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High-precision structural studies of the antiprotonic helium atom $\bar{p}\,^4\mathrm{He}^+$ by observing laser resonances with $\Delta v = \Delta(n-l-1) = 2$

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Very weak laser resonances of unfavored transitions $(n,l)\rightarrow(n+1,l-1)$ have been observed in metastable $\bar{p}\,^4\mathrm{He}^+$ atoms by using a pulsed antiproton beam. The observed wavelengths (713.578 ± 0.006 nm for $l=34$ and 726.095 ± 0.004 nm for $l=35$), as well as those of the known favoured transitions, are to a few ppm accounted for by a recent variational calculation of Korobov [Phys. Rev. A **54**, R1749 (1996); and (unpublished)] which includes the relativistic correction to the motion of the electron. [S1050-2947(97)50405-7]

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Since the discovery of the anomalous longevity of antiprotons against annihilation in liquid helium [1] comprehensive studies of this interesting phenomenon have been made at LEAR (low energy antiproton ring) of CERN [2–6]. With the advent of laser resonance spectroscopy of antiprotonic helium atoms $\bar{p}\mathrm{He}^+$ [7–11] our microscopic understanding of this phenomenon in terms of individual states of large quantum numbers (n,l) has been definitely established to be in accordance with previous theoretical expectations [12,13]. So far, we have detected the three resonances in ^{4}He and the two in ^{3}He, listed in Table I. The method used [14] involved laser stimulation of the last radiative transition (metastable parent to a short-lived daughter) in a sequence or band of transitions with constant ''vibrational'' quantum number (or equivalently, radial node number) $v=n-l-1$. In this way we have determined the transition energies, individual level lifetimes, and initial populations of the states in the $v=2$ and $v=3$ bands. Recently, the wavelengths of all measured $\Delta v=0$, $(n,l)\rightarrow(n-1,l-1)$ transitions have been either accounted for or predicted remarkably well by a large-configuration molecular-expansion variational calculation of the $\bar{p}\mathrm{He}^+$ energy levels developed by Korobov [15]. This is referred to below as KNR, since it did not take relativistic effects of the electron motion into account. The deviation between experimental and KNR wavelengths turned out to be always ~50 ppm and always positive. It is generally believed that the validity of such three-body Coulomb theories will be lost for less stable (i.e., highly excited, higher-v) states, but it was not clear whether the systematic deviation was due to this, or to relativistic or other QED effects not considered in KNR. As $\Delta v=0$ transitions alone do not yield energy differences between bands of differing v, information on interband transitions such as $\Delta v=2$, $(n,l)\rightarrow(n+1,l-1)$ was vitally important for a stringent test of KNR, and we therefore developed a technique to stimulate these. The present paper reports our first measurements of such resonances; these constitute a crucial test not only of KNR, but also of a more recent calculation, also by Korobov, that includes the electron relativistic correction [16]. This is referred to below as KR.

As a selection rule favors transitions with the largest overlap of radial wave functions with the same node [12,13], the strength of the $\Delta v=2$ transitions was expected to be smaller by two orders of magnitude than that of the $\Delta v=0$ transitions [14]. We shall sometimes therefore refer to them as ''unfavored'' transitions, and to the $\Delta v=0$ ones as ''favored'' ones. For the experiments on these transitions we developed an experimental technique in which pulsed antiprotons created a large number of metastable $\bar{p}\mathrm{He}^+$ atoms

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TABLE I. Comparison of the observed transition wavelengths λ_{exp} with the theoretical prediction of Korobov λ_{th} (KNR, without relativistic corrections [15]; KR, with relativistic corrections [16]). The errors reflect the experimental uncertainties only.

Isotope	Δv	$(n_i,l_i)\rightarrow(n_f,l_f)$	λ_{exp} (nm)	λ_{th} KNR (nm)	KR (nm)	$(\lambda_{th}-\lambda_{exp})/\lambda_{exp}$ KNR (ppm)	KR (ppm)	Ref.
^{4}He	0	(39,35)→(38,34)	597.259(2)	597.229	597.262	−50±3	+5.0±3	[7]
^{4}He	0	(38,35)→(37,34)	529.621(3)	529.596	529.623	−47±6	+3.0±6	[11]
^{4}He	0	(37,34)→(36,33)	470.724(2)	470.705	470.725	−41±4	+2.1±4	[9]
^{3}He	0	(38,34)→(37,33)	593.388(1)	593.360	593.394	−48±2	+8.6±2	[10]
^{3}He	0	(36,33)→(35,32)	463.946(2)	463.928	463.949	−38±4	+5.4±4	[10]
^{4}He	2	(37,34)→(38,33)	713.578(6)	713.515	713.594	−81±9	+21.3±9	herein
^{4}He	2	(37,35)→(38,34)	726.095(4)	726.021	726.102	−102±6	+10.0±6	herein

