OBSERVATION OF FORBIDDEN RESONANCES IN OPTICALLY DRIVEN SPIN SYSTEMS

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In a recent Letter[1] we described experiments in which a macroscopic moment precessing at the Larmor frequency was induced in a spin system by the synchronous modulation of an incident beam of optical pumping radiation. It was pointed out there that this resonance effect does not involve a perturbation directly coupling the magnetic substates; instead it may be regarded as an indirect effect employing the coupling of each of the magnetic sublevels to a common optically excited state. This statement carries the important corollary that such a resonance might be observed even if a direct coupling between the sublevels does not exist, i.e., even if there is no possible matrix element for the direct transition. We report here the observation of such a forbidden resonance in the $\Delta m = 2$ ($g = 4$, 5.6 Mc sec^{-1} gauss^{-1}) transition between the sublevels $m = 1$ and $m = -1$ in the $2\,^3S$ metastable state of helium. It is clear that the method is generally applicable to other optically pumped systems having more than two sublevels.

In order to describe the experiment, we bear in mind that the transformation properties of triplet state wave functions under rotations are the same regardless of whether the angular momentum is spin or orbital. It is therefore convenient to take advantage of the spatial representation afforded by the orbital functions, whose angular parts can be written as follows:

$$m = 1, \quad \psi_1 = (x + iy)\exp(-i\omega_0 t),$$

$$m = 0, \quad \psi_0 = \sqrt{2}\,z,$$

$$m = -1, \quad \psi_{-1} = (x - iy)\exp(i\omega_0 t),$$

the functions being suitably normalized on a sphere of radius r. ω_0 is the Larmor angular frequency in a field H_0 parallel to the z axis for the usual magnetic transition $\Delta m = 1$. If an ensemble of triplet helium metastables is irradiated by resonance radiation, then, as shown by Colegrove and Franken,[2] optical pumping results in an alignment process tending to populate the state described by $\sqrt{2}\,z$, the effect being a maximum when the axis of the light beam is in the z direction. (The axis of the light is either the direction of propagation of unpolarized light or the direction of the electric vector of plane-polarized light. For our purposes it is immaterial whether the actual alignment results in an excess or a deficit in the specified state.)

Consider now what happens if the light axis is rotated so that it is perpendicular to H_0, specifically if it is in the x direction. Instantaneously the light pumps a small alignment in the state described by $\sqrt{2}\,x$. This alignment immediately proceeds through a time development given by

$$\sqrt{2}\,(x\cos\omega_0 t + y\sin\omega_0 t) = (\psi_1 + \psi_{-1})/\sqrt{2},$$

whose expectation value for population excess in the x direction varies as $\cos^2\omega_0 t$ and is therefore periodic at twice the Larmor frequency. If the light is left on continuously, then the successive smearing-out of phases still results in a net alignment, but much weaker than the maximum.[2] However, let the light be modulated at frequency $2\,\omega_0$; then the result is a synchronous reinforcement of the time-dependent effect resulting in a relatively large precessing alignment. By a treatment exactly analogous to that used in reference 1, it can be shown that the observable effect should be an increase in intensity of the transmitted light when the light modulation frequency ω is within about one linewidth of $2\,\omega_0$.

The possibility of obtaining double-frequency optical effects upon driving a spin-1 system at its Larmor frequency has been pointed out elsewhere.[3] However, the unique feature of the present experiment is the fact that the time-dependent alignment defined by the state $(\psi_1 + \psi_{-1})/\sqrt{2}$ does not correspond to any kind of directly observable macroscopic moment in the case of helium. Furthermore, note that the $m = 0$ level does not enter in the description of the resonant state. Thus the resonance should occur as described even if the $m = 0$ level is displaced from its median position between the $m = \pm 1$ levels for any reason. The resonance linewidth is expected to be about the same, in frequency units, as that of the Larmor resonance and therefore only half as large in terms of magnetic field changes.

