Laser Spectroscopy of Protonium

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High-precision laser spectroscopy of protonium (pp) is one of the future experiments being considered by ASACUSA collaboration at CERN AD. A possible scheme to produce protonium in vacuum and to detect laser transitions is presented, and implications of reaching high precision are discussed.

1. INTRODUCTION

Production of ultra-slow p beam and its use for atomic collision and spectroscopy studies are important goals of ASACUSA collaboration at AD. As described in detail by Widmann at this conference[1], we plan to decelerate the 5.3 MeV beam from AD to $10 \sim 50$ keV with a radio frequency quadruple (RFQ) decelerator, and then inject this beam further into a p catching trap similar to the PS200 trap at LEAR. Antiprotons will be cooled in the trap by the electron-cooling technique, and then extracted at very low energies of $1 \sim 100$ eV.

With such an ultra low energy p beam, many new experiments will become possible, and production and spectroscopy of protonium (pp) in a near-vacuum condition is one of the interesting possibilities. It is well known that protoniums produced in gaseous hydrogen are quickly quenched by Stark collisions. However, if we can make protoniums in vacuum, for example by colliding ultra-slow p’s on an atomic gas jet target, protoniums can only deexcite by slow radiative transitions, and should be quite long lived. In Fig.1, we show the expected protonium radiative lifetimes vs orbital angular momentum $L$ for principal quantum numbers between $n = 30$ and $n = 50$. As shown, radiative lifetimes exceed $1 \mu s$ for near-circular states for $n = 30$, and exceed $10 \mu s$ for $n = 50$. As was demonstrated already at LEAR by the PS205 collaboration[2,3], such metastable antiprotonic atoms can be studied in detail by using high-precision laser spectroscopy techniques. Of course, such experiments with protoniums are practically impossible at present due to the lack of high-intensity ultra-slow p beams.

2. A POSSIBLE SCHEME

We show in Fig.2 a possible scheme to carry out the laser spectroscopy of protonium. The method comprises the following steps:

1. Ultra slow antiprotons ($E_p \sim 30$ eV) are extracted from a catching trap, hit an atomic hydrogen gas target and form protoniums. The kinetic energy of antiproton
is adjusted to populate $n \sim 40$ for which the lifetime is a few microseconds. The density of the atomic target is low enough so that Stark collisions, which is the dominant quenching process in $\text{H}_2$ target, are unimportant.

2. Protoniums are selectively excited by two counter-propagating laser beams to $n = 84$, where the lifetime exceeds 100 microseconds.

3. On-resonance protoniums survive the 1 m flight path (\~{}30\,\mu s flight time) and are detected with the annihilation detector placed at the end of the flight path, but off-resonance protoniums annihilate in flight and do not reach the detector. By counting the number of protonium arriving at the detector as a function of laser frequency, we can determine the protonium energy level spacings.

2.1. Expected $(n, L)$ distribution

In order for the proposed method to work efficiently, the initial $n$ distribution must have a well defined peak, so that a large fraction of produced protonium can contribute to the laser resonance. The initial $L$ distribution must have a peak in the near-circular region, otherwise the lifetime of the produced protonium would be too short (see Fig. 1). It appears that these conditions can be fulfilled if a suitable initial $\bar{p}$ energy is chosen.

This is illustrated in Fig.3, which shows the expected $n$ and $L$ distribution for $E_{\bar{p}}^{CM} = 6.7$ eV, estimated by using the parametrized results of classical trajectory Monte Carlo (CTMC) calculation by Cohen[4]. As shown in the top panel, the $n$ distribution peaks
at $n = 40$, with the expected initial distribution of about 25%. The $L$ distribution is nearly statistical and peaks towards large $L$ values, hence most of the initially-produced protonium at this energy should be metastable. Also note that the states above $n = 43$ are initially empty, which makes it possible to detect laser resonant transitions to higher-$n$ states with good signal-to-noise ratio.

Note that the peak position in $n$ and initial $\bar{p}$ kinetic energy are correlated. For larger value of $E_{\bar{p}}$, the initial $n$ distribution is expected to shift toward higher $n$ value and the width become wider. We chose $E_{\bar{p}}^{CM} = 6.7$ eV (or $E_{\bar{p}}^{Lab} = 27$ eV) in the discussion below, but the actual $(n,L)$ distribution may be different from what we assumed here, and should be experimentally measured.

### 2.2. Two-photon excitation

Protoniums thus produced move with large velocities of a few cm/μs, hence we need to employ the method of two-photon excitation to cancel the first-order Doppler shift in order to reach high precision. The initial and final states of the laser transition must satisfy the following criteria: i) large enough transition probability (within the reach of typical pulsed laser power density), ii) transition wavelength reachable with tunable lasers, and iii) a large difference in the initial and final level lifetimes.

