Hyperfine dependent lifetimes in Neon like ions

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Abstract. As part of the investigation of what could be considered as the third generation of forbidden transitions, an investigation of the hyperfine quenching of the two metastable levels, $2p^53s\,{}^3P_2$ and $2p^53s\,{}^3P_0$, in the Neon like iso-electronic sequence has been performed. It is shown that the lifetime of the first excited level, $\,{}^3P_2$, is sensitive to hyperfine quenching all along the sequence $Z = 13 − 79$, and accurate predictions of this lifetime can only be obtained by including hyperfine quenching into the theoretical model. $2p^53s\,{}^3P_0$ is the third excited level in all Neon like ions up to $Z ≈ 51$. An investigation of the hyperfine quenching of this state has been performed for ions up to $Z = 49$, and it is shown that the lifetime of this state is very sensitive to hyperfine quenching in the beginning of the iso-electronic sequence, but the sensitivity decreases going to the higher end.

1. Introduction

As part of our ongoing investigation of what could be considered as the third generation of forbidden transitions [1, 2, 3, 4], an investigation of the influence of hyperfine quenching on two metastable levels in the Neon like iso-electronic sequence, have been performed. The first excited level in this sequence, $2p^53s\,{}^3P_2$, can only decay to the ground state through a magnetic quadrupole (M2) transition. In the presence of a nuclear spin, the hyperfine interaction introduce a mixing with $2p^53s\,{}^3P_1$ and $1P_1$ respectively, opening up a hyperfine induced electric dipole (hpf-E1) transition channel to the ground state. Calculations of the hyperfine quenching of the $\,{}^3P_2$ hyperfine levels were performed for all stable isotopes with a nuclear spin in the range $Z = 13 − 79$, and it was investigated how this influenced the lifetime of these states.

For all ions up to $Z ≈ 51$, $2p^53s\,{}^3P_0$ is the third excited level. Going higher in the sequence, the $2p^53d\,{}^3P_0$ level comes plunging down and becomes the lowest excited $J = 0$ level [5]. The $2p^53s\,{}^3P_0$ level can only decay through a magnetic dipole (M1) and an electric quadrupole (E2) transition withing the triplet. The hyperfine interaction opens an additional hpf-E1 transition channel to the ground state and calculations of this quenching of the $\,{}^3P_0$ hyperfine level were performed for all stable isotopes with a nuclear spin up to $Z = 49$, and it was investigated how this influenced the lifetime of this state and the spectrum of the ion.

To our knowledge, besides Helium like systems, not much work have been performed concerning hyperfine quenching of states which can decay not only through a two-photon transition. Besides [1, 2, 3, 4], [6] investigated the hyperfine quenching of the lowest lying $\,{}^3P_2$ state in neutral Mg, Ca, Sr and Yb in connection with the design of an ultra precise atomic clock and [7] measured the hyperfine dependent lifetimes of the $3d^{10}4s\,{}^3D_3$ state in Ni-like $^{129}$Xe confirming our earlier predictions in [1, 2].
2. Method
In the presence of a nuclear spin, there is a non-central interaction between the electrons and the nuclear electromagnetic moments. This interaction splits each fine structure level into multiple closely spaced hyperfine levels which is defined by the quantum number $F$. The hyperfine interaction can also introduce a mixing between states with different $J$ quantum numbers and potentially opening up new transition channels. In the Ne-like system, the hyperfine interaction between $2p^53s\,^3P_0$ ($^3P_2$) and $2p^53s\,^3P_1$ and $^1P_1$ respectively opens up hpf-E1 transition channels to the ground state. To calculate the rate of these transitions, first order perturbation calculations were performed.

The $^3P_0$ can only mix with these two states through magnetic dipole hyperfine interaction. Using off-diagonal hyperfine interaction constants, $A$ (see for example [8]), the rate of the hyperfine induced transition to the ground state can be calculated using

$$A_{hpf-E1}(^1S_0,^3P_0) = \frac{(2\pi)^3}{9\hbar^2\lambda^3} I(I+1) \left[ \frac{A(^3P_1,^3P_0)}{E_3P_0 - E_1P_1} \right]^2 \left[ \frac{A(^3P_1,^3P_0)}{E_3P_0 - E_1P_1} \right]^2$$

where $\left\langle ^1S_0|D^{(1)}|^1P_1 \right\rangle$ and $\left\langle ^3S_0|D^{(1)}|^3P_1 \right\rangle$ are the reduced transition matrix elements of the transitions to the ground state from $2p^53s\,^1P_1$ and $^3P_1$ respectively.

The corresponding expression for the $^3P_2$ hyperfine induced transition rate are more complicated since this quenching can occur both due to the nuclear dipole and electric quadrupole hyperfine interaction. Using off-diagonal $A$ and $B$ hyperfine constants [8], the rate can be calculated using

$$A_{hpf-E1}(^1S_0,^3P_2) = \frac{(2\pi)^3}{9\hbar^2\lambda^3} \left[ (I + F + 1)^2 - 4 \right] \left[ 4 - (I - F)^2 \right] \frac{1}{E_3P_2 - E_1P_1} \left\langle \frac{A(^3P_1,^3P_2)}{E_3P_2 - E_1P_1} \right\rangle^2$$

Using off-diagonal hyperfine interaction constants were convenient for our project since all $F$ dependence are gathered in a simple algebraic expression. Also by knowing the constants for one isotope of an ion, they can easily be rescaled to other isotopes.