The experiment was performed with substantially the same apparatus described in reference 1 but without the circular polarizer. Since alignment effects in He are much smaller than the orientation obtained with a circular polarizer,[4] it was necessary to assure virtually 100% modulation of the light beam in order to make the signal detectable. This was accomplished most simply by operating in a weak field $H_0 \approx 0.01$ gauss and an observed Larmor frequency $\omega_0/2\pi$ of 24 kc/sec. The $g=4$ resonance at 48 kc/sec was clearly observable on the oscilloscope with or without a linear polarizer in the light beam. Rotation of the linear polarizer verified, within signal-to-noise limitations, that the signal amplitude obeyed the $\sin^2\theta$ dependence to be expected by generalizing the above arguments (θ is the angle between light axis and H_0).

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[3]A. Kastler, Compt. rend. (to be published).
[4]L. D. Schearer, Second International Conference on Quantum Electronics (to be published).

PION-PION INTERACTION IN PION PRODUCTION BY π^+-p COLLISIONS*

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Since the first conjectures[1] that rise in the total π^--p cross section between 300 and 600 Mev might be caused by a pion-pion interaction, this subject has received considerable attention. Theoretical analysis[2] of high-energy electron scattering on protons and neutrons has predicted a resonance in the pion-pion interaction at a total di-pion energy (ω) of 4 to 5 pion masses, with isotopic spin and angular momentum both equal to one. Several analyses of π^--p experiments[3] in the 1-Bev energy range have tended to confirm this prediction, and application[4] of the Chew-Low method has indicated a steep rise in the pion-pion cross section above $\omega=4$. Recent work[5] with 1.9-Bev π^--p collisions shows a peak in the pion-pion interaction at $\omega \sim 5.5$. We report here evidence of pion-pion interaction in π^+-p collisions at three separate energies, which show striking effects attributable to a pion-pion resonance with ω of about 5.5 pion masses.

The data presented are results of a systematic study of pion-proton reactions at kinetic energies of 910 Mev, 1090 Mev, and 1260 Mev, which is still in progress. Photographs taken at the Cosmotron in the Brookhaven 20-inch hydrogen bubble chamber have been scanned for all interactions. All two-pronged collisions have been measured on a projection microscope of the Franckenstein type and have been processed by the Yale spatial reconstruction and kinematical fitting programs on the IBM 704 of the New York University Computing Center. Each possible identification assigned by the computation has been compared by a physicist with other information (including ionization densities) available from the photographs, to establish the final identification. Cross sections for the various reactions, based upon the first compilation of these events, are shown in Table I.

The influence of pion-pion interaction will appear most readily in the single pion production processes: $\pi^+ + p \rightarrow p + \pi^+ + \pi^0$ and $\pi^+ + p \rightarrow n + \pi^+ + \pi^+$. Accordingly, the Q value of the two outgoing pions (that is, the kinetic energy of their relative motion in their mutual center of momentum) has been computed for each individual occurrence of single pion production. The distribution of Q values at each energy is shown in Fig. 1. This figure includes all identified events, without additional selection.

In the reaction $\pi^+ + p \rightarrow p + \pi^+ + \pi^0$, a definite peak appears at each energy in the Q-value region of 400-500 Mev, extending well above the number of events to be expected from a uniform momentum-space distribution of secondary particles. The peaks also extend well above the distribution to

Table I. π^+-p cross sections (in mb) at 910-Mev, 1090-Mev, and 1260-Mev kinetic energy.

	910 Mev	1090 Mev	1260 Mev
σ_{total}	24.5 ± 1.3	30.1 ± 1.6	40.3 ± 2.2
σ_{elastic}	10.3 ± 0.9	12.6 ± 1.1	16.5 ± 1.4
$\sigma(p\pi^+\pi^0)$	10.4 ± 0.9	10.8 ± 1.0	11.9 ± 1.2
$\sigma(n\pi^+\pi^+)$	2.6 ± 0.4	2.5 ± 0.5	4.6 ± 0.7
$\sigma_{\text{multiple } \pi \text{ prod.}}$	1.3 ± 0.3	3.9 ± 0.6	6.9 ± 0.9
$\sigma(\Sigma$-$K)$	$0.034^{+0.018}_{-0.012}$	0.25 ± 0.02	0.42 ± 0.07