Lifetime and Hyperfineinteraction in $^1P_1$ States with Nuclear Spin $I = 1/2$

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In evaluating the hfs coupling constant A from levelcrossing signals in excited $J = 1$ states with $I = 1/2$ where the hfs splitting is smaller than the radiation width, an independent determination of the lifetime of the state under study is essential. This is demonstrated in the $6s7p\ ^1P_1$-state of ^{171}Yb ($I = 1/2$). The results are: $\tau(7p\ ^1P_1) = 8.9(3)$ nsec and $|A(7p\ ^1P_1)| = 9(2)$ MHz.

Hyperfine (hfs)-measurements in $^1P_1$ states with $I = 1/2$ are usually very easily performed with the level-crossing (lc) technique because there is only *one* $\Delta m = 2$ lc-signal in the field range unequal zero apart from the zero field crossing signals (Hanle-effect) [1].

If the natural radiation width $\Gamma = \hbar/\tau$ in the excited state is small compared to the hfs splitting the non zero lc-signal is well resolved. On the other hand if Γ is larger than the hfs the crossing signal may be completely overlapped by the Hanle-signal, which makes an evaluation of a hfs splitting from a measured curve rather delicate or even impossible.

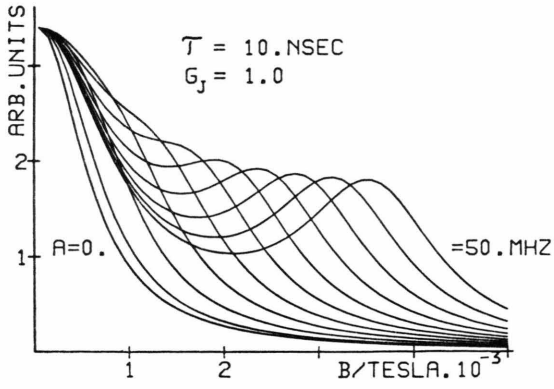

Fig. 1. Calculated lc-signals due to the Breit formula.

In order to demonstrate this range where Γ changes from values far below the hfs splitting to values much larger than the hfs splitting we have calculated due to the Breit formula [2, 3] a number of lc-signals for a $^1P_1$ state with nuclear spin $I = 1/2$ by varying the A-factor from 0 to 50 MHz in steps of 5 MHz. The parameters g_J and τ have been chosen as fixed values. The results are given in Figure 1. Starting from a negligible hfs splitting with $A = 0$ MHz first of all the line width of the curves becomes larger with increasing hfs coupling constant A. If the hfs splitting is larger than Γ the signal is eventually a superposition of a well resolved single lc-signal and a Hanle curve, but at the same time the line width of the Hanle-effect decreases and converges to a value quite different from the fwhm value of the signal curve with $A = 0$ MHz.

The explanation may be given in terms of the Breit formula [3]:

$$I(\boldsymbol{f}, \boldsymbol{g}) \sim \sum_{\substack{mm' \\ uu'}} \frac{f_{mu} f_{um'} g_{m'u'} g_{u'm}}{\Gamma + i(E_m - E_{m'})},$$

where $I(\boldsymbol{f}, \boldsymbol{g})$ gives the intensity at which photons of polarization $\boldsymbol{f}$ are absorbed and photons of polarization $\boldsymbol{g}$ are reemitted in the resonance fluorescence process; $f_{mu} = \langle m | \boldsymbol{f} \cdot \boldsymbol{r} | u \rangle$ is the dipole matrix element etc. and $(E_m - E_{m'})$ is the Zeeman-splitting of the corresponding states $|m\rangle$ and $|m'\rangle$.

If the hfs splitting is large compared to Γ the matrix elements are nearly constant and the signal curve of the Hanle effect is determined only by the resonant denominator in the Breit formula. On the other hand if the hfs splitting is comparable with — or less than Γ the hfs states are close together within the radiation width Γ and a very strong mixing of the eigenstates $|F, m_F\rangle$ occurs. This gives rise to a large alteration of the matrix elements in the magnetic field region of interest. Therefore the signal curves are influenced not only by the resonant denominator in the Breit formula but also — or even more — by the change of the matrix elements.

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The extreme cases can be easily described: The line width of the Hanle-signal is determined by the g_F-values of the excited state if the hfs splitting is large compared with Γ whereas in the case of a negligible hfs splitting the g_J-value of the fine structure term determines the line width of the signal curve.

Therefore it is possible *only* with the aid of the lifetime of the excited state to distinguish between a very small hfs-splitting and a hfs which is much larger than Γ provided that the lifetime of the excited state under investigation has been measured independently e.g. from the Hanle effect of the even isotopes.

