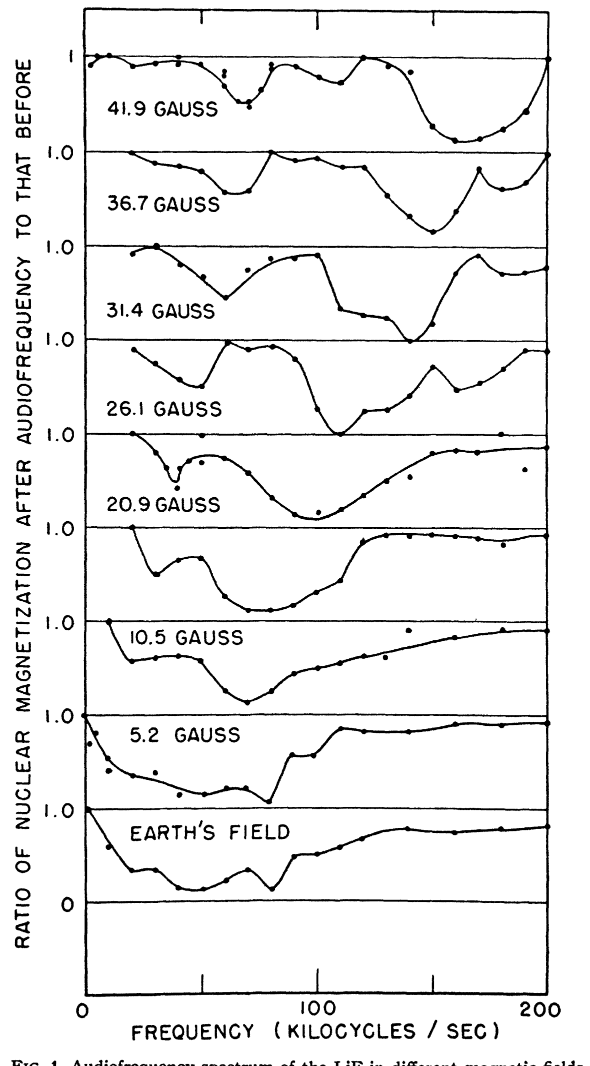

FIG. 1. Audiofrequency spectrum of the LiF in different magnetic fields. The ordinate is the ratio of the strong field Li^7 nuclear magnetization after and before the resonant heating of the nuclear spin system in the indicated magnetic field.