Hyperfine Structure of the Laser Induced Transition $(n, l) = (37, 35) \rightarrow (38, 34)$ in Antiprotonic Helium ◇

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The first laser induced transitions observed in antiprotonic helium atoms were of the type $(n, l) \rightarrow (n-1, l-1)$ $(\Delta v = \Delta(n-l-1) = 0)$. Recently we developed a novel technique employing a pulsed antiproton beam [1], which led to the observation of two much weaker transitions with $\Delta v = 2$, $(n, l) \rightarrow (n+1, l-1)$, connecting two cascades with different v [2]. A precise scan of the $\Delta v = 2$ transition $(37, 35) \rightarrow (38, 34)$ revealed a doublet structure in the line profile [3], which is ascribed to the interaction of the antiproton orbital magnetic moment and the electron spin.

Among the variety of possible interactions of magnetic moments in the $\bar{\mathrm{p}}\mathrm{e}^-\mathrm{He}^{2+}$-system ($\equiv \bar{\mathrm{p}}\mathrm{He}^+$) the one-body 'fine structure' due to the $\vec{l_{\bar{\mathrm{p}}}} \cdot \vec{s_{\bar{\mathrm{p}}}}$ coupling of the antiproton can be estimated to be $\sim 10^{-7}$ eV (25 MHz) for $n \simeq 37$. This is much smaller than our present experimental resolution and can therefore be neglected in the following discussion. The dominant splitting of energy levels in $\bar{\mathrm{p}}\mathrm{He}^+$ arises from the interaction of the antiproton magnetic moment and the electron. The antiproton magnetic moment, which is the vector sum of the magnetic moments arising from the orbital angular momentum and the spin, $\vec{\mu}(\bar{\mathrm{p}}) = (g_\mathrm{s}(\bar{\mathrm{p}})\vec{s_{\bar{\mathrm{p}}}} + g_\mathrm{l}(\bar{\mathrm{p}})\vec{l_{\bar{\mathrm{p}}}})\mu_\mathrm{N}$, interacts with the magnetic moment of the ground state electron $\vec{\mu}(\mathrm{e}) = g_\mathrm{s}(\mathrm{e})\vec{s}_\mathrm{e}\mu_\mathrm{B}$, leading to a quadruplet substructure of any given (n, l) level. The contribution of the antiproton spin to $\vec{\mu}(\bar{\mathrm{p}})$, however, is much smaller than that of the $\bar{\mathrm{p}}$ orbital momentum and the corresponding level splitting is, like the one-body fine structure, far beyond the resolution achievable with our present laser system. Thus, the quadruplet is effectively reduced to a doublet structure of each (n, l) state with $F = l \pm s_\mathrm{e}$, as shown in fig. 1. Although this splitting by far exceeds the 'fine structure', we will refer to it as 'hyperfine splitting', because it is caused by the interaction of two different particles. Since crossover transitions are strongly suppressed, a laser pulse of the corresponding wavelength will induce E1-transitions A) $(F_+ = l + 1/2) \rightarrow (F'_+ = l' + 1/2)$ and B) $(F_- = l - 1/2) \rightarrow (F'_- = l' - 1/2)$, causing a double hump structure in the resonance profile with a separation of the two sublines $\Delta\nu_\mathrm{HF} = \nu_\mathrm{HF}(n, l) - \nu_\mathrm{HF}(n', l') = \nu_\mathrm{A} - \nu_\mathrm{B}$. Calculations [4,5] indicate that this separation is very small for $\Delta v = 0$ transitions between adjacent levels in a cascade, since the splitting energies of the parent and the daughter state are very similar and therefore nearly compensate each other. For $\Delta v = 2$ transitions, on the other hand, this cancellation does not occur and $\Delta\nu_\mathrm{HF}$ is expected to be of the order of 1 GHz, the minimum bandwidth achievable with our present dye laser system. Fig. 2 shows the resonance profile obtained for the $\Delta v = 2$ transition $(37, 35) \rightarrow (38, 34)$ by scanning the laser wavelength in 0.3 pm steps.

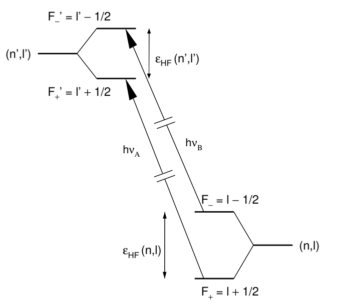

Fig. 1: Level diagram of parent and daughter doublet states showing allowed E1 transitions.

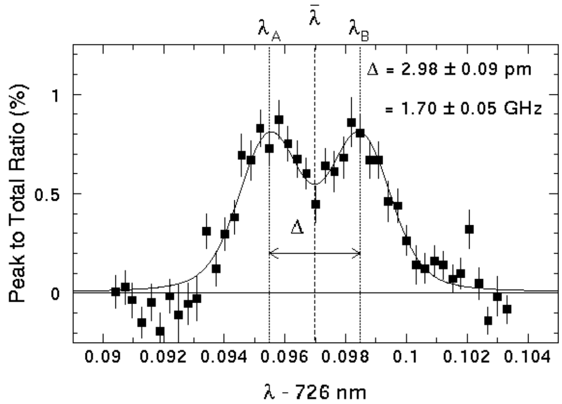

Fig. 2: Resonance profile of the transition $(37, 35) \rightarrow (38, 34)$.

The observed doublet structure was fitted with a sum of two identical functions, each of which consisted of a Gaussian representing the laser bandwidth convoluted with a Lorentzian describing the resonance width. Fixing the laser bandwidth at the measured value of 1.2 GHz and assuming that the amplitudes and widths of the two sublines are equal, we obtained a separation of the two line centers of 2.98 ± 0.09 pm, which corresponds to $\Delta\nu_\mathrm{HF} = 1.70 \pm 0.05$ GHz.

References

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