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 $1/\kappa=1.17\times 10^{-13}$ cm one finds that

$$d\sigma/d\Omega=19f^2(1-0.7\cos^2\theta)\times 10^{-30}\text{ cm}^2.$$

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.

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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

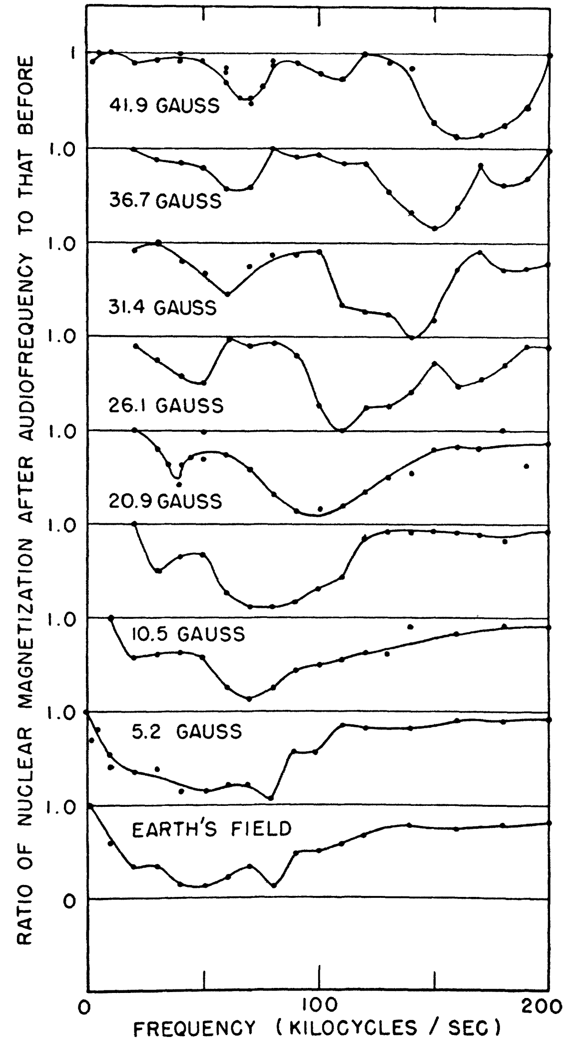

Fig. 1. Audiofrequency spectrum of the LiF in different magnetic fields. The ordinate is the ratio of the strong field Li^7 nuclear magnetization after and before the resonant heating of the nuclear spin system in the indicated magnetic field.

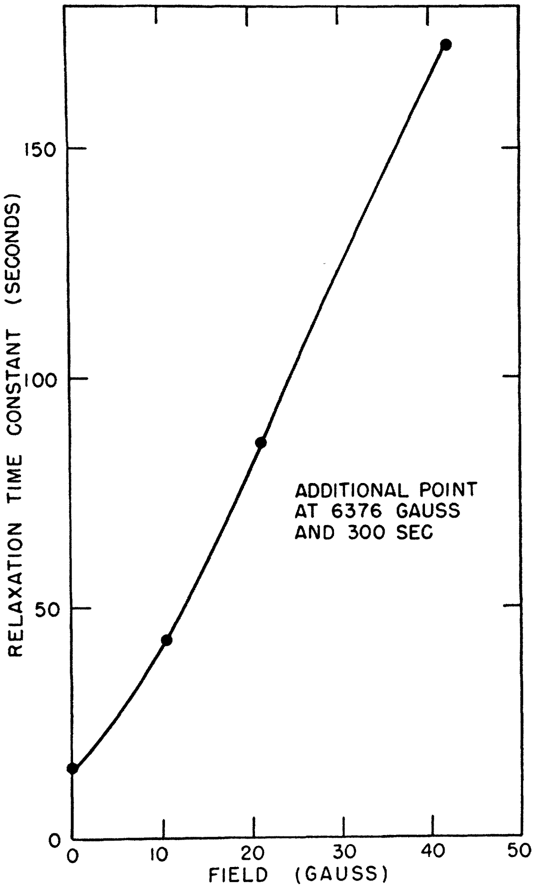

FIG. 2. Relaxation time constant as a function of magnetic field for Li^7 in LiF.

concerned and the reduction in the energy of the photons emitted and absorbed.

