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

H. A. Torii, M. Hori, T. Ishikawa, F. E. Maas,* and R. S. Hayano
Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113, Japan

N. Morita and M. Kumakura
Institute for Molecular Science, Myodaiji, Okazaki 444, Japan

I. Sugai
Institute for Nuclear Study, University of Tokyo, 3-2-1 Midori-cho, Tanashi, Tokyo 188, Japan

B. Ketzer, H. Daniel, F. J. Hartmann, R. Pohl, R. Schmidt, and T. von Egidy
Physik-Department, Technische Universität München, D-85747 Garching, Germany

D. Horváth
KFKI Research Institute for Particle and Nuclear Physics, H-1525 Budapest, Hungary

J. Eades and E. Widmann
CERN, CH-1211 Geneva 23, Switzerland

T. Yamazaki
*Institute for Nuclear Study, University of Tokyo, 3-2-1 Midori-cho, Tanashi, Tokyo 188, Japan
and CERN, CH-1211 Geneva 23, Switzerland*

Laser-induced resonant transitions in metastable antiprotonic ³He 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.

PACS number(s): 36.10.Gv

In previous publications [1–3], we reported the observation of two laser-induced resonant transitions in metastable antiprotonic ⁴He 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 $\bar{p}$-e^--⁴He²⁺ three-body system ($\equiv\bar{p}$⁴He⁺) established that the previously observed longevity of $\bar{p}$ stopped in ⁴He 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 ³He atoms. We had already shown that a metastability effect occurred in ³He and was characterized by an average lifetime ~14% shorter than in ⁴He [5,6,9]. A search for resonant transitions in ³He 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 ⁴He and ³He data should provide valuable supplementary information.

The experiment described herein was done recently at the CERN Low Energy Antiproton Ring (LEAR), with an ar-

rangement nearly identical to that used in our ⁴He experiments. The $\bar{p}$ stopping target was a ³He 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 $v=n-l-1=3$ metastable cascade and the $(36,33)\rightarrow(35,32)$ 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 $\tau\sim1$ μs) and an Auger-dominated short-lived state ($\tau\lesssim20$ 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 ⁴He, 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 $\bar{p}$He²⁺ (ionic states being represented by dashed lines in Fig. 1). For those states that can proceed by Auger transitions with $|\Delta l|\leq3$, the Auger rates are much larger than the radiative rates (~1 μs⁻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 ⁴He mentioned above. There was no such calcula-

---
*Present address: Institut für Kernphysik, Universität Mainz, D-55099 Mainz, Germany.

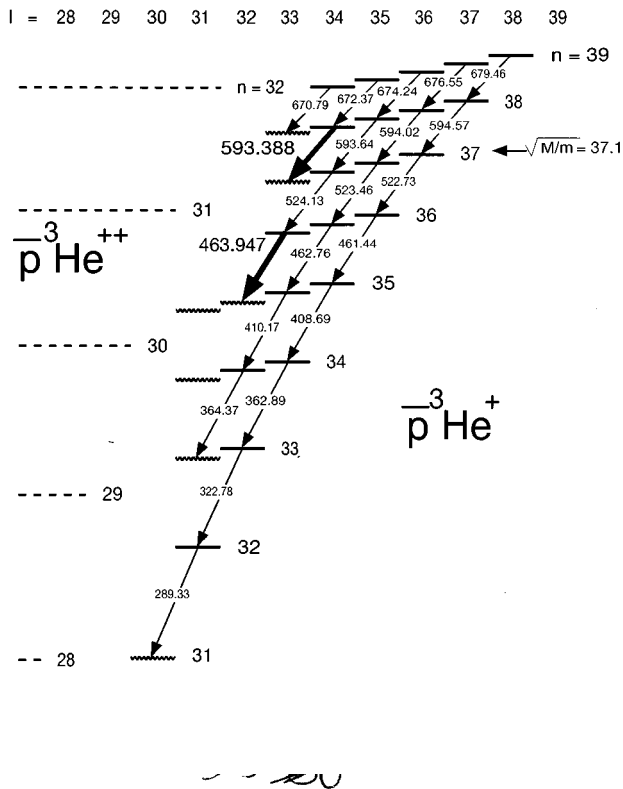FIG. 1. Energy-level diagrams of the $\bar{p}\,^3\mathrm{He}^+$ atom and of the $\bar{p}\,^3\mathrm{He}^{2+}$ ion. The transitions found in the present work are shown by thick arrows, with the observed wavelengths. All other transition wavelengths are taken from Korobov [17]. Metastable levels are indicated by solid lines and Auger-dominated short-lived states are drawn by wavy lines. The metastable–short-lived boundary was assumed to follow the "$|\Delta l| \leq 3$ 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 $|\Delta l| = 3$.