almost instantaneously. These were then collectively illuminated with a single laser pulse. This differs from our previous experiments in which a continuous $\bar{p}$ beam was used and the laser pulse was applied every time a metastable $\bar{p}He^+$ atom was known to have been formed in a helium target. In the present case, antiprotons of 200 MeV/c momentum were extracted from the LEAR storage ring in the form of a train of 200-ns-wide pulses. The initial pulse of each train contained some 10^7-10^8 particles, while subsequent ones decreased exponentially in intensity as the ring was emptied. Each pulse was ejected from the ring on receipt of a master command generated from the experiment, and was brought to rest in the helium gas target. The intensity and position of the $\bar{p}$ beam were monitored with a parallel-plate ionization chamber with x and y readouts of 1.5-mm resolution, which indicated a beam spot size of 4 mm×4 mm. The target was refrigerated to about 6 K and maintained at pressures near 500 mbar. Under these conditions, the antiprotons stopped in a region with a cross section of 1 cm^2 and a length of some 5 cm, and produced between 3×10^5 and 3×10^6 metastable $\bar{p}He^+$ atoms per 10^7 to 10^8 incident particles.

These annihilated over a period of several microseconds, producing via their annihilation pions a light pulse of similar duration in a nearby lucite Cerenkov radiator. This was preceded by a sharp initial flash of light from the 97% fraction of the antiproton pulse that annihilated instantaneously. Superimposed on this time spectrum was the background light from the π^+-μ^+-e^+ decay chain produced by those annihilation pions that stopped in the cryostat wall and other material surrounding the helium target. The composite light pulse was viewed by a photomultiplier tube, the second and fourth dynodes of which were gated to suppress the initial prompt annihilation [17]. The shape of the resulting current pulse was thus an analog of the delayed annihilation time spectrum but included the π^+-μ^+-e^+ decay background mentioned above. This pulse is referred to in what follows as the analog delayed annihilation time spectrum (ADATS).

The $\bar{p}$ stopping region was illuminated by the laser pulse at a suitable time (0.5 μs or more) after the $\bar{p}$ beam pulse arrived. When the laser was on a given resonance, most of the metastable atoms in the corresponding parent state could be forced to annihilate, as described in [14] for the continuous $\bar{p}$ case. This collective annihilation produced an easily detectable flash of Cerenkov light superimposed on the continuous ADATS. For the same number of resonance events in the continuous $\bar{p}$ beam mode, we would, of course, have had to apply some 10^6 laser pulses, one for each delayed event.

The laser system used was essentially the same (except for the trigger mode) as in our previous experiments [7–9]. A combination of excimer and dye lasers produced light pulses of some 30 ns length. The excimer laser and the kicker magnet that ejected the $\bar{p}$ pulse from LEAR were fired with a suitable relative time delay by the common master command pulse. In practice a series of excimer trigger pulses was sent for 3 s before each master command to warm up the lasers and assure constant laser power and timing stability. The laser power used was about 3 mJ per pulse.

We tuned the laser light to the ''red'' region to search for the two candidates from the $n=37$ states near values of 713.54 nm [for (37,34)→(38,33)] and 726.02 nm [for (37,35)→(38,34)] (the values predicted by KNR). In fact, we found the 726-nm resonance almost immediately. Figure 1(a) shows a single-pulse ADATS when the laser was tuned to 726.096 nm. The resonance spike is very clear with an overwhelming statistical significance, though the peak-to-background ratio was not large. The measured resonance profile is shown in Fig. 1(b) and has a central vacuum wavelength of 726.095±0.004 nm. The error includes the wavelength calibration error of ±0.003 nm.

We then searched for the (37,34)→(38,33) resonance, which turned out to be more difficult. Figure 1(c) shows an ADATS when the laser was tuned to 713.588 nm, at which a small but significant spike appeared at 0.96 μs. The resonance profile measured [Fig. 1(d)] shows a very broad peak. Its full width at half maximum (FWHM) (fitted by a Lorentzian) is 0.067±0.006 nm (94 ppm), which is much larger than the laser bandwidth of 0.007 nm. The central wavelength was determined to be 713.578±0.006 nm.

Its broadness may be explained in terms of a large natural width of the $v=4$ (38,33) daughter state. This has the unusual feature that it undergoes an L (multipolarity)$=\Delta l=2$ Auger transition and can therefore be expected to have a lifetime in the 10-ps range, while all the other daughter states so far observed are located at the metastability boundary, and should have the 10-ns lifetime characteristic of $L=3$ Auger transitions. We deduce the lifetime of the (38,33) state to be 4.1±0.2 ps, which is consistent with the above expectation. Very recent calculations of the Auger transition rates by Korobov [18] and by Kartavtsev [19] give a decay lifetime of 3.2 and 5 ps, respectively, which agree excellently with the present observation.

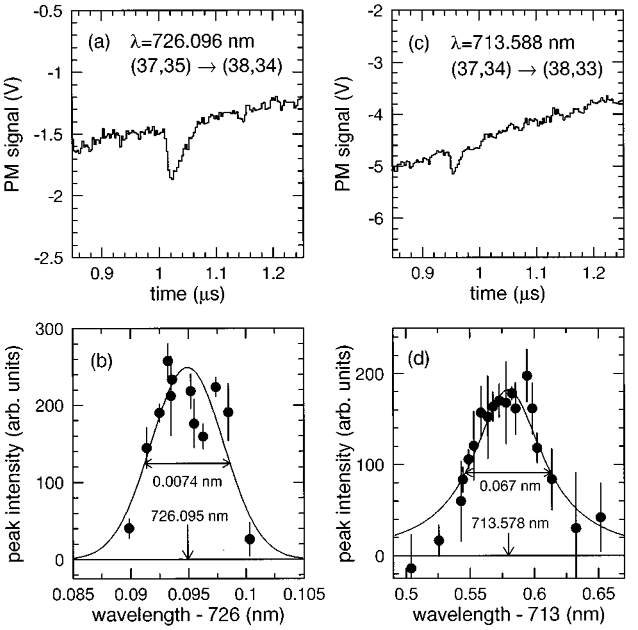

FIG. 1. The 726-nm and 714-nm ''unfavored'' resonance spikes in ADATS and their resonance profiles. (a) ADATS showing a resonance spike at 726.096 nm. (b) Resonance profile of the 726-nm transition. The vertical bars indicate variances of ADATS peak intensities after repeated measurements and a single Gaussian function is used to determine the central wavelength. (c) ADATS showing a resonance spike at 713.588 nm. (d) Resonance profile of the 714-nm transition.

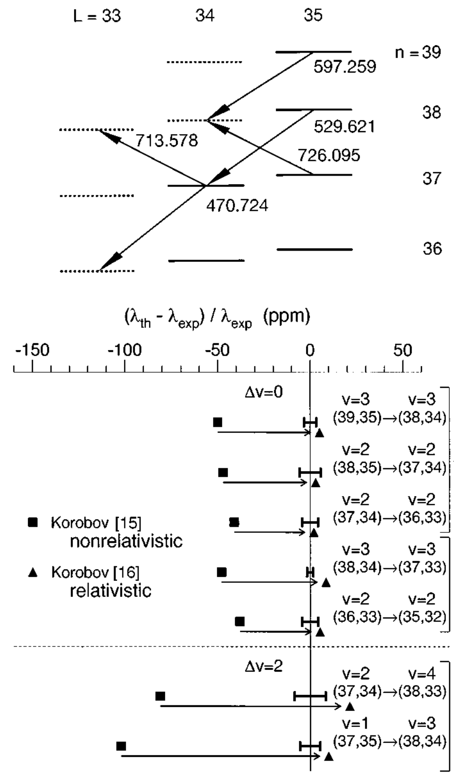

FIG. 2. (Upper) Partial level scheme established by the present laser resonance spectroscopy. The observed resonance wavelengths are shown. (Lower) Comparison of the experimental wavelengths of various transitions with Korobov predictions (closed squares without [15] and closed triangles with [16] relativistic corrections). The upper part is for $\Delta v = \Delta(n-l-1) = 0$ intraband transitions and the lower part is for $\Delta v = 2$ interband transitions. The error bars are the experimental ones.

The established level sequence is presented in Fig. 2 (upper), and all the resonance transitions so far observed are summarized in Table I, where both the KNR and the KR values are also listed. The deviations of the theoretical wavelengths (λ_{th}) from the experimental ones (λ_{exp}), are shown in Fig. 2 (lower).

Both for $\Delta v = 2$ and $\Delta v = 0$, the KNR values deviate by 50–100 ppm from the experimental ones, earlier theoretical values [12,13,20,21] having a scatter and deviation of the order of 1000 ppm. But while the deviations for ''intraband'' ($\Delta v = 0$) transitions show the systematic 50-ppm negative deviation already noted, those for the ''interband'' ($\Delta v = 2$) transitions are both near -100 ppm. Does this indeed imply a limit to the applicability of KNR as mentioned above?