The first condition demands that there exists a real state energetically close to the intermediate virtual state. One of the candidate set of levels which can satisfy these conditions is shown in Fig. 4. The initial level $n_1$ is 40, the final level $n_3$ is 84, with the intermediate level $n_2$ being 51. In this case, the $n_1$ to $n_2$ wavelength $\lambda_{1,2}$ is 413 nm while the $n_2$ to $n_3$ wavelength $\lambda_{2,3}$ is 409 nm. If we use two counter-propagating laser beams
(not necessarily of the same wavelengths) tuned at an intermediate virtual state close to $n = 51$, we can nearly cancel the first-order Doppler, while achieving saturation of the transition to $n = 84$ with a power density of $\sim 1$ MW/cm$^2$, which is within a reach of conventional tunable pulsed laser systems.

### 2.3. Resonance Detection

For $E_{\text{CM}}^{p} = 6.7\text{eV}$, the velocities of incident $\bar{p}$ and produced protonium are $v = 7.2\text{cm}/\mu\text{s}$ and $3.6\text{cm}/\mu\text{s}$, respectively. If an annihilation detector is placed 1 m downstream of the target, it would take $28\mu\text{s}$ for protonium to reach the detector. The antiprotons which did not form protonium can be rejected based on the flight time difference (they would hit the detector $14$ $\mu\text{s}$ earlier) or can be swept away.

The laser resonance can be detected by using the life-time difference of the on-resonance and off-resonance protonium; the resonant laser transitions promote protonium to long-lived levels, so that the probability of reaching the annihilation detector increase. In the case of $n_1 = 40$ and $n_3 = 84$, the probability of non-resonant protonium ($n = 40$) to reach the annihilation detector is $1\%$ while $95\%$ of $n = 84$ component reach the detector. This should make it possible to detect the resonance with good S/N ratio.
2.4. Expected rates and precision

If $10^7$ antiprotons can be extracted from the trap and can be focused on an atomic hydrogen target with $\sim 10^{11}$ atoms/cm$^3$ (beam and target both having diameter of about 2mm), about 80 protonium can be produced in $n = 40$.

Two pulsed lasers of $\sim 1$ MW/cm$^2$ producing counter-propagating beams at wavelengths of 408 nm and 413 nm can saturate the $n = 40 \rightarrow n = 84$ transition. For each pulse, about 7.1 protonium with $n = 84$ can reach the end of a one meter long flight path while only 0.9 with $n = 40$ can survive, hence laser resonance can be detected with a good S/N of about 9.

The $n = 40 \rightarrow n = 84$ transition frequency $\nu$ is about $1.5 \times 10^{15}$ Hz. If a commercial pulsed dye lasers are used, which typically have bandwidths of $\sim 1$GHz, $\Delta \nu/\nu \sim 10^{-6}$ can be achieved. This is similar to what we have already achieved for antiprotonic helium atomcules. To go to higher precision, it is necessary to use pulse-amplified CW lasers, for which the band widths of $\sim 15$ MHz can be achieved. Then, $\Delta \nu/\nu \sim 10^{-8}$, and the peak center can be determined with at least an order of magnitude better, e.g., $10^{-9}$.

3. CONCLUSIONS

Production of ultra-slow antiprotons using RFQ+TRAP will open new possibilities, such as protonium production and spectroscopy, which would make it possible to improve the precision of the “(anti)protonic Rydberg” constant, or equivalently, the (anti)proton to electron mass ratio $m_{\overline{p}}/m_e$. As of today, the precision of CODATA value of Rydberg
constant $R_\infty \equiv \alpha^2 m_e c^2/2\hbar$ is 1.2 ppb[5], but this will be soon updated by incorporating the recent measurement of 1s-2s atomic hydrogen transition having an astounding precision of 0.008 ppb[6]. Experimental and theoretical values for all electronic transitions should in principle agree to this precision.

The situation is different for antiprotonic atoms. For example, in the case of antiprotonic helium, theoretical values are calculated in atomic unit, which involves the conversion of proton mass (as well as alpha-particle mass) into atomic unit. Here, the 20 ppb uncertainties in the proton to electron and alpha-particle to electron mass ratios come into play. As discussed by Korobov at this conference, the comparison of experimental and theoretical values of antiprotonic helium transitions will lead to a better determination of antiproton mass[7]. Similarly, from the spectroscopy of protonium, we can improve the proton to electron mass ratio, but in this case without referring to the results of three-body theoretical calculations. When we reach this high precision, it should become possible to resolve and study in detail the protonium hyperfine structure as well. In a few years, therefore, we may be able to measure antiproton mass much more precisely than proton mass.

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REFERENCES

1. E. Widmann, invited talk at LEAP98 (this volume) and references therein.
2. H. Torii invited talk at LEAP98 (this volume).
3. B. Ketzer, invited contribution to LEAP98 (this volume), and references therein.
7. V.I. Korobov, invited talk at LEAP98 (this volume).