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Laser Induced Resonant Transitions in the $v = n - l - 1 = 2$ and 3 Metastable Cascades of Antiprotonic ^{3}He Atomcules

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Abstract

Laser-induced resonant transitions in metastable antiprotonic ^{3}He atoms have been found. The observed transitions at wavelengths 593.388 ± 0.001 nm and at 463.947 ± 0.002 nm have been respectively ascribed to the (n,l) = (38,34) → (37,33) and the (36,33) → (35,32) transitions.

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In previous publications[1, 2, 3], we reported the observation of two laser-induced resonant transitions in metastable antiprotonic ^{4}He atoms[4, 5, 6, 7, 8]. The resonances observed at 597.259 nm[1, 2] and 470.724 nm[3] were assigned to the (n,l) = (39,35)→(38,34) and (37,34)→(36,33) transitions respectively. The fact that the observed wavelengths were close to values[9, 10, 11, 12, 13] obtained theoretically for a $\overline{p}$ - e^--^{4}He^{++} three-body system (= $\overline{p}\,^4$He$^+$) established that the longevity of $\overline{p}$ stopped in ^{4}He is due to the formation of the so-called antiprotonic helium "atomcules".

In the present paper, we report the observation of resonant transitions in metastable antiprotonic ^{3}He atoms. We had already shown that a metastability effect occurred in ^{3}He and that the average lifetime was $\sim$ 14 % longer in ^{4}He than in ^{3}He[5, 6]. A search for resonant transitions in ^{3}He was thus a natural extension of our experimental programme.

The experiment described herein was done recently at the CERN Low Energy Antiproton Ring (LEAR), with an arrangement nearly identical to that used in our ^{4}He experiments. The $\overline{p}$ stopping target was a ^{3}He gas cell kept at temperature of 5.5 K and pressure of 200 - 300 mb. We searched for the (38,34)→(37,33) transition that lies at the end of the $v = n - l - 1 = 3$ metastable cascade and the (36,33)→(35,32) transition at the end of the $v = 2$ cascade (See Fig.1).

In our present laser spectroscopy technique, we induce resonant transitions between a metastable state (level lifetime $\tau \sim 1$ μs) and an Auger-dominated short-lived state ($\tau \leq 20$ ns). The sharp increase in annihilation rate from the lower (Auger) level constitutes an extremely sensitive indication of the resonance condition[14]. It was essential that we had some idea beforehand of the location of the metastable/short-lived boundary in the (n, l) plane of Fig. 1. For ^{4}He, the Auger-rate calculation by Ohtsuki[14, 15] indicated that metastable $\overline{p}$He$^+$ levels are those for which the Auger decay ($\overline{p}$He$^+$ $\rightarrow$ $\overline{p}$He^{++}) requires an orbital angular momentum change $|\Delta l| > 3$. This led us to the successful observation of the two transitions mentioned above. No such calculation was available for ^{3}He, but we applied the above "$|\Delta l| > 3$" rule to the ^{3}He case to obtain the metastable/short-lived boundary shown in Fig. 1, and the aforementioned candidates were selected according to this diagram.

Although the Auger lifetime estimates were unavailable for $\overline{p}\,^3$He$^+$, high-precision theoretical values for transition wavelengths have recently been calculated. By using a molecular-expansion variational method, Korobov[16] has calculated the transition energies for $\overline{p}\,^4$He$^+$ and $\overline{p}\,^3$He$^+$ atomcules. His values for $\overline{p}\,^4$He$^+$ are 597.23 nm for the (39,35)→ (38,34) transition (experimental value 597.259 ± 0.002 nm) and 470.71 nm for the (37,34)→(36,33) transition (experimental value 470.724 ± 0.002 nm), both within 50 ppm of the observed values. These are much closer to the experimental values than the theoretical values available to us during our previous resonance scans, which typically had an accuracy of ~ 1 nm. We therefore set our scan range to a few hundredths of a nanometer around Korobov's prediction, and succeeded in observing new resonant transitions within an amazingly short searching time (about 100 times shorter than that spent on the $\overline{p}\,^4$He$^+$ transitions).

