EXAMINATION ATOMS AND MOLECULES 9-11-2017

ATOMS AND MOLECULES. 14:00-17:00, MARTINIPLAZA, #QUESTIONS: 4, #POINTS: 100

YOU CAN MAKE USE (IF YOU THINK YOU HAVE TO) OF THE FOLLOWING FORMULA'S:

$$g_J = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}$$

$$g_F = \frac{F(F+1) - I(I+1) + J(J+1)}{2F(F+1)} g_J$$

QUESTION 1. ATOMIC STRUCTURE # POINTS: 25

A. *(13 points).* ^{223}Fr (Francium) has a single valence electron in the 7s shell and a nuclear spin of $I = 3/2$. Make a schematic sketch of the energy level structure of the electronic ground state and the first excited electronic state, taking into account the spin-orbit splitting and the hyperfine structure. Assume that the spin-orbit coupling constant β_0 and the hyperfine coupling constant A are both positive. Label all electronic levels with their F quantum number, and give the term symbols for the electronic states. Also indicate the distances between the energy levels in units of A, β_0 or the quantum defect energy E_{qd}.

B. *(6 points).* An external magnetic field leads to splittings and shifts of the energy levels, effectively re-arranging the ordering of the levels. In the figure below you see the energy levels of the electronically excited state (an electron is promoted from the 7s shell to the 7p shell), at increasing magnetic field strengths. In each of the panels the vertical scale is quite different. The two groups of levels in panel a) are quite far apart, indicated by the dashed line. Explain why the energy levels are spaced and grouped as indicated for each of the panels. Where possible, use quantum numbers to label the energy levels.

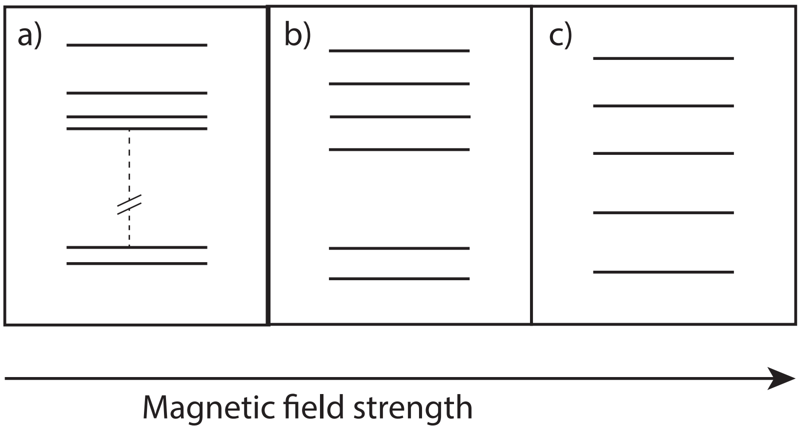

FIGURE 1. The energy levels in the electronically excited state of ^{223}Fr at increasing magnetic field strenghts.

C. *(6 points).* Consider an atomic beam that consists of ^{223}Fr atoms in the $F = 1$ state in $^2P_{1/2}$ level. An experimental physicist is interested in using magnetic fields to separate the atoms in the $m_F = 1$ substate from the other magnetic substates. Draw a configuration of magnets that could do this.

QUESTION 2. ATOM-LIGHT INTERACTION # POINTS: 25

A. *(7 points).* The steady-state solutions to the optical Bloch equations for the interaction of light with a two-level atom, for times large compared to the natural lifetime of the excited state, are as follows:

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \frac{1}{\delta^2 + \Omega^2/2 + \Gamma^2/4} \begin{pmatrix} \Omega\delta \\ \Omega\Gamma/2 \\ \delta^2 + \Gamma^2/4 \end{pmatrix}.$$

Explain, using these formula's, the steady state population that arises in the limit of large light intensity.

B. *(7 points).* When scanning the laser frequency over a resonance in a gas of two-level atoms, some of the light will be absorbed. The amount of absorption as a function of the frequency is measured, giving the shape of the absorption profile (the lineshape). A student does such a measurement at room temperature, and is surprised that the lineshape is Gaussian. Based on an analysis of the optical Bloch equations the student expected a Lorentzian line profile. Then the gas is cooled to liquid nitrogen temperature (77 K), and the experiment is repeated. Again a Gaussian line-shape is found. Please explain this finding, and suggest a method that allows the student to observe the Lorentzian lineshape.

C. *(11 points).* Following a 2π-pulse, a two-level system originally in the ground state is back in the original state - except for a minus sign in the phase. Show how by using a third level and two $\pi/2$ pulses this phase change can be detected.

QUESTION 3. LASER COOLING # POINTS: 25

A. *(7 points).* Show, starting from the optical Bloch equations from question 2, that the maximum of the scattering force is given by $F_{max} = \hbar k\Gamma/2$. As a reminder, the fraction of the population in the excited state is given by $\rho_{22} = \frac{1-w}{2}$.

B. *(8 points).* Explain how the maximum scattering rate influences the design of a Zeeman slower. Also explain the shape of the magnetic field required for optimal deceleration efficiency. What determines the maximum velocity of the atoms that can still be captured and decelerated by a Zeeman slower?

C. *(10 points).* The slow atoms from the Zeeman slower can be further cooled using lasers in an optical molasses configuration. Surprisingly low temperatures (below the Doppler limit) have been found in optical molasses, resulting from Sisyphus cooling. Explain what Sisyphus cooling is, using the concepts of optical pumping, transition strengths, light shifts and the polarization gradient.

QUESTION 4. MOLECULES # POINTS: 25

A. *(5 points).* Give the order of magnitude of typical transition frequencies (in Hz) of vibrational transitions, rotational transitions and electronic transitions in a diatomic molecule like SrF.

B. *(10 points).* The SrF molecule has a $^2\Sigma_{1/2}$ ground state, and the electronically excited state is split into a $^2\Pi_{1/2}$ and $^2\Pi_{3/2}$ state. The excited state can be described using Hund's case (a). Draw the angular momentum coupling for the two excited states, and use this to explain the difference in the magnetic moment of these two states.

C. *(10 points).* For various reasons the laser cooling of molecules is much more challenging compared to atoms. One of the problems is related to so-called dark states. Explain what these dark states are, why the molecules end up in these dark states, and how this problem can be solved.