Therefore, when one of us (R.V.P.)[2] discovered the long relaxation time of a pure single crystal of LiF, it was suggested by the other (N.F.R.) that such long relaxation times make possible a new nuclear magnetic resonance technique which would have high sensitivity at low frequencies of the oscillating magnetic field. With the new method, the crystal is removed from a strong magnetic field for a time short compared to the relaxation time of the crystal in the absence of a strong field (15 sec for LiF) and during this short time is placed in a weak audiofrequency magnetic field. For one isotope of the crystal, the ratio of the nuclear magnetization immediately before and immediately after the removal from the strong field is measured[2] with a radiofrequency spectrometer. This ratio is then observed as a function of the frequency of the audio-oscillator. The dependence of this ratio on the audio-oscillator frequency presumably arises from resonant heating of the nuclear spin system to a temperature above the low value attained by adiabatic demagnetization when the crystal is removed from the strong magnetic field.

In this way the audiofrequency spectrum of LiF was studied between 20 and 200,000 cycles/sec with the strong field (6376 gauss) observations being of the Li^7 resonance. With audiofrequency magnetic fields of about 0.2 gauss, it was found that resonant heating did not take place below 100 cycles but did occur continuously and completely at frequencies between 1000 cycles and 200,000 cycles. However, when the amplitude of the audiofrequency field was reduced to 0.018 gauss applied for 3 sec, a nuclear audiofrequency spectrum was observed which possessed a broad maximum centered at 50 kc and with a width at half maximum of about 45 kc as shown in the lowest curve in Fig. 1. The first practical application of the 50 kc audiofrequency spectrum of LiF was its indication that the magnetic field reversal in the negative temperature experiments described in an accompanying paper[3] must be accomplished in a time short compared to 1/50 of a msec.

The effect of an external fixed magnetic field on the audiofrequency spectrum was also measured and is shown for different values of the magnetic field between 0 and 42 gauss in the upper curves of Fig. 1. It is of interest to note that the ratios of frequency to field for the two pronounced minima of the highest field curve correspond to nuclear g-factors 5.2 and 2.2 in surprisingly close agreement with the nuclear g-factors 5.26 and 2.17 for F^{19} and Li^7 respectively. The reduction of the subsequent Li^7 magnetization by an oscillatory field appropriate to F^{19} indicates that during or subsequent to the application of the oscillatory field the Li and F spin systems are in at least partial thermal equilibrium.

The effect of the external fixed magnetic field on the relaxation time in the absence of an audiofrequency field is shown in Fig. 2, where the length of time for reduction of the strong field resonance by a factor of two is plotted as a function of the strength of the weak magnetic field in which the sample is stored.

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A Nuclear Spin System at Negative Temperature

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A NUMBER of special experiments have been performed with a crystal of LiF which, as reported previously,[1] had long relaxation times both in a strong field and in the earth's field. These experiments were designed to discover the conditions determining the sense of remagnetization by a strong field when the initially magnetized crystal was put for a brief interval in the earth's field.

At field strengths allowing the system to be described by its net magnetic moment and angular momentum, a sufficiently rapid reversal of the direction of the magnetic field should result in a magnetization opposed to the new sense of the field. The reversal must occur in such a way that the time spent below a minimum effective field is so small compared to the period of the Larmor precession that the system cannot follow the change adiabatically. The experiments in zero field reported above[2] showed a zero field resonance at about 50 kc and therefore the following experiment was tried.

The crystal, initially at equilibrium magnetization in the strong (6376 gauss) field, was quickly removed, through the earth's field, and placed inside a small solenoid, the axis of which was

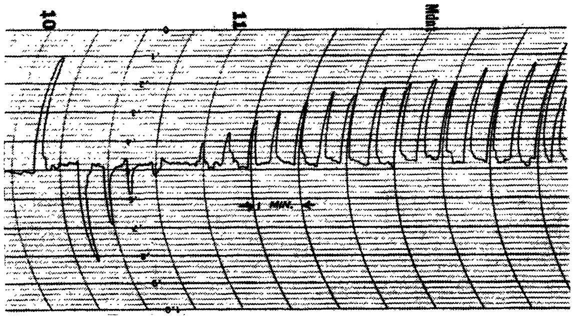

FIG. 1. A typical record of the reversed nuclear magnetization. On the left is a deflection characteristic of the normal state at equilibrium magnetization ($T \approx 300°K$), followed by the reversed deflection ($T \approx -350°K$), decaying ($T \rightarrow -\infty$) through zero deflection ($T = \infty$) to the initial equilibrium state.