Figs. 2a and 2b show on-resonance $\overline{p}$ annihilation time spectra for the two transitions we discovered. The peaks occur at the time of arrival of the laser light in the target gas and as the laser wavelengths are scanned over the resonance region they grow to a maximum and then disappear as shown in Figs. 2c and 2d. The central wavelengths for these two resonant transitions are 593.388 ± 0.001 nm and 463.947 ± 0.002 nm, where the errors cover both statistical errors and calibration errors for the wavelength meter. We must note that at temperature and pressure mentioned above the helium gas density is rather high. It is therefore very likely that the present resonant wavelengths are subject to pressure shifts of ~ 0.001 nm.

In Fig. 3, we compare the experimental values for the four laser-induced transitions found so far (two for the $\overline{p}\,^4$He atomcule previously reported and two for the $\overline{p}\,^3$He atomcule discussed here) with the theoretical values of Ref.[16]. A striking feature of Fig. 3 is that the theoretical wavelengths are always some 30 - 50 ppm shorter than the experimental ones.

From this agreement with Korobov's values we conclude that the 593 nm resonance is the (38,34)→(37,33) transition in the $v = n - l - 1 = 3$ chain, and that the 464 nm resonance is the (36,33)→(35,32) transition in the $v = 2$ chain. If the l-value were changed by one unit for the 593 nm (464 nm) transitions the measured and predicted wavelengths would disagree by more than 0.3 nm (1.0 nm). The present assignment is also consistent with the aforementioned "$|\Delta l| > 3$" rule on the Auger decay rates, and justifies the level scheme in Fig. 1.

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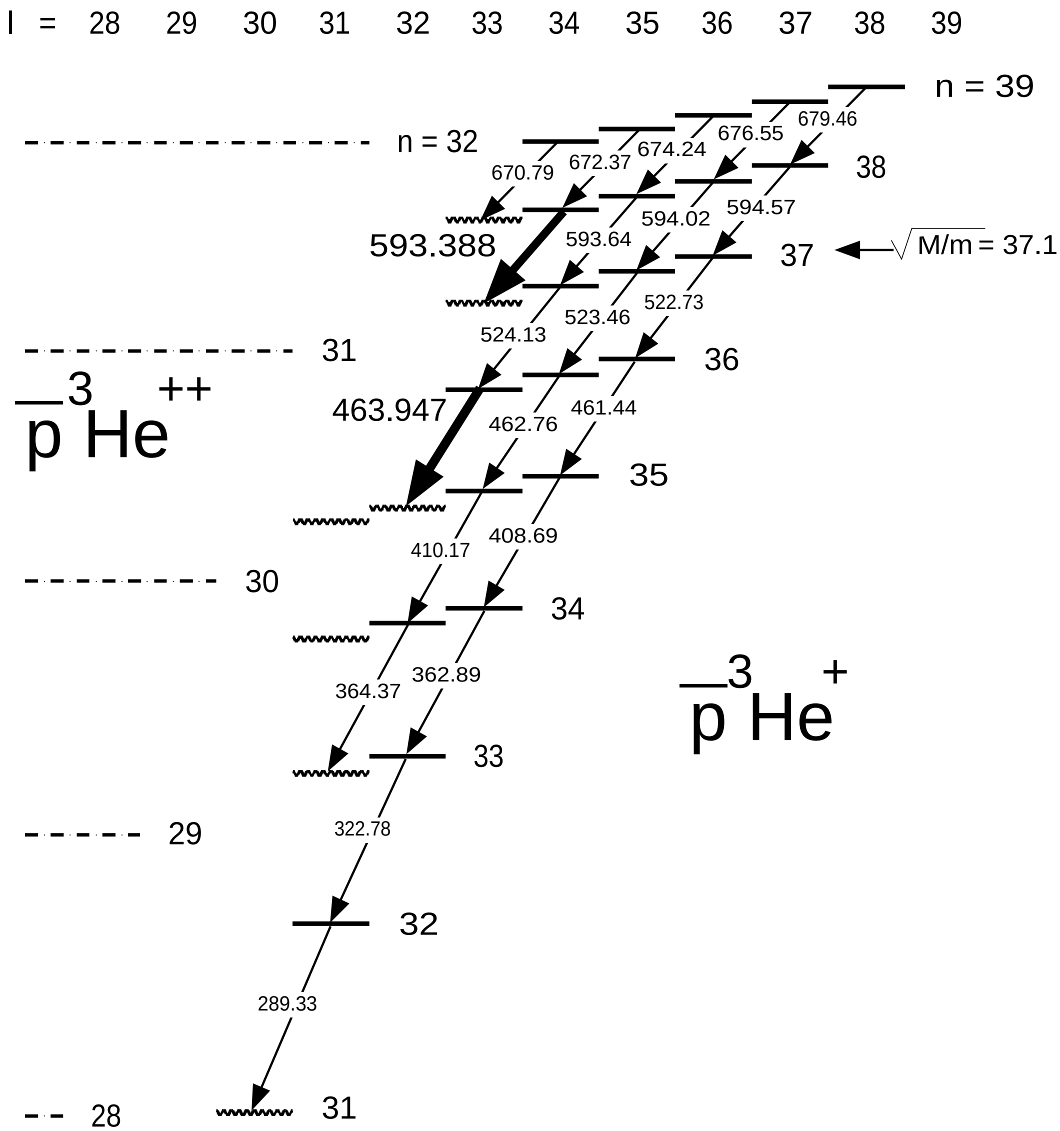

