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HYPERFINE STRUCTURE OF GALLIUM 69 IN CROSSED ELECTRIC AND MAGNETIC FIELDS*

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May 1970

Abstract

Level crossings which occur in the hyperfine structure of ^{69}Ga under the combined influence of electric and magnetic fields are investigated with respect to the field orientation. The possibility of detecting "anti-crossings" by the atomic beam method is considered.

In recent years several experiments have been reported in which electric fields were used in the C-region of an atomic beam apparatus [1]. Some of these experiments were concerned with a study of the Stark effect while others took advantage of the Stark effect as a means of tunning energy levels. In all of these experiments the electric field was used either alone or in parallel with a magnetic field except for possible accidental off-axis field components. Most atomic beam experiments involving electric fields have been on J = 1/2 states (e.g. alkalies) whose interaction with an electric field is a scalar and therefore independent of the field direction. More recently atomic beam electric field experiments involving gallium, indium and thallium have been reported [2]. Atomic beams of gallium and indium usually contain both the ground $^2P_{1/2}$ state and the metastable $^2P_{3/2}$ state and thus regardless of which state is the object of study both are present. The $^2P_{3/2}$ state possesses a tensor polarizability

and consequently the direction as well as magnitude of the electric field is important in determining the combined Zeeman-Stark effect. We examine the influence of crossed fields on the $^2P_{3/2}$ state taking ^{69}Ga as an example.

The interaction of the $^2P_{3/2}$ state of ^{69}Ga with uniform static external electric and magnetic fields is given in the Fm representation by

$$\langle F'm'|\mathcal{H}|Fm\rangle = \left(ha\,\frac{K}{2} + hb\,\frac{K(K+1) - 75/4}{24}\right)\delta_{F'F}\,\delta_{m'm}$$

$$+ \sqrt{15}\,\mu_0 H\,[(2F+1)(2F'+1)]^{1/2}(-1)^{1-m}\begin{pmatrix} F' & 1 & F \\ -m' & 0 & m \end{pmatrix}\begin{Bmatrix} 3/2 & F' & 3/2 \\ F & 3/2 & 1 \end{Bmatrix}[(-1)^{F-F'}g_J + g_I]$$

$$- \frac{5\sqrt{6}}{2}\,\alpha_2\,[(2F+1)(2F'+1)]^{1/2}(-1)^{1-m}\begin{pmatrix} F & 2 & F' \\ -m & Q & m' \end{pmatrix}\begin{Bmatrix} 3/2 & F & 3/2 \\ F' & 3/2 & 2 \end{Bmatrix}\sum_{qq'}\begin{pmatrix} 1 & 1 & 2 \\ q & q' & Q \end{pmatrix}E_q E_{q'} \quad ,$$

where $K = F(F+1)-15/2$; a, b are the usual hyperfine constants; $\alpha_2 = -2.76\ KH_z/(\frac{hV}{cm})^2$ is the tensor polarizability and E_q the spherical components of the electric field $\underline{E}$ [3]. The Z-axis is taken along the magnetic field $\underline{H}$. $\langle F'm'|\mathcal{H}|Fm\rangle$ was diagonalized by machine for different orientation of the electric field in the X-Z plane. The result for $\underline{E}$ parallel to $\underline{H}$ is shown in Fig. 1a for the F = 3 hyperfine state [4]. Nine crossings occur between magnetic levels for which $\Delta m = 1, 2, 3, 4$ or 5. When $\underline{E}$ is rotated the Stark operator is no longer diagonal in m but rather levels for which $\Delta m = 1, 2$ are now directly coupled, while levels for which $\Delta m > 2$ interact in higher order perturbations. The coupling leads to a repulsion of the levels removing the degeneracy at the crossing points. This is shown in Fig. 1b for an angle of $\phi = 5°$. When $\phi \to 90°$ all crossings become "anti-crossing." Of particular interest in the crossing of the m = -1 and m = -2 levels since transitions between these lead

to a refocusing of the atomic beam. Application of degenerate perturbation theory shows that for $\phi(\text{rad}) \ll 1$ the degeneracy is removed by $\nu \approx \frac{3}{\sqrt{5}} \alpha_2 E_0^2 \phi$ where E_0 is the value of E at the crossing. This amounts to $\approx$ 7KHz/1° for the example shown in Fig. 1. Thus the coupling between the levels is strong and the alignment of $\underline{E}$ is very critical.

At the point where levels m and m+1 would cross in the absence of perturbation the wavefunction oscillates with frequency $\nu = \langle Fm+1|\mathcal{H}|Fm\rangle \sim \alpha_2 E^2\phi$ between the levels $|Fm\rangle$, $|Fm+1\rangle$ so that transitions take place between the levels m = -1 and m = -2 [5]. Such transitions, induced by static fields, are known from anti-crossing experiments in excited states and their connection with zero frequency rf transitions has been discussed by Series [6]. The observation of anti-level crossing in ground and low lying metastable states should be possible by the atomic beam method provided transitions between the crossing levels lead to a refocused beam. Detection of anti crossing by atomic beams would have the advantage that no light is required in addition to the usual advantage of beams.

