Laser-induced resonant transitions in the $\nu = n - l - 1 = 2$ and 3 metastable cascades of antiprotonic $^3$He atoms

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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 $(n,l) = (38,34)\rightarrow(37,33)$ and the $(36,33)\rightarrow(35,32)$ transitions, showing excellent agreements to 50 ppm with recent predictions of Korobov.

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In previous publications [1–3], we reported the observation of two laser-induced resonant transitions in metastable antiprotonic $^4$He atoms [4–9]. The resonances observed at 597.259 nm [1,2] and 470.724 nm [3] were assigned to the $(n,l) = (39,35)\rightarrow(38,34)$ and $(37,34)\rightarrow(36,33)$ transitions, respectively. The fact that the observed wavelengths were close to values [10–14] obtained theoretically for a $\bar{p}\cdot e^-\cdot^4$He$^{2+}$ three-body system (=$\bar{\rho}^4$He$^+$) established that the previously observed longevity of $\bar{p}$ stopped in $^4$He is due to the formation of the neutral antiprotonic helium atoms.

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 was characterized by an average lifetime $\sim 14\%$ shorter than in $^4$He [5,6,9]. A search for resonant transitions in $^3$He was thus a natural extension of our experimental program. Many theoretical studies on the antiprotonic helium atom are currently being done worldwide, for which the comparison of $^4$He and $^3$He data should provide valuable supplementary information.

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 $\bar{p}$ stopping target was a $^3$He gas cell kept at a temperature of 5.5 K and pressure of 200–300 mb. We searched for the $(38,34)\rightarrow(37,33)$ transition that lies at the end of the $\nu = n - l - 1 = 3$ metastable cascade and the $(36,33)\rightarrow(35,32)$ transition at the end of the $\nu = 2$ cascade (see Fig. 1).

In our present laser spectroscopy technique, we induce resonant transitions between a metastable state (level lifetime $\tau \sim 1\mu$s) and an Auger-dominated short-lived state ($\tau \approx 20$ ns). The sharp increase in annihilation rate from the lower (Auger) level constitutes an extremely sensitive indicator of the resonance condition [15]. 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. According to Ohtsuki’s calculation [15,16] for $^4$He, the Auger transition rate depends drastically on its multipolarity $|\Delta l|$, namely, the change of $l$ between the initial $\bar{p}$He$^+$ state and a lower-lying final ionic state of $\bar{p}$He$^{2+}$ (ionic states being represented by dashed lines in Fig. 1). For those states that can proceed by Auger transitions with $|\Delta l| \leq 3$, the Auger rates are much larger than the radiative rates ($\sim 1\mu$s$^{-1}$ [10,11]), and hence the states are short-lived, as denoted by wavy lines in Fig. 1. This led us to the successful observation of the two transitions in $^3$He mentioned above. There was no such calcula-
FIG. 1. Energy-level diagrams of the $p^3\text{He}^+$ atom and of the $p^3\text{He}^2+$ ion. The transitions found in the present work are shown by thick arrows, with the observed wavelengths. All other transition wavelengths are taken from Korobov [17]. 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 “$|\Delta l| = 3$ Auger dominance” rule. For example, the $(n,l) = (38,34)$ metastable state of the atom follows the slow radiative cascade, while the $(37,33)$ state has a short lifetime due to the fast Auger decay to the $(n,l) = (31,30)$ ionic state, which is energetically possible with $|\Delta l| = 3$.

FIG. 2. On-resonance time spectra of the 593.388-nm transition (a) and the 463.947-nm transition (b) found in the present work. (c) and (d) show the dependence of the resonance intensity (i.e., the peak area divided by the total number of delayed events in each delayed annihilation time spectrum) on the laser wavelength.
The Auger dominance rule was applied to the $^3$He case to obtain the molecular-expansion variational method. Korobov calculated the transition energies for theoretical values always appearing 30 ppm lower than the Korobov values show agreement to better than 50 ppm, with the transition energies found so far compared with the theoretical values by Korobov.

In contrast to the situation with Auger lifetime estimates, high-precision theoretical values for transition wavelengths have recently been calculated. By using a molecular-expansion variational method, Korobov [17] has calculated the transition energies for $^5\bar{\text{He}}^+$ and $^7\bar{\text{He}}^+$ atoms. His values for $^5\bar{\text{He}}^+$ are $597.23\text{ nm}$ for the $4\text{He} \rightarrow (38,34)$ transition (experimental value, $597.259\pm0.002\text{ nm}$) and $470.71\text{ nm}$ for the $(37,34) \rightarrow (36,33)$ transition (experimental value, $470.724\pm0.002\text{ nm}$), both within 50 ppm of the observed values. These are much closer to the experimental values than the theoretical values [10–14] available to us during our previous resonance scans, which typically had an accuracy of $\sim 1\text{ nm}$. This close agreement in the $^4\text{He}$ case was what prompted us to search for resonant transitions in $^3\bar{\text{He}}^+$. In fact, we only had to scan for a few hundredths of a nanometer around Korobov’s prediction, observing them after an amazingly short search time (about 100 times shorter than that spent on the $^5\bar{\text{He}}^+$ transitions).

Figures 2(a) and 2(b) show on-resonance $\bar{\nu}$ annihilation time spectra for the two transitions we discovered. The annihilation-rate 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. 2(c) and 2(d). The central wavelengths for these two resonant transitions are $593.388\pm0.001\text{ nm}$ and $463.947\pm0.002\text{ nm}$, where the errors cover both statistical errors and calibration errors for the wavelength meter.

In Fig. 3, we compare the experimental values for the four laser-induced transitions found so far (two for the $^5\bar{\text{He}}^+$ atom previously reported and two for the $^3\bar{\text{He}}^+$ atom discussed here) with the theoretical values of Ref. [17]. 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 $(38,34) \rightarrow (37,33)$ transition in the $n=\ell-1=3$ chain, and that the $464$-nm resonance is the $(36,33) \rightarrow (35,32)$ transition in the $\ell=2$ chain. If the $\ell$ 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 $|\Delta l|\leq3$ Auger dominance rule, and justifies the level scheme in Fig. 1.

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