Figure 1: Energy level diagrams of $\overline{p}\,{}^3\mathrm{He}^+$ atomcule (solid and wavy) and of $\overline{p}\,{}^3\mathrm{He}^{++}$ ion (dashed). The transitions found in the present work are shown in thick arrows, with the observed wavelengths. All other transition wavelengths are taken from Korobov [16]. Metastable levels are indicated by solid lines and Auger-dominated short-lived states are drawn by wavy lines. The metastable/short-lived boundary was assumed to follow the "$|\Delta l| > 3$" rule. See text.

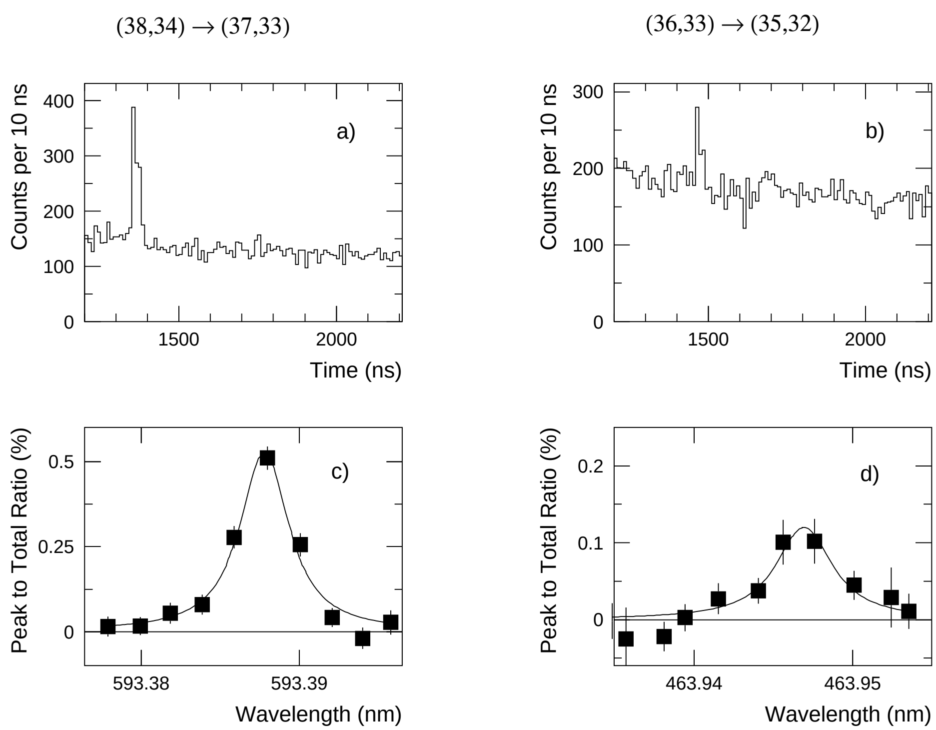

Figure 2: On-resonance time spectra of the 593.388 nm transition (a) and the 463.947 nm transition (b) found in the present work. Figs 2 c) and d) show the dependence of the resonance intensity (i.e. the peak area divided by the total number of delayed events) on the laser frequency.