3. Result
In figure 1 we present two plots for an overview of the results. The $2p^53s\,^3P_0$ hyperfine level have three different transition channels. It can decay through M1 transitions to the $^3P_1$ hyperfine levels, through E2 transitions to the $^3P_2$ hyperfine levels and through a hpf-E1 transition to the ground state. The E2 transition rate is though very small compared to the M1 rate so we ignore the former and treat the $^3P_0$ hyperfine level as having two transition channels. In the left of the plots in figure 1 we have plotted the branching ration, $Q_A$, between the hpf-E1 and the M1 transition, defined as

$$Q_A = \frac{A_{hpf-E1}}{A_{M1}}$$

Besides telling us the predicted ratio between the two lines in a spectrum, $Q_A$ times 100 is the percent with which the hyperfine quenching is shortening the lifetime of the $^3P_0$ hyperfine level. From this plot it is found that this hyperfine level is very sensitive to hyperfine quenching and the transition channel to the ground state is in many cases the dominant one in the beginning of the iso-electronic sequence. Going to the higher end, the general trend is that the M1 transition...
Figure 1. Branching ratio between the hpf-E1 $2p^6\, ^1S_0 - 2p^53s\, ^3P_0$ and the M1 $2p^53s\, ^3P_1 - 2p^53s\, ^3P_0$ M1 transitions in the left plot. In the right plot the branching ratio between the hpf-E1 and the M2 transition channels $2p^6\, ^1S_0 - 2p^53s\, ^3P_2$.

channel becomes heavily dominant. This can be understood from that the system becomes more and more pair coupled so the energy gap between the $^3P_0$ and the $^3P_1$ hyperfine levels increase quickly. Since the M1 transition rate depends on this energy gap to the power of three, it increases very rapidly. Even so, if the nuclear magnetic dipole moment is large, the hyperfine quenching could still have a rather large impact also in the end of the sequence. For example is it shortening the lifetime of the hyperfine level in In$^{39+}$ by about 25%.

Comparing the spectra from two different isotopes of the same ion, one with nuclear spin and one without, could show some dramatic differences. Since the hyperfine interaction opens up a new transition to the ground state, this additional line should be seen in the former spectrum but being absent in the latter. The hyperfine quenching would also decrease the intensity of the $2p^53s\, ^3P_1 - 2p^53s\, ^3P_0$ transition, so also in this part of the spectra should differences be expected. This M1 transition attracted some interest in the 80:s, and it was studied for different ions in the solar corona to experimentally determine the fine structure splitting in Ne-like ions. It was found though that these lines many times were surprisingly weak and in some cases could not even be found, see for example [9]. To our knowledge, this was never understood, but we believe that we have found parts of the explanation.

In the right plot of figure 1 we present the result for the $2p^53s\, ^3P_2$ hyperfine levels along the iso-electronic sequence. In the absence of a nuclear spin this state can only decay through a M2 transition to the ground state. In the presence of nuclear electromagnetic moments, the hyperfine interaction opens an additional hpf-E1 transition channel to the ground state. Depending on the nuclear spin $I$, the isotope has two to five different hyperfine levels and one or two of these have no hyperfine quenching. To present the importance of the hyperfine quenching, we have plotted the $F$-dependent branching ratio, $Q_A$, between the hpf-E1 and the M2 transition in figure 1. Just as above is the $Q_A$ value a variable telling us how much the lifetime of the hyperfine level is shortened due to the hyperfine quenching. It is found that there is no such dramatic effects for the $^3P_2$ hyperfine levels as there were for the $^3P_0$ hyperfine level. On the other hand does the importance of the hyperfine quenching not seem to decrease going along the sequence, but the sensitivity tends to be constant. Whether the hyperfine quenching has a large or a small impact on the lifetime is entirely determined by the size of the nuclear electromagnetic moments and throughout the sequence there are examples of hyperfine levels which have their lifetime halved due to the hyperfine quenching.

To obtain a better understanding of the importance of the two different types of hyperfine
**Figure 2.** The ratio between the $A_{hpf-E1}(2p^6\, {}^1S_0, 2p^53s\, {}^3P_2)$ including both types of hyperfine interaction and only including magnetic dipole hyperfine interaction in the plot to the left. To the right, the corresponding relative lifetimes.

interaction, we also investigated the contribution from the electric quadrupole hyperfine interaction. In figure 2 we present two different plots. In the left one we have plotted the hyperfine induced transition rate, $A_{hpf-E1}$, including both types of hyperfine interaction, relative the transition rate $A^{mag}_{hpf-E1}$ where only the magnetic dipole hyperfine interaction was included. From this plot it is found that the mixing in equation 2 due to the two types of interactions could have both constructive and destructive interference. It is also found that even for isotopes where the nuclear electric quadrupole moment is small compared to the nuclear magnetic dipole moment, the electric quadrupole hyperfine interaction still have a rather large impact on the hyperfine induced transition rate. For some isotopes, the electric quadrupole hyperfine interaction is the most dominant one. For example have we left out two of the results for $^{153}$Eu from our plot since the relative transition rates were about 17 and 18.

In the right plot of figure 2 we have plotted the lifetime of the $2p^53s\, {}^3P_2$ hyperfine levels relative the lifetime if only the magnetic dipole hyperfine interaction was included. Except for a few isotopes with large nuclear electric quadrupole moment, the inclusion of this interaction only changed the lifetime with a few percent. This is of course directly related to the relative size of the hpf-E1 and the M2 transition rates.

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