Curran and Strothers, found resonances in reaction (3) at 290, 314, 336, 388, 430, 451, and 494 kv, and resonances at 222, 310, 392, 417, 492, 508, and 525 kv accompanied by positron activity. Finding the γ-radiation from the strongest of the latter resonances, those at 222 and 417 kv, to have a mean energy of 1.5 Mev or less, he concluded that these resonances probably belong to reaction (1).

To solve this problem targets of separated Mg isotopes have been prepared in the isotope separator of the Nobel Institute in Stockholm,[4] and exposed to protons from the 500 kv van de Graaff machine of the University of Oslo. The thickness of the targets was about 35 μg/cm^2 Mg^{24}, for Mg^{25} and Mg^{26} the isotopic quantities corresponded to twice the amount of Mg^{24}. The targets were bombarded for 20 sec., giving saturation intensity of the positron activity, and the positrons escaping through a thin window in the target tube were counted for 15 sec. with a thin-walled G-M tube. As the proton current at present does not exceed 2 μA, only the strong resonances at 222 and 417 kv could be investigated. Positron activity corresponding to these resonances was found only on the Mg^{24} target, showing that the reaction $Mg^{24}(p, \gamma)Al^{25}$ is that actually taking place. Of course, there may also be resonances yielding positrons from the Mg^{25} reaction, such as suggested by Curran and Strothers.

[1] S. C. Curran and J. E. Strothers, Proc. Roy. Soc. London **A172**, 72 (1939).
[2] N. Hole, J. Holtsmark, and R. Tangen, Naturwiss. **28**, 399 (1940).
[3] R. Tangen, Kgl. Norske Vid. Selsk. Skr., No. 1 (1946).
[4] I. Bergström, S. Thulin, N. Svartholm and K. Siegbahn, Arkiv f. Fysik 1, 11 (1949).

Pd Film Fast Neutron Detector

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November 28, 1949

PRELIMINARY information has been obtained on resistance variations of a palladium film fired on a ceramic core due to recoil-proton bombardment. In view of the large magnitude of resistance changes, it is proposed here that this resistor might be employed to measure the energy absorbed per gram of tissue as a result of fast neutron flux, after L. H. Gray.[1] The resistors which have been exposed this far were manufactured by Continental Carbon, Inc., according to a process described in "Printed Circuit Techniques."[2] Through the courtesy of Dr. J. W. Jira, of Continental Carbon, resistors with exposed palladium films were obtained before the protective coats of vitreous enamel and paint were applied. One of these resistors was coated with paraffin and placed in an-air-cooled hole in the Oak Ridge pile. A fifteen-hour exposure at full power reduced the resistance from 48,300 to 234 ohms. A similar resistor in a chamber evacuated to approximately nine microns showed a resistance change of from 51,000 to 252 ohms within two minutes after 44 centimeters of hydrogen were applied to the system. The resistors were maintained at approximately room temperature during both the proton-recoil and hydrogen gas experiments.

Another resistor of the same type was placed in a stream of nitrogen within an oven which was brought to 900°C, and then allowed to cool. Again the resistance change was approximately from 50,000 to 200 ohms.

The resistance film initially has a dull gray appearance, and a negative temperature coefficient of resistance, indicating the presence of palladium oxide, but, after the resistance has been reduced by any one of the three treatments described above, the film is bright and shiny and the temperature coefficient of resistance is positive. This would suggest that the oxide has been reduced to the metal. The surface of the film is rough as seen under a low power microscope, both before and after the resistance has been reduced. It is doubtless important to the mechanism that palladium itself is a reducing catalyst, and can also occlude large quantities of hydrogen.

This phenomenon was first observed in the fall of 1947 at Argonne National Laboratory, when NEPA conducted radiation damage tests on electronic components under the direction of Mr. E. S. Bettis and Dr. E. R. Mann. In these tests, and again recently at the Oak Ridge pile, the vitreous enamel covered palladium film resistors of Continental Carbon were exposed in jackets of paraffin, polystyrene, graphite, cadmium, and aluminum. The resistance decreased substantially in the case of the hydrogenous covered resistors, sometimes to 4 percent of the initial value. The agreement in the results between resistors of the same value exposed under identical conditions was poor, and it seems probable that this was due to variations in the thickness of the protective vitreous enamel. Under the same bombardment the resistors covered with graphite, aluminum, and cadmium did not suffer an appreciable change in resistance.

[1] L. H. Gray, Proc. Camb. Phil. Soc. **40**, 72 (1944).
[2] Nat. Bur. Stand., Circular No. 468, November 15, 1947, page 16.

Nuclear Induction Due to Free Larmor Precession*

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December 5, 1949

IN the study of transient and steady state phenomena concerning nuclear magnetic resonance it is well known that the nuclear magnetic moment possesses a flipped spin state having a phase memory of the order of T_2, the total relaxation time, which ranges from $\sim 10^{-5}$ to a few seconds in various substances. On the basis of this property Bloch[1] has pointed out that one can expect to obtain a nuclear induction signal in the absence of an applied r-f field after having suddenly perturbed the spin ensemble by the application of an r-f field pulse of short duration at the resonance condition $\omega = \omega_0 = \gamma H_0$. ω is the applied r-f angular frequency, γ is the gyromagnetic ratio, H_0 is the large d.c. magnetic field applied to a given ensemble of spins, and ω_0 designates the natural Larmor frequency of this ensemble. Directly following the removal of the pulse a resultant component of nuclear magnetization M_{xy} will remain the xy plane perpendicular to the large field H_0, which formerly established this magnetization in the z direction at thermal equilibrium. An inductive coil with its axis in the xy plane first provides the pulse, and thereafter has induced in it a nuclear induction r-f voltage as a consequence of the free Larmor precession of the magnetic moment M_{xy}.

Reported here is an experiment which displays this effect using conventional r-f techniques for providing r-f pulses and amplifiers capable of fast response in conjunction with typical nuclear induction apparatus. Only a single LC tuned circuit is essential for

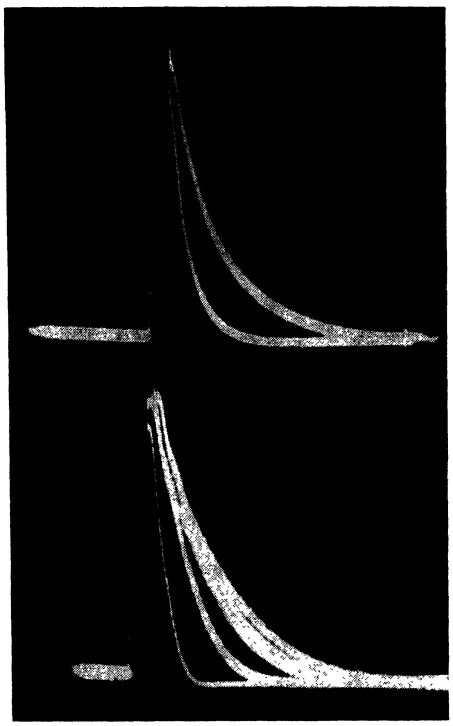


FIG. 1. The top oscillographic trace indicates by double exposure the nuclear induction decay due to protons in two water solutions of $Fe(NO_3)_3$ of different concentrations. The longer decay corresponds to 2×10^{19} Fe^{+++}/cc and the shorter decay corresponds to 9×10^{19} Fe^{+++}/cc, causing a T_2 of 0.0018 sec. and 0.0004 sec. respectively. T_2^* for both cases is ~0.00046 sec. and $t_w\sim100$ μsec. H_1 is adjusted to an intensity such that $\omega_1 t_w\sim\pi/2$ and nutation provides an appreciable $M_{xy}(t_w)$.
Multiple exposures in the bottom photograph show various values of $T_m\sim T_2^*\ll T_2$ for protons in glycerine as T_2^* is arbitrarily changed from a maximum of 6.7×10^{-4} sec. (longest decay) to a minimum of 1.9×10^{-4} sec. (shortest decay). The slight dip following the pulse is due to momentary saturation of the receiver. The exposures are slightly displaced to indicate how $M_{xy}(t_w)$ is affected by changes in T_2^* as well as T_2 (upper photograph) due to decay of nutation during the pulse.

transmitting and receiving r-f energy, and critical balancing procedures are no longer a necessity. R-F pulses are applied at time intervals $>T_1\gtrsim T_2$ at pulse width $t_w<T_2$, at a maximum r-f field intensity H_1 (T_1 is the spin-lattice relaxation time).[2] *Following the pulse an exponential nuclear induction signal (Figs. 1 and 2) appears whose decay time depends upon (1) the extent of external magnetic field inhomogeneities over the sample, and (2) the intrinsic T_2 of the spin ensemble due to lattice conditions.* The condition brought about by (1) obscures a direct measurement of T_2 since the oscillations of M_{xy} over a spectrum of Larmor frequencies begin to interfere destructively and cause the integrated nuclear signal to decay more quickly than would otherwise be effected by T_2. T_1 can be directly measured, similar to a previous method,[3] by comparison of initial decay amplitudes for various known times between pulses. It will be shown in a later paper that (1) is the principal condition contributing to the spin echo effect,[4] which, however, permits direct measurement of T_2. The mechanism of free precession reported here is fundamental to obtaining the echo effect.

A qualitative prediction of the decay is indicated by integrating a simple solution (for M_{xy}) of Bloch's equations[1] over all Larmor frequencies imposed by the magnet, using a symmetric distribution function $g(\Delta\omega)$, where $\Delta\omega=\omega_0-\omega$ and $g(\Delta\omega)$ is maximum for $\Delta\omega=0$. The maximum voltage, V_{max}, of free induction is proportional to the following:

$$V_{max}\sim\omega\, e^{-(t-t_w)/T_2}\int_{-\infty}^{\infty} g(\Delta\omega)M_{xy}(\Delta\omega, t_w)\times\cos[\Delta\omega(t-t_w)+\phi]d(\Delta\omega),$$

where $\phi=\arctan(\Delta\omega/\beta\tan\beta t_w/2)$, $\beta=(\omega_1^2+(\Delta\omega)^2)^{\frac{1}{2}}$, and $\omega_1=\gamma H$. It is convenient to assume

$$g(\Delta\omega)=\frac{2T_2^*}{1+(\Delta\omega)^2T_2^{*2}},$$

where $T_2^*=2/(\Delta\omega)_{\frac{1}{2}}$ and $(\Delta\omega)_{\frac{1}{2}}$ is the total width at half-maximum of the spectrum due to external field inhomogeneities. If we further assume $\omega_1\gg(\Delta\omega)_{\frac{1}{2}}$ then $\phi\to0$ and $M_{xy}(\Delta\omega, t_w)$ is nearly constant in the region of $\Delta\omega\sim0$ where the integral does not vanish. Therefore, integration gives approximately

$$V_{max}\sim M_{xy}(t_w)\omega\exp\left[-t\left(\frac{1}{T_2}+\frac{1}{T_2^*}\right)\right],$$

where t is measured from the end of the pulse. The decay times T_m directly measured from oscillographic traces appear to obey the relationship $1/T_m=1/T_2+1/T_2^*$. A systematic variation in T_2 for protons in water solutions of ferric ions of known concentrations C has been obtained to confirm the known relationship $T_2\sim1/C$, having the knowledge of T_2^*. The values of T_2 so obtained are in agreement with results obtained by Bloembergen *et al.*,[5] using the line width method.

