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SPIN-EXCHANGE FREQUENCY SHIFT OF THE CRYOGENIC DEUTERIUM MASER

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We derive expressions for the spin-exchange frequency shift and line broadening of the deuterium maser for low temperatures and present the results of a preliminary calculation based on the Degenerate-Internal-States approximation and its first-order correction.

Of the two atomic species expected to remain gaseous down to the absolute zero of temperature (1), hydrogen (H) has been studied much more than deuterium (D). Experimentally, high densities of D have been much harder to achieve (2-5), both because of H contamination and the recently discovered tendency of D to dissolve in liquid helium films (5). Theoretically, H has attracted more interest because of the possibility of achieving Bose condensation of spin-polarized H (1). Electron spin-exchange collisions between H atoms have been studied theoretically because of their important role in determining the decay of trapped H gas (6). In connection with cryogenic hydrogen masers (7-9) such collisions have also been investigated theoretically (10-11) because they produce potentially important frequency shifts limiting the frequency stability. The calculations showed a remarkable sensitivity to non-adiabatic effects at low collision energies (10).

Recently, densities of D up to 10^{15} cm^{-3} have been achieved using liquid helium storage surfaces at temperatures near 1 K (5). In addition, there are possibilities of studying D at higher temperatures using solid neon storage surfaces (12) and at lower temperatures using trapping magnetic fields (13). It therefore seems useful to investigate the influence of hyperfine effects on electron spin-exchange collisions between D-atoms at low temperatures.

We concentrate on the $\beta \leftrightarrow \epsilon$ transition (adopting the usual labels $\alpha\beta\gamma\delta\epsilon\zeta$ of hyperfine levels in order of increasing energy). Its transition frequency goes through a minimum at about 30 mG. Hence, if the maser is operated at this field, the output frequency is quite insensitive to variations in the applied magnetic field. On the basis of the weakness of the field one would expect that a calculation of spin-exchange collisions at zero field would be sufficient. Some care is called for, however, as we will see.

Using the methods and notation of Ref. 10 and 11 we find for the frequency shift $\delta\omega_c$ due to collisions the general expression

$$\delta\omega_c = n\langle v\rangle \Big[\bar{\lambda}_0(\rho_{\epsilon\epsilon}-\rho_{\beta\beta}) + \bar{\lambda}_1(\rho_{\epsilon\epsilon}+\rho_{\beta\beta}) + \bar{\lambda}_2\rho_{\alpha\alpha} + \bar{\lambda}_3\rho_{\gamma\gamma} + \bar{\lambda}_4\rho_{\delta\delta} + \bar{\lambda}_5\rho_{\zeta\zeta}\Big].$$

The collisional line broadening Γ_c is given by a similar expression with λ_i replaced by σ_i. The complex quantities $\sigma_i - i\lambda_i$ are linear combinations of "coherent cross-sections"

$$\sigma_{\beta\epsilon,\nu\to\lambda} = \frac{\pi}{k^2}\sum_{\ell}(2\ell+1)\Big[S^{\ell}_{\{\beta\lambda\},\{\beta\nu\}}S^{\ell *}_{\{\epsilon\lambda\},\{\epsilon\nu\}} - \delta_{\lambda\nu}\Big].$$

For deuterium odd (even) ℓ are correlated with (anti-)symmetrized spin states $\{\alpha\beta\}$.

Previous calculations (14,15) of $\delta\omega_c$ and Γ_c for D were based on the high-temperature limit, which allows one to neglect the influence of the hyperfine splitting on the S-matrix, as well as nuclear identity effects. For the lower temperatures, which interest us, this is no longer permitted. We use the Degenerate-Internal-States (DIS) approximation, as well as a first-order correction. An interesting aspect is that for deuterium these approximations have to be extended to inelastic scattering, as pointed out in a separate contribution to this conference (16). The complexity due to nuclear spin 1 prompted us to use computer algebra to derive the relevant expressions.

For B=0 we find the DIS values for λ_1 and λ_4 to be zero, while $\lambda_2 = -1/2\lambda_3 = \lambda_5$, so that

$$\delta\omega_c^{DIS,B=0} = n\langle v\rangle \left[\bar{\lambda}_0(\rho_{\epsilon\epsilon}-\rho_{\beta\beta}) + \bar{\lambda}_2(\rho_{\alpha\alpha}+\rho_{\zeta\zeta}-2\rho_{\gamma\gamma})\right].$$

All σ_i and λ_0,λ_2 can be expressed in singlet and triplet phase-shifts. In the high-temperature limit the difference of phase-shifts for subsequent ℓ values as well as the difference of initial and final wave numbers for inelastic transitions can be neglected. This yields $\lambda_2=0$. The resulting $\delta\omega_c$ differs from that of Ref. (15) by a factor 2. In the same limit the line broadening Γ_c agrees with Ref. (15).

In view of the weakness of the field the B=0 DIS values describe λ_0, λ_2, λ_3, λ_5 and all σ_i approximately also at 30 mG. For λ_1, λ_4 a more subtle treatment is called for. Both the small $B\neq0$ DIS values and the first-order B=0 hyperfine-induced corrections are of interest. In Fig. 1 we present λ_1 and λ_4 (for B = 30 mG) as a function of energy from 0.01 to 10 K. We also show the λ_0 and λ_2 DIS predictions for B=0.

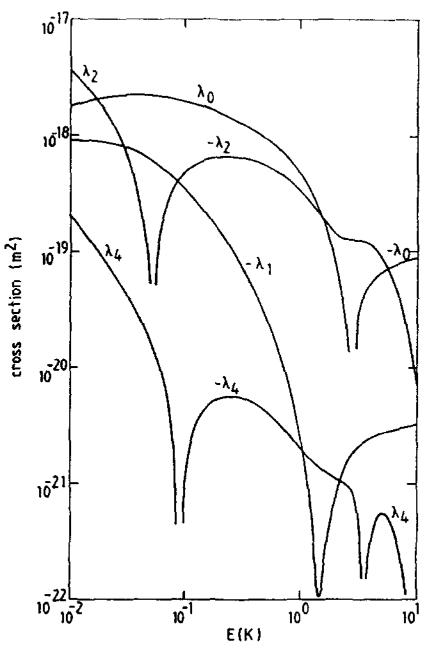

FIGURE 1: Frequency-shift cross-sections

As for atomic H our numerical results show a remarkable sensitivity to non-adiabaticity, this time for $\ell=1$. Estimating non-adiabaticity effects by comparing results for the reduced mass equal to half the deuteron mass instead of half the deuterium mass (differing by 0.02%) we find 30% variations of some relevant spin-exchange S-matrix elements in the lower part of the above energy-range. Experimental study of frequency shifts for the cryogenic deuterium maser may therefore be of interest.

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