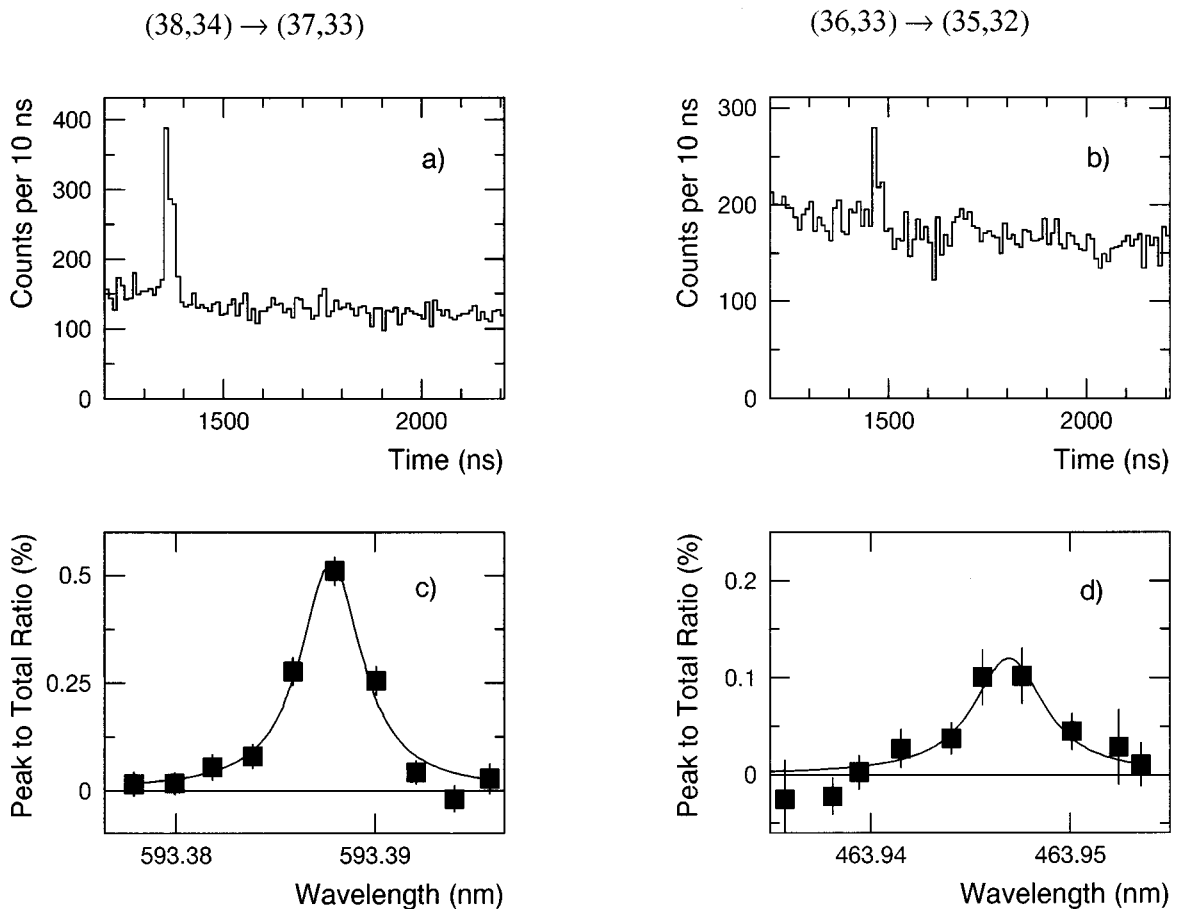$(38,34) \rightarrow (37,33)$

$(36,33) \rightarrow (35,32)$

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.
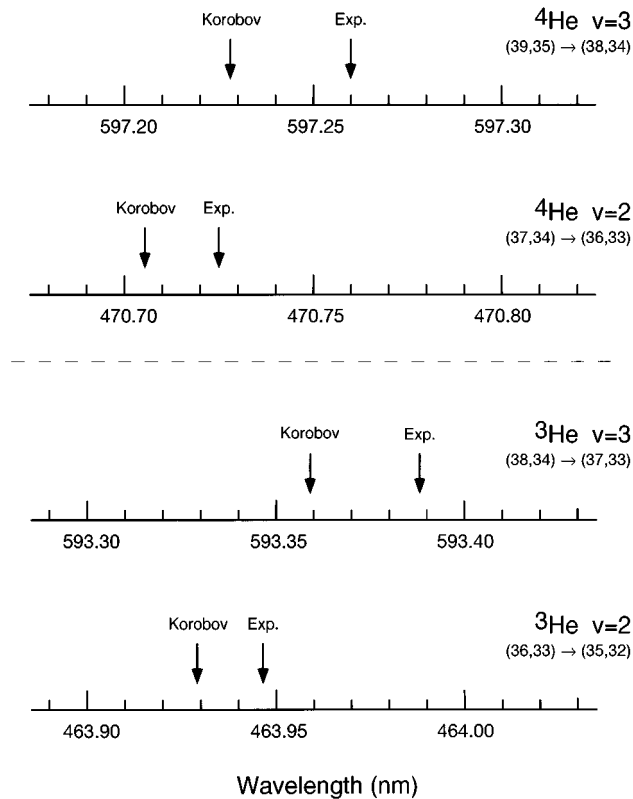
FIG. 3. Experimental values for the four laser-induced transitions found so far compared with the theoretical values by Korobov [17]. Two are for $\bar{p}^4\mathrm{He}^+$ from previous works [1,3] and two for $\bar{p}^3\mathrm{He}^+$ reported in the present paper. The experimental values and the Korobov values show agreement to better than 50 ppm, with the theoretical values always appearing $30-50$ ppm towards shorter wavelengths.

tion available for $^3\mathrm{He}$, but we applied the above "$|\Delta l| \leqslant 3$ Auger dominance" rule to the $^3\mathrm{He}$ case to obtain the metastable–short-lived boundary shown in Fig. 1, and the aforementioned candidates were selected according to this diagram.

In contrast to the situation with Auger lifetime estimates for $\bar{p}^3\mathrm{He}^+$, 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 $\bar{p}^4\mathrm{He}^+$ and $\bar{p}^3\mathrm{He}^+$ atoms. His values for $\bar{p}^4\mathrm{He}^+$ are 597.23 nm for the

$(39,35) \rightarrow (38,34)$ transition (experimental value, 597.259 ± 0.002 nm) and 470.71 nm for the $(37,34) \rightarrow (36,33)$ 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 [10–14] available to us during our previous resonance scans, which typically had an accuracy of ~ 1 nm. This close agreement in the $^4\mathrm{He}$ case was what prompted us to search for resonant transitions in $\bar{p}^3\mathrm{He}^+$. 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 $\bar{p}^4\mathrm{He}^+$ transitions).

Figures 2(a) and 2(b) show on-resonance $\bar{p}$ 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 ± 0.001 nm and 463.947 ± 0.002 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 $\bar{p}^4\mathrm{He}$ atom previously reported and two for the $\bar{p}^3\mathrm{He}$ 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 $v = n - l - 1 = 3$ chain, and that the 464-nm resonance is the $(36,33) \rightarrow (35,32)$ 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 $|\Delta l| \leqslant 3$ Auger dominance rule, and justifies the level scheme in Fig. 1.