To answer this question we consider the relativistic effects discarded in KNR, but included in KR, the dominant contribution of which comes from the motion of the bound electron. These corrections are all toward the longer-wavelength direction and are state dependent. Qualitatively this can be understood because the effective nuclear charge registered by the electron depends on the state-dependent spatial distribution of the $\bar{p}$ and thus changes the velocity (and energy) of the bound electron. The striking difference between the intraband and interband transitions that results has thus been proven experimentally by the results reported herein, the KR theoretical values for both the $\Delta v = 0$ and the $\Delta v = 2$ transitions being within some ppm of the experimental ones. The KNR deviations were not therefore due to a loss of theoretical validity, but to a higher-order correction (the relativistic one). Table I further demonstrates the validity of KR at the level of several ppm, and suggests that an even smaller pattern of deviations at the few-ppm level exists, which may be accounted for by calculations of still higher-order QED and other terms.

Since the daughter state (38,33) of the 714-nm broad resonance is very short lived and is located far outside the metastable zone, it should provide the most stringent test of the applicability of the theoretical treatment on such unstable states. The difference between the KR wavelength and the experimental one in the broad resonance transition is somewhat larger than in the other $\Delta v = 2$ transition (726 nm). The deviation of 21 ppm, however, appears remarkably small in consideration of the broadness (94-ppm FWHM) of the daughter state.

In conclusion, we have developed a method to study extremely weak $\Delta v = 2$ transitions using a pulsed antiproton beam and observed two such resonances. The presently found transitions constitute a stringent test of the three-body theories of Korobov by revealing (a) the importance of state-dependent relativistic corrections [16], and (b) that even at some distance from the metastable (n,l) zone, Korobov's nonrelativistic (KNR) variational calculation of metastable $\bar{p}\mathrm{He}^+$ states [15] retains its excellent level of validity. The difference between the relativistic (KR) theory and experiment for all the wavelengths so far observed is only several ppm (except for the broad resonance case). The constant sign of these discrepancies implies that closer and closer constraints are being placed on the principal scaling factor for all transitions (the antiproton equivalent of the Rydberg constant), while their small magnitude indicates that our measurements are now testing the fundamental properties of the antiproton as well as few-body theories. In view of further theoretical developments to be expected in the near future it is very important to achieve higher and higher experimental precisions.

The present experiment thus marks a departure in the elucidation of the structure of the metastable $\overline{p}\mathrm{He}^{+}$ atom. What is perhaps more important is that, in conjunction with recent theoretical developments, this atom is being brought into an arena where it can play a role as a laboratory for the study of the fundamental properties of the antiproton. In this respect, steps in the measurement of the antiproton's magnetic properties via the hyperfine structure of the metastable $\overline{p}\mathrm{He}^{+}$ exotic atom will shortly be reported.

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[1] M. Iwasaki *et al.*, Phys. Rev. Lett. **67**, 1246 (1991).
[2] T. Yamazaki *et al.*, Nature (London) **361,** 238 (1993).
[3] S.N. Nakamura *et al.*, Phys. Rev. A **49**, 4457 (1994).
[4] E. Widmann *et al.*, Phys. Rev. A **51**, 2870 (1995).
[5] E. Widmann *et al.*, Phys. Rev. A **53**, 3129 (1996).
[6] B. Ketzer *et al.*, Phys. Rev. A **53**, 2108 (1996).
[7] N. Morita *et al.*, Phys. Rev. Lett. **72**, 1180 (1994).
[8] R.S. Hayano *et al.*, Phys. Rev. Lett. **73**, 1485 (1994); **73**, 3181(E) (1994).
[9] F.E. Maas *et al.*, Phys. Rev. A **52**, 4266 (1995).
[10] H.A. Torii *et al.*, Phys. Rev. A **53**, R1931 (1996).
[11] R.S. Hayano *et al.*, Phys. Rev A **55**, R1 (1997).
[12] T. Yamazaki and K. Ohtsuki, Phys. Rev. A **45**, 7782 (1992).
[13] I. Shimamura, Phys. Rev. A **46**, 3776 (1992).
[14] N. Morita, K. Ohtsuki, and T. Yamazaki, Nucl. Instrum. Methods Phys. Res. A **330**, 439 (1993).
[15] V.I. Korobov, Phys. Rev. A **54**, R1749 (1996).
[16] V.I. Korobov (unpublished).
[17] A. Niestroj *et al.*, Nucl. Instrum. Methods Phys. Res. A **373,** 411 (1996).
[18] V.I. Korobov (private communication).
[19] O. Kartavtsev (private communication).
[20] O. Kartavtsev (private communication).
[21] Y. Kino (private communication).