Letters to the Editor

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Modulation of a Light Beam by Precessing Absorbing Atoms

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RECENT experiments[1,2] have demonstrated that the orientation of atoms (and molecules) can be effectively monitored by observing the transmission of a beam of polarized optical resonance radiation. This note will serve to point out that the monitoring technique can be extended to faster motions like the precession in a magnetic field where the result is a high-frequency modulation of the transmitted light beam. For simplicity we will assume a ground state angular momentum $J=\frac{1}{2}$ and complete polarization. Then the state for which the vector $\langle\mathbf{M}\rangle$ formed from the expectation values of the angular momentum components, $\langle M_x\rangle$, $\langle M_y\rangle$, and $\langle M_z\rangle$, points in the direction (ϑ,φ) can be described by

$$\Psi_{\vartheta,\varphi}=\cos(\vartheta/2)e^{-i\varphi/2}(+)+\sin(\vartheta/2)e^{i\varphi/2}(-),$$

where $(+)$ and $(-)$ denote the two eigenstates with $m_z=+\frac{1}{2}$ and $m_z=-\frac{1}{2}$. Now for the simplest case of an optical transition $J=\frac{1}{2}\rightarrow J'=\frac{1}{2}$ under the influence of circularly polarized light incident parallel to the z axis for which the selection rule $\Delta m_z=+1$ applies, only the fraction of Ψ in the $(-)$ state will contribute to the absorption. This fraction is given by

$$f=\sin^2(\vartheta/2)=\tfrac{1}{2}[1-\cos\vartheta],$$

where ϑ is the angle between the angular momentum vector and the beam. This result must be independent of the special choice of coordinate system and eigenstates. Consequently it must hold quite generally that

$$f=\tfrac{1}{2}[1-(\mathbf{m}\cdot\mathbf{p})],$$

where $\mathbf{m}$ and $\mathbf{p}$ are unit vectors in the direction of the angular momentum vector $\langle\mathbf{M}\rangle$ and the beam direction. In the important case that $\langle\mathbf{M}\rangle$ precesses around a magnetic field in the z direction with a circular frequency ω forming an angle ϑ against it while the direction of the light beam is parallel to the x axis one obtains

$$f_x=\tfrac{1}{2}[1-\sin\vartheta\cos\omega t]$$

indicating a sinusoidal variation at the frequency ω of the absorption. Similar expressions are to be expected for optical transitions involving higher J, J' values when the ground state is executing a precessing motion. Further examples of precessing motions which could be used for modulation purposes are found in the ones caused by crystalline electric fields or the ones due to electric and magnetic interaction with the atomic nucleus.

One example of experimentally realizing the precession of the momentum vector $\langle\mathbf{M}\rangle$ essential in the proposed modulation scheme is discussed in the following: Sodium atoms contained in a spherical absorption cell are subjected to an intense beam of circularly polarized resonance light, "z beam," and a static magnetic field of the order of one gauss, both in the z direction. This creates a polarization of the atomic momenta by optical pumping,[3] the vector $\langle\mathbf{M}\rangle$, of absolute value M_0, pointing in the z direction. The time dependence of $\langle\mathbf{M}\rangle$ now is governed by the Bloch equations[4] for the angular momentum components,

$$\dot{M}_x-\gamma(M_yH_z-M_zH_y)+(1/T_2)M_x=0,$$
$$\dot{M}_y-\gamma(M_zH_x-M_xH_z)+(1/T_2)M_y=0,$$
$$\dot{M}_z-\gamma(M_xH_y-M_yH_x)+(1/\tau)M_z=(1/\tau)M_0.$$

Here and in the following the angular brackets to indicate expectation values have been omitted. The polarization decay time τ depends on the light intensity, being of the order of 0.01–0.1 sec in practical cases.[2] The phase memory time is denoted by T_2 as usual. Experimentally it can be made to approach τ. Under these conditions all the methods discussed by Bloch,[4] Hahn,[5] and Packard and Varian[6] can be used to create a precessing angular momentum component, the most common one being the application of a rf field perpendicular to the z axis whose frequency fulfills the resonance condition. For the two hfs substates of sodium this frequency turns out to be very nearly equal to 700 (kc/sec)/gauss, the Back-Goudsmit effect being negligible. A second (weaker) beam of circularly polarized resonance light, "x beam," applied in the x direction, will then exhibit the modulation at the precession frequency after passing through the cell since the absorption coefficient K_x of the partially polarized sodium vapor will vary according to

$$K_x=K[1-a(M_x/M_0)].$$

Here K is the absorption coefficient for the unpolarized vapor while a is a dimensionless constant depending on the degree of polarization attained and also on nuclear effects. The absorption of the z beam on the other hand, as determined by

$$K_z=K[1-a(M_z/M_0)],$$

provides a measure of M_z. Under favorable conditions[2] rf fields of the order of microgauss can be made to modulate intense light beams.