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FOOTNOTES AND REFERENCES

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2. F. R. Petersen, Bull. Am. Phys. Soc. 14, 833 (1969); T. R. Fowler and J. Yellin, Bull. Am. Phys. Soc. 14, 832 (1969).
3. For the theory of the Stark interaction see J. R. P. Angel and P. G. H. Sandars, Proc. Roy. Soc. A305, 125 (1968).
4. Details of the calculation are given in Lawrence Radiation Laboratory Report UCRL-19569 (March 1970).
5. For an elementary discussion of degenerate perturbations see Quantum Theory by David Bohm, Prentice-Hall, Inc. (1951), Chapter 19.
6. T. G. Eck, J. J. Foldy and H. Wieder, Phys. Rev. Letters 10, 239 (1963); in this experiment the anti-crossing is caused by an internal perturbation. For a discussion see G. W. Series, Phys. Rev. Letters 11, 13 (1963); J. J. Forney and E. Geneux, Phys. Letters 20, 632 (1966).

FIGURE CAPTION

Fig. 1. Combined Zeeman-Stark effect in the F = 3 $4^2P_{3/2}$ state of ^{69}Ga. The calculations were performed for a magnetic field of 0.100 gauss. (a) $\underline{E}$ is parallel to $\underline{B}$. (b) $\underline{E}$ is inclined 5° to $\underline{B}$.

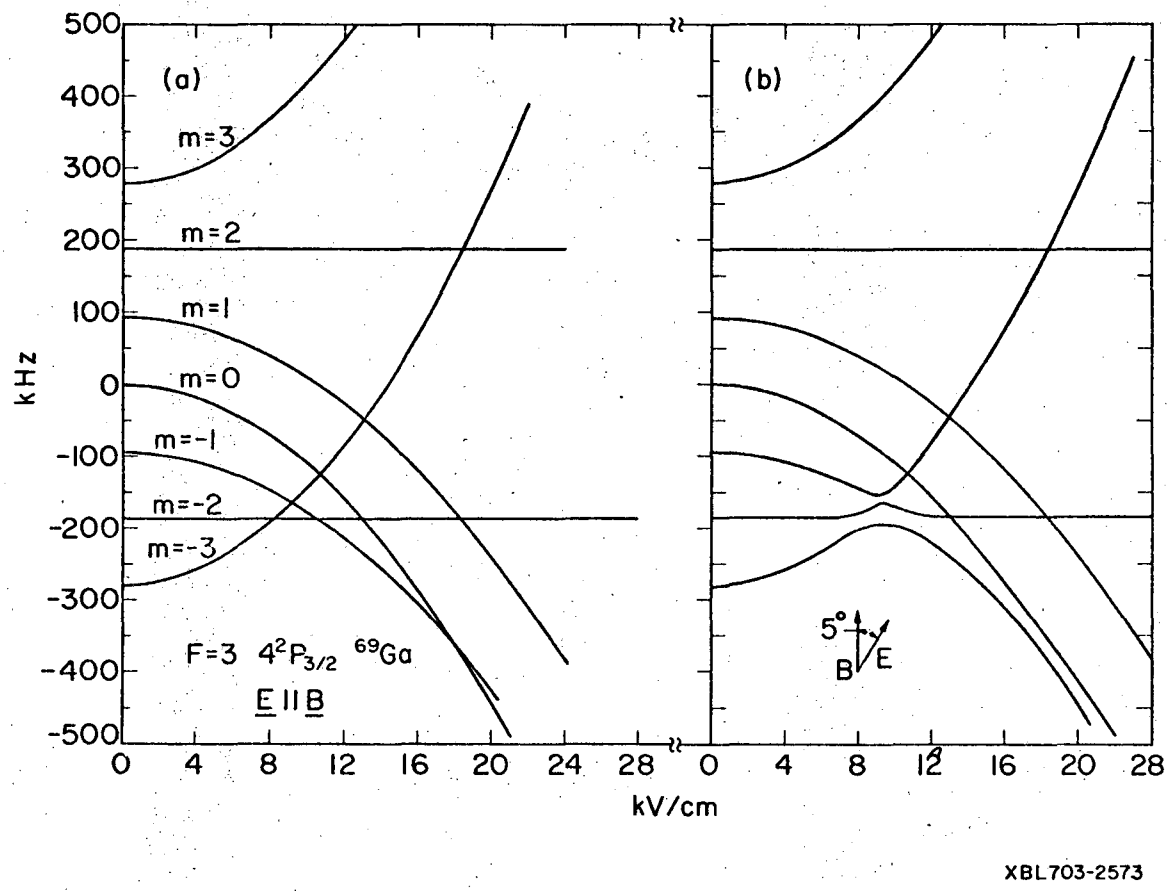
500
400
300
200
100
0
-100
-200
-300
-400
-500
kHz
(a)
m=3
m=2
m=1
m=0
m=-1
m=-2
m=-3
F=3 $4^2P_{3/2}$ ^{69}Ga
E II B
(b)
5°
B
E
0 4 8 12 16 20 24 28
0 4 8 12 16 20 28
kV/cm
XBL703-2573

Fig. 1

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