[1] N. Morita, M. Kumakura, T. Yamazaki, E. Widmann, H. Masuda, I. Sugai, R. S. Hayano, F. E. Maas, H. A. Torii, F. J. Hartmann, H. Daniel, T. von Egidy, B. Ketzer, W. Müller, W. Schmid, D. Horváth, and J. Eades, Phys. Rev. Lett. **72**, 1180 (1994).

[2] R. S. Hayano, F. E. Maas, H. A. Torii, N. Morita, M. Kumakura, T. Yamazaki, H. Masuda, I. Sugai, F. J. Hartmann, H. Daniel, T. von Egidy, B. Ketzer, W. Müller, W. Schmid, D. Horváth, J. Eades, and E. Widmann, Phys. Rev. Lett. **73**, 1485 (1994); **73**, 3181(E) (1994).

[3] F. E. Maas, R. S. Hayano, T. Ishikawa, H. Tamura, H. A. Torii, N. Morita, T. Yamazaki, I. Sugai, K. Nakayoshi, F. J. Hartmann, H. Daniel, T. von Egidy, B. Ketzer, A. Niestroj, S. Schmid, W. Schmid, D. Horváth, J. Eades, and E. Widmann, Phys. Rev. A **52**, 4266 (1995).

[4] M. Iwasaki, S. N. Nakamura, K. Shigaki, Y. Shimizu, H. Tamura, T. Ishikawa, R. S. Hayano, E. Takada, E. Widmann, H. Outa, M. Aoki, P. Kitching, and T. Yamazaki, Phys. Rev. Lett. **67**, 1246 (1991).

[5] T. Yamazaki, E. Widmann, R. S. Hayano, M. Iwasaki, S. N.

Nakamura, K. Shigaki, F. J. Hartmann, H. Daniel, T. von Egidy, P. Hofmann, Y.-S. Kim, and J. Eades, Nature **361**, 238 (1993).

[6] S. N. Nakamura, R. S. Hayano, M. Iwasaki, K. Shigaki, E. Widmann, T. Yamazaki, H. Daniel, T. von Egidy, F. J. Hartmann, P. Hofmann, Y-S. Kim, and J. Eades, Phys. Rev. A **49**, 4457 (1994).

[7] E. Widmann, I. Sugai, T. Yamazaki, R. S. Hayano, M. Iwasaki, S. N. Nakamura, H. Tamura, T. M. Ito, A. Kawachi, N. Nishida, W. Higemoto, Y. Ito, N. Morita, F. J. Hartmann, H. Daniel, T. von Egidy, W. Schmid, J. Hoffmann, and J. Eades, Phys. Rev. A **51**, 2870 (1995).

[8] E. Widmann, I. Sugai, T. Yamazaki, R. S. Hayano, M. Iwasaki, S. N. Nakamura, H. Tamura, T. M. Ito, A. Kawachi, N. Nishida, W. Higemoto, Y. Ito, N. Morita, F. J. Hartmann, H. Daniel, T. von Egidy, W. Schmid, J. Hoffmann, and J. Eades, Phys. Rev. A (to be published).

[9] B. Ketzer, F. J. Hartmann, H. Daniel, T. von Egidy, A. Niestroj, S. Schmid, W. Schmid, T. Yamazaki, I. Sugai, K. Nakayoshi, R.S. Hayano, F. E. Maas, H. A. Torii, T. Ishikawa, H. Tamura, N. Morita, D. Horvath, J. Eades, and E. Widmann, Phys. Rev. A **53**, 2108 (1996).

[10] T. Yamazaki and K. Ohtsuki, Phys. Rev. A **45**, 7782 (1992); K. Ohtsuki (private communication).

[11] I. Shimamura, Phys. Rev. A **46**, 3776 (1992), and private communication.

[12] P. T. Greenland and R. Thürwächter, Hyperfine Interact. **76**, 355 (1993); P. T. Greenland (private communication).

[13] O. I. Kartavtsev (unpublished).

[14] Y. Kino (private communication).

[15] N. Morita, K. Ohtsuki, and T. Yamazaki, Nucl. Instrum. Methods Phys. Res. Sect. A **330**, 439 (1993).

[16] K. Ohtsuki (private communication).

[17] V. I. Korobov (unpublished).