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INS-Rep.-1061
September 1994

See 8440

Invited talk at HYP94, Vancouver, July 4-8, 1994

EXOTIC STATES OF HADRONIC ATOMS

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SCAN-9409360

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Abstract

Recently discovered metastable antiprotonic helium atoms are described.

1. Introduction

The physics of exotic atoms has a long history, and a large amount of important information has been obtained from the x-ray spectroscopy of exotic atoms. As shown in Fig.1, the x-ray region is an intermediate region in the whole scheme of exotic atoms. Namely, it starts after the Auger-dominated processes followed by the initial formation of the exotic atoms. The principal quantum number n at the formation is believed to be distributed around the most probable value

$$n_0 = \sqrt{M^*/m_e}, \quad (1)$$

where M^* is the reduced mass of the exotic atom. For instance, $n_0 = 16$ for pionic atoms, 30 for kaonic atoms and 40 for antiprotonic atoms. The above estimate can be obtained by assuming in a simple atom like hydrogen and helium that the formed bound state has the same energy as the target atom, or equivalently, that the radius of the bound exotic particle is the same as the electron radius. This initial region had not been touched upon until very recently.

The intermediate x-ray region, however, terminates when the exotic particle cascades down close to the nuclear radius; at $r \sim 10R_N$, typically, the exotic particle is absorbed by the nucleus. The x-ray region terminates when the absorption width exceeds the radiative transition width, which is of the order of keV. The "last orbital" carries important information on the optical potential of the exotic particle, but this is still a "slightly touched" nuclear surface phenomena. What is the inner region? There has been a long-held misunderstanding about the inner region. In the case of pionic atoms, Toki and Yamazaki [1] clarified that deeply bound pionic atoms in

heavy nuclei may exist and, if so, can be produced by certain nuclear reactions. The search for this new region is in progress, but the problem is still open for the future.

In the present talk the author presents a very new information on the initial region obtained from the studies of metastable antiprotonic helium atoms.

Fig.1 Three regions of exotic atoms.

It is to be noted that the above two problems were triggered in connection with our studies of strange particle and hypernuclear physics. The problem of deeply-bound pionic atoms was raised during our struggling with "deeply bound" Σ^- states, when we proposed to study the Coulomb-assisted hybrid bound states of Σ^- [2]. The longevity of negative hadrons in liquid helium was accidentally discovered when we were searching for Σ hypernuclei produced in (stopped K^- , π^{+-}) reactions on liquid helium target [3]. First, trapping of K^- stopped in liquid helium was revealed as discrete peaks of $K^- \rightarrow \mu^- \nu$ and $\rightