Table II. The measured hyperfine splitting obtained by extrapolating to zero pressure.

Hydrogen isotope	Buffer gas	Number of bulbs at different pressure	Number of observations per bulb	Hyperfine splitting in Mc/sec
H^1	A	4	40	1420.405712
H^1	Ne	8	20	754
H^1	H_2	4	40	721
H^1	He	4	10	698
Average				1420.405726
H^2	A	3	20	327.384352
H^2	Ne	4	15	347
Average				327.384349
H^3	A	3	40	1516.701382
H^3	Ne	3	40	410
Average				1516.701396

the lines determined for the various buffer gases fail to meet in a point at zero pressure has been taken as a measure of the error in the hyperfine splittings of these two isotopes. The results for hydrogen and tritium are

$$\Delta\nu(H^1) = 1420.405726 \pm 0.000030 \text{ Mc/sec},$$

$$\Delta\nu(H^3) = 1516.701396 \pm 0.000030 \text{ Mc/sec}.$$

The result for hydrogen agrees very well with the most recent atomic beam result of Kusch[4] and the paramagnetic resonance result of Wittke and Dicke[5] with no pressure shift correction. The value for deuterium is slightly outside the quoted error in the atomic beam measurement of Kusch.[4] The value for tritium disagrees with the atomic beam measurement of Prodell and Kusch.[6]

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NUCLEAR RESONANCE ABSORPTION AND NUCLEAR ZEEMAN EFFECT IN Fe^{57}†

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Mössbauer recently demonstrated that the 129-kev gamma ray in Ir^{191} underwent resonance absorption when the osmium source and iridium absorber were both at low temperatures.[1] The resulting absorption peak displayed the natural line shape.[2] Mössbauer explained this effect by adapting a theory of Lamb.[3] If the emitting atom is bound, at a low ambient temperature, in a solid of high Debye temperature, it cannot always recoil freely. In a certain fraction of the transitions, the recoil momentum is given to the entire solid. The emitted photon then suffers no Doppler shift, but possesses the full transition energy and can be resonantly absorbed or scattered by another nucleus of the same type, also bound in a solid. Mössbauer's experiments have been repeated and extended[4,5] and the theory has been refined.[6,7]

In the present Letter, we report on a resonance absorption experiment with Fe^{57} in ferromagnetic iron. The pertinent nuclear data appear in Fig. 1(a).[8] The low recoil energy due to the 14.4-kev photon, 0.002 ev, and the high Debye temperature of iron, 335°K, permit experiments up to temperatures of about 200°C. The large cross section at resonance,[9] $\sigma_0 \approx 1.5\times10^{-18}$ cm^2, renders experiments feasible with natural iron even though the natural abundance, a, for Fe^{57} is only 2.17%. Furthermore, the Zeeman splitting of the nuclear levels due to the hyperfine coupling of the nucleus with the electrons is larger than the natural line width Γ ($\Gamma = \hbar/\tau = 4.6\times10^{-9}$ ev) and can be observed directly.

Our experimental arrangement is shown in Fig. 1(b). The source consists of carrier-free Co^{57} in less than 1 mg of iron. The absorber is an iron foil, sandwiched between two Lucite disks. The absorber disk can be rotated over a continuous range of constant speeds. The component of disk velocity in the direction of the gamma ray thus yields a continuous relative motion between source and absorber and provides for the Doppler shift necessary to sweep over the absorption curve. A collimating slit is cut in such a way that the velocity component varies by about ±10% over the area of the slit. A Philips beryllium-window thin NaI(Tl) scintillation counter is used to measure the 14.4-kev gamma ray. The resonance absorption is expressed by a ratio

$$\epsilon(v) = [N(\infty) - N(v)]/N(\infty).$$

Here, v denotes the average component of velocity of the absorber in the direction of the incoming gamma rays, $N(v)$ is the corresponding counting rate, and $N(\infty)$ is the counting rate at a velocity which is so large that no resonance absorption occurs ($v \approx 1$ cm/sec).

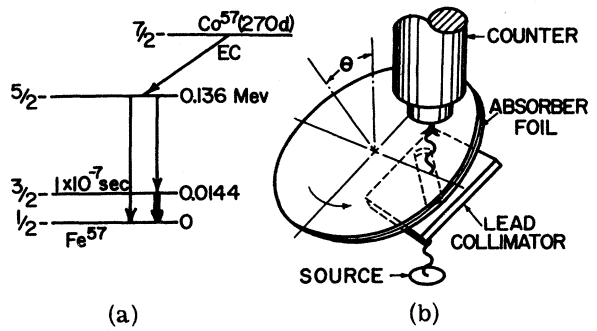

FIG. 1. (a) Decay scheme of Fe^{57}. (b) Experimental arrangement. The velocity component of the rotating absorber disk in the direction of the gamma rays provides a continuous and adjustable relative motion between source and absorber.

The maximum resonance absorption $\epsilon(0)$ as a function of temperature of the Fe^{57} source was measured with a steel absorber of thickness 16.5 mg/cm^2 at an angle $\theta = 30°$. The curve $\epsilon(0)$ stays essentially constant from 25°C to 200°C, then begins to decrease slowly, and approaches zero asymptotically at about 550°C.

Figure 2 displays $\epsilon(0)$ as a function of absorber thickness. The absorption curve is analyzed by a method used by the Los Alamos group.[4,10] If f is the fraction of the 14.4-kev line which is resonant, and f' the probability of absorption without recoil, then

$$\epsilon(0) = f[1 - I_0(x/2)\exp(-x/2)].$$

Here, $I_0(z) = J_0(iz)$ is the Bessel function of order 0 and imaginary argument, $x = f'na\sigma_0$, and n is the number of iron atoms per cm^2. Fitting the experimental points to curves $\epsilon(0)$ vs x, calculated for several values of f, yields unique values for f and f'. From Fig. 3 it follows that $f = 0.20 \pm 0.04$ and $f' = 0.22 \pm 0.06$.

Figure 3 exhibits the resonance absorption curve $\epsilon(v)$, not corrected for absorber thickness or finite velocity resolution. To discuss Fig. 3, we assume initially that the magnetic moment μ_g of the Fe^{57} ground state is zero and that the excited state in both source and absorber is split into four equally spaced magnetic sublevels. This splitting is due to the interaction of the magnetic moment μ^* of the excited state with the

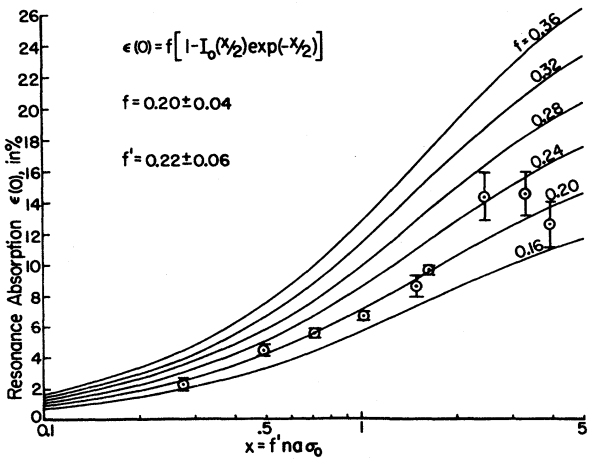

FIG. 2. Resonance absorption $\epsilon(0)$ as a function of absorber thickness. The abscissa $x = f'na\sigma_0$ is proportional to the absorber thickness.

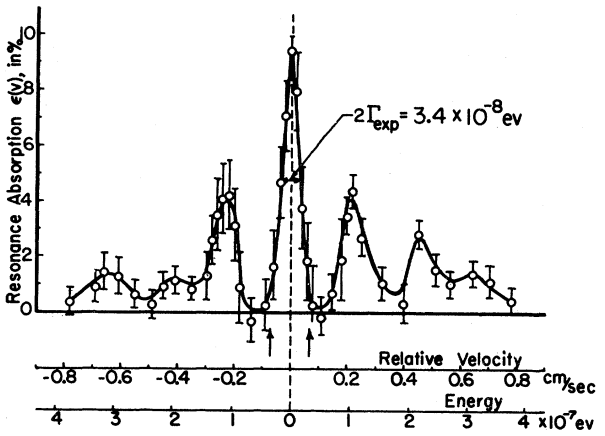

FIG. 3. Resonance absorption curve $\epsilon(v)$ of the 14.4-kev gamma transition in Fe^{57}, exhibiting Zeeman splitting. Source and absorber consist of natural iron and are at room temperature.

magnetic field H at the nucleus. The 14.4-kev lines emitted by the source then consist of four components, separated in energy by $\mu^* H/I^*$, where $I^* = 3/2$ is the spin of the excited state. At zero relative velocity between source and absorber, these emission components match the corresponding four absorption components yielding the resonance absorption $\epsilon(0)$. Moving the absorber with a velocity component v shifts the absorption components with respect to the emitted ones by an energy $(v/c)E$, where $E = 14.4$ kev. One can thus trace out the central line. Since both emission and absorption components are Breit-Wigner curves of width Γ, the central line should approximate a Breit-Wigner curve of width $2\Gamma = 1.1 \times 10^{-8}$ ev. At velocities $v = \pm c\mu^* H/I^* E$, three of the four components should overlap again and produce, on either side of the center, a line of smaller intensity. Similarly, two more lines of even weaker intensity should appear on either side at twice and three times the distance of the first one. The ratio of intensities of the lines depends on the relative orientation of emitting and absorbing nuclei. For random orientation, one expects intensities 4:3:2:1.

Figure 3 clearly shows the Zeeman splitting of the 14.4-kev transition. In order to interpret Fig. 3, some information about H is required. No direct measurement is available, but from the isotropic hyperfine splitting of iron group salts, a value $H \approx 10^5$ gauss is expected.[11,12] This value will be used for the following discussion, although the actual field may be considerably larger.[13] The assumption that the resolved lines are due to splitting of the excited state may be justified by considering the positions of the first lines that would result from a ground-state moment. With the experimental upper limit[8] $\mu_g = 0.05\mu_n$ and $H = 10^5$ gauss, these lines would appear at the positions of the arrows in Fig. 3. This ground-state splitting could not be resolved in our equipment, but it would broaden the observed lines if present.

The measured value for the width of the central line, $2\Gamma_{exp} = 3.4 \times 10^{-8}$ ev, is considerably larger than the predicted one. This broadening may be due to a small magnetic moment of the ground state or to extranuclear interactions.[13]

From the separation of the observed lines the magnetic moment of the excited state may be estimated to be $\mu^* = 0.50\mu_n$. Because of the uncertainty in H this value should be accepted with caution. A direct splitting of the lines in an external magnetic field will yield a more reliable value of μ^*.

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