The method described here has been tested experimentally in the case of the very small hfs of the $4f^{14}6s7p\ ^1P_1$ state of ^{171}Yb ($I=1/2$). The experimental arrangement for detecting $\Delta m=2$ lc signals is similar to that described elsewhere [4]. The atomic beam was irradiated perpendicularly to the magnetic field B with the unpolarized light of a hollow cathode lamp. The fluorescence light in the direction of B has been detected through a rotating analyser with a lock-in detector and a multi-channel analyser as an averager. A special rooting system serves to eliminate drifts and instabilities of the exciting lamp, the atomic beam and the magnetic field.

In order to get a first idea of the hfs splitting of the $6s7p\ ^1P_1$ state a simple estimation yields a magnetic field of approximately 10 mT where the lc signal should occur, using the Goudsmit-formula [5] and the known value of the A-factor of the $6s6p\ ^1P_1$ state of ^{171}Yb [6, 7]. Furthermore the ratio (Hanleeffect/lc-signal) of the signal amplitudes approximately should be 2 [3]. The measurements have been performed with a 95% enriched isotope ^{171}Yb in magnetic fields up to 40 mT without any success. No isolated lc-signal could be detected.

Therefore the lifetime of this $^1P_1$ state has been examined very carefully by measuring the Hanle-effect of the even isotopes. This may be performed by using an atomic beam with a natural isotopic mixture of Yb where the even isotopes predominate. A detailed fit procedure with regard to the influences of the coherence narrowing [8] as well as the odd isotopes gives the following result for the mean lifetime of the $6s7p\ ^1P_1$ state of Yb:

$$\tau(6s7p\ ^1P_1) = (8.9 \pm 0.3)\ \text{nsec}.$$

Using this value as a fixed parameter the calculated signal curves of ^{171}Yb due to the Breit formula were fitted to the experimental one by a systematic variation of the A-factor. The result is given in Figure 2. The noisy curve is the experimental $\Delta m=2$ lc signal, the smooth curve gives the best fit to the experimental one as may be seen in the lower part of Fig. 2 where the difference between measured and fitted signals is drawn. Furthermore the sensitivity of the line shape to the A-factor is demonstrated in the two additional curves with $A=0$ MHz and $A=13$ MHz giving no fit to the measured signal. As a best result we get the following hfs splitting constant of the $6s7p\ ^1P_1$ state of ^{171}Yb:

$$|A(6s7p\ ^1P_1)| = (9.0 \pm 2.0)\ \text{MHz}.$$

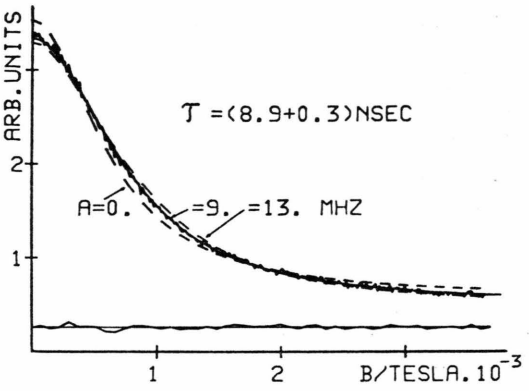

Fig. 2. $\Delta m=2$ lc-signals of the $6s7p\ ^1P_1$ state of ^{171}Yb ($I=1/2$). The smooth line shows the best fit; in the lower part the difference between experimental and fitted curve is drawn. The two other curves demonstrate the sensitivity of the line shape to the A-factor.

The evaluation of a very small hfs splitting by the method described here is based on a detailed

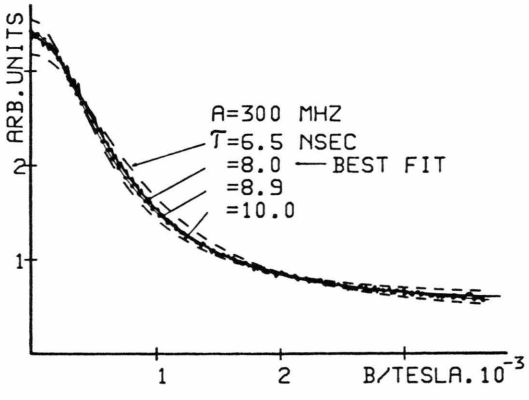

Fig. 3. Calculated and fitted lc-signals assuming a hfs splitting much larger than the radiation width (see text).

analysis of the measured signal curve. Nevertheless this procedure seems to be very secure as may be explained in Fig. 3 where a futile attempt was made by fitting the signal curve assuming a hfs splitting (here $A = 300$ MHz arbitraryly chosen) much larger than Γ. The dotted line is the theoretical signal curve with the exact value for the lifetime whereas the best fit yields a lifetime of 8 nsec which is two times out of the limit of the error we deduced in the investigation of the even isotopes.

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