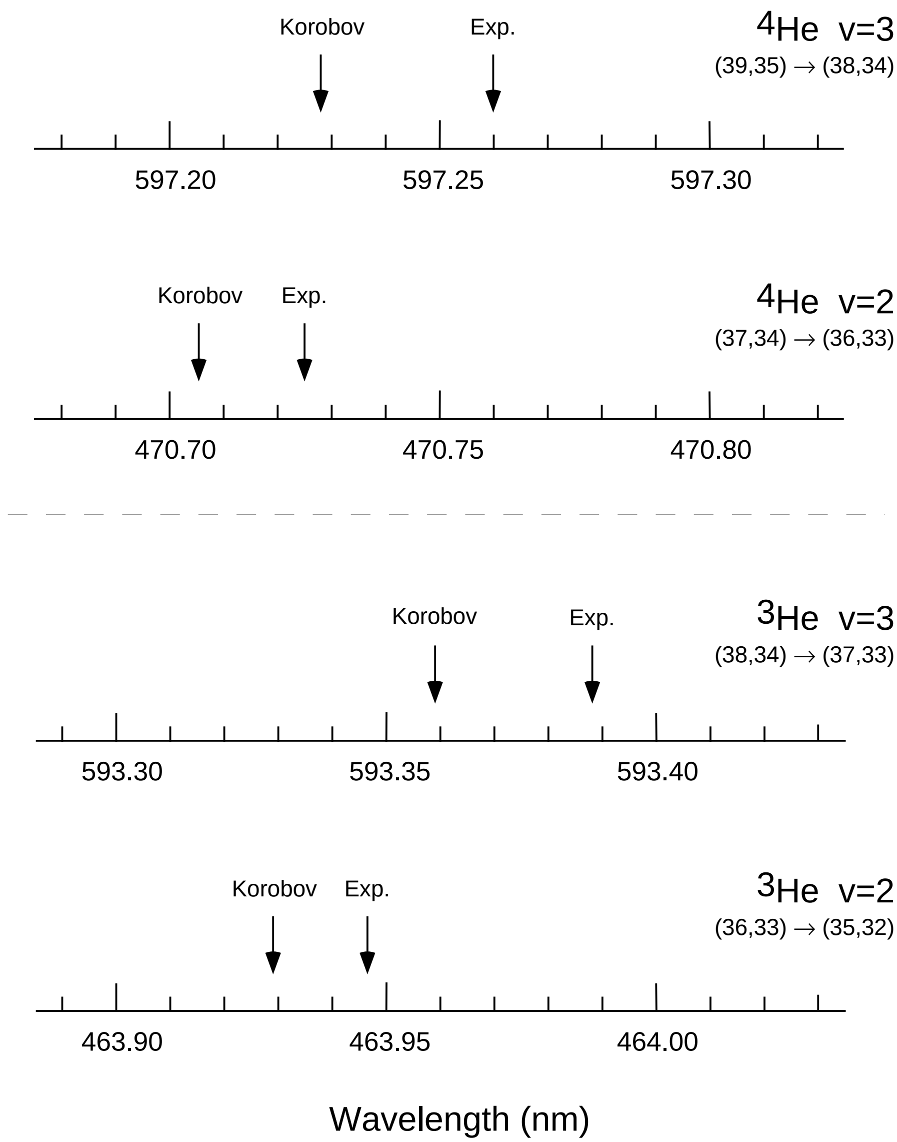

Figure 3: The experimental values for the four laser-induced transitions found so far compared with the theoretical values by Korobov. Two are for $\overline{p}\,{}^4\mathrm{He}^+$ from previous works and two for $\overline{p}\,{}^3\mathrm{He}^+$ reported in the present paper. The experimental and theoretical values of Korobov [16] show agreement better than 50 ppm, with the theoretical values always appearing $30-50$ ppm towards shorter wavelengths.