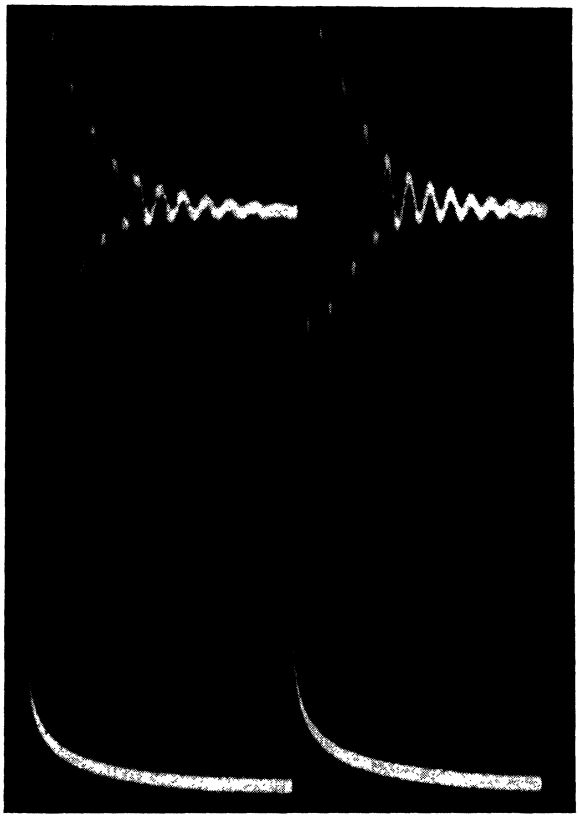
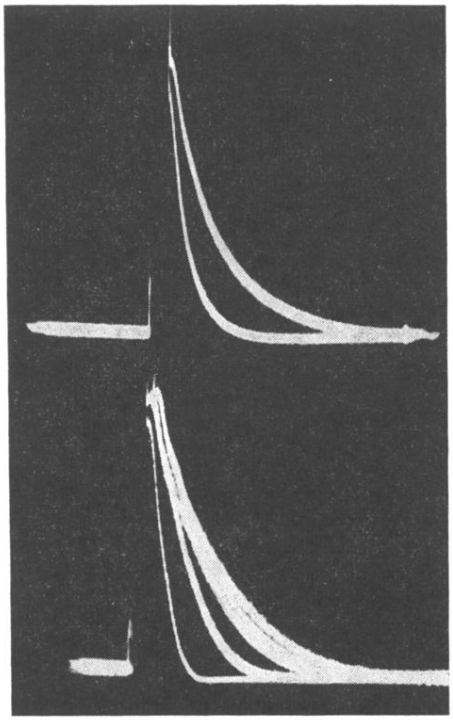


FIG. 2. The top trace indicates a beat note between an external r-f signal generator (near the Larmor frequency, loosely coupled to the inductive coil) and the nuclear signal shown alone (after detection) on the bottom trace. This beat note is identical in principle with the "wiggle effect" (see reference 5) except that H_0 is held constant in this case.

The author is indebted to H. W. Knoebel for his valuable assistance in the arrangement and design of the apparatus.

* Supported in part by ONR.

[1] F. Bloch, Phys. Rev. **70**, 460 (1946).
[2] T_2 includes the effect of T_1 in limiting the phase memory of Larmor precession.
[3] E. L. Hahn, Phys. Rev. **76**, 145 (1949).
[4] E. L. Hahn, Bull. Am. Phys. Soc. **24**, No. 7, 13 (1949).
[5] Bloembergen, Purcell, and Pound, Phys. Rev. **73**, 679 (1948).



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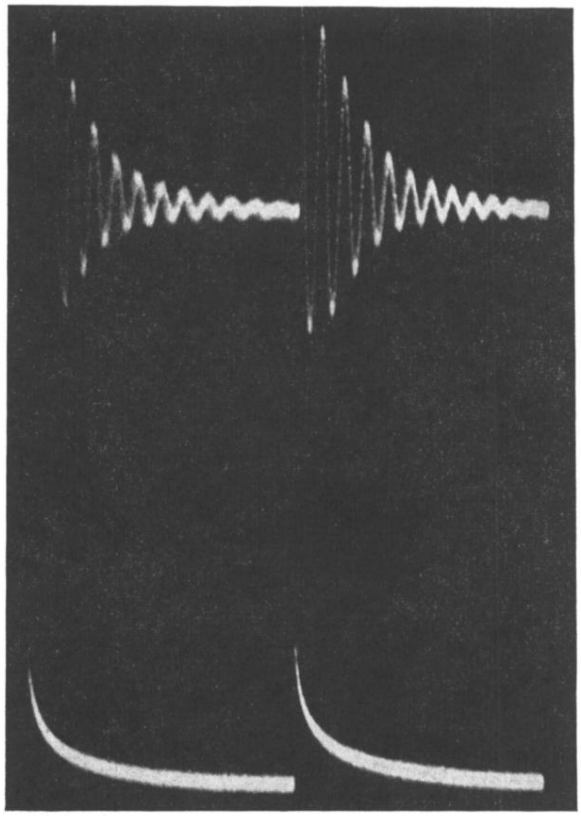

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