Very strong and narrow resonance signals have been obtained by observing the variation of the transmitted z beam. By feeding the rf field from the (amplified) photocurrent generated by the modulated x beam an atomic oscillator can be constructed. Further experiments along the above lines are under way in collaboration with Dr. A. Bloom and Dr. E. Bell and with Mr. E. S. Ensberg.

[1] H. G. Dehmelt, Phys. Rev. **103**, 1125 (1956).
[2] H. G. Dehmelt, Phys. Rev. **105**, 1487 (1957).
[3] A. Kastler, J. phys. radium **11**, 255 (1950).
[4] F. Bloch, Phys. Rev. **70**, 1 (1946).
[5] E. L. Hahn, Phys. Rev. **80**, 580 (1950).
[6] M. E. Packard and R. Varian, Phys. Rev. **93**, 941 (1954).

Isotope Shift in the Spectrum of Indium I

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DETERMINATIONS of the isotope shifts in five lines of the arc spectrum of indium[1] were derived from measurements of the differences in wavelength of the lines emitted by natural indium and by indium enriched in In^{113}; they depended on the accuracy of the mass spectrograph analysis of the enriched isotope, since the measured displacement had to be multiplied by a conversion factor derived from the isotope abundance ratio. This was stated by the Atomic Energy Research Establishment, Harwell, England to be $(49.7\pm0.1)\%$ In^{113}, from which follows the conversion factor 2.20.

It has since been possible by observing the absorption of an atomic beam of indium enriched in In^{113} to resolve the lines of In^{113} from those of In^{115} in the strong hfs components (0 and 662 millikaysers) of the line 4101 A, and thus to measure the isotope shifts directly. These were, respectively, 7.8 and 9.9 mK, with a probable error of ±0.5 mK. The conversion factors required to obtain these shifts from the displacements (4.77 and 5.41 mK) measured in the earlier work are, respectively, 1.64 and 1.83; the mean, 1.74 ± 0.1, corresponds to an abundance of $(61.5\pm3)\%$ of In^{113}.

The indium enriched in In^{113} actually used in the earlier work had been kept; it was sent for reanalysis to the Commissariat à l'Énergie Atomique, Saclay, France. Three analyses gave values of 60.0, 61.4, and 64.6% In^{113}; a new analysis made at Harwell gave the value 61.5% In^{113}. These results confirm the requirements of the purely spectroscopic measurements, and it appears that the analysis of 49.7% must have been in error; and that the conversion factor to be used should be 1.74 ± 0.1, which is independent of isotope analyses, though in good agreement with the new analyses. The isotope shifts calculated with this conversion factor are

Wavelength (A)	4511	4101	3256	3039	2710
Displacement (mK)	5.0	5.1	4.3	4.3	4.0
Isotope shift (mK)	8.7	8.9	7.5	7.5	7.0.

In all cases the lines of In^{113} are shifted to the red. The value for 4101 A is the average of the individual shifts of the four hfs components, which were

Component (mK)	0	281	381	662
Displacement (mK)	4.8	4.9	5.3	5.4
Isotope shift (mK)	8.3	8.5	9.2	9.4.

The probable error of the isotope shifts is 0.5 mK for the visible lines and 1 mK for the ultraviolet lines.

[1] D. A. Jackson, Phys. Rev. **101**, 1425 (1956).

Report on Long-Lived K^0 Mesons*

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THE experiment previously reported[1] which established the existence of a long-lived neutral V particle is being continued. In this report, we give evidence that (1) strengthens the previous surmise[1] that these are indeed K-mass particles with decay modes primarily into $\pi e\nu$ and $\pi\mu\nu$, (2) establishes rather convincingly the existence of the $\pi^+\pi^-\pi^0$ mode[2], (3) provides additional evidence for the particle mixture theory.[3]

We have now examined 5000 photographs taken in the neutral V beam at the Cosmotron. The experimental arrangement differed from that previously employed[1] in that a $\frac{1}{16}$ in. Lucite "thin window" was placed on the entrance side of the cloud chamber and the collimation and shielding arrangements were im-

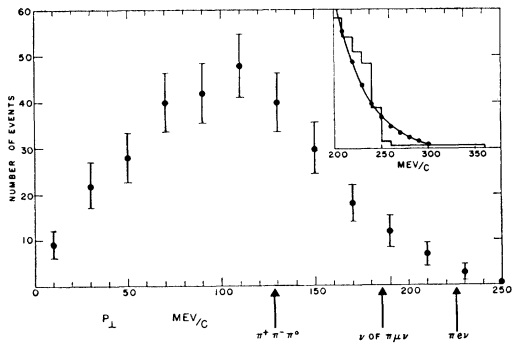

FIG. 1. Transverse momenta of the positive, negative, and neutral secondaries of 100 events. The arrows indicate the cutoffs for various decay modes. The inset magnifies the end point and compares with a resolution folded linear cutoff at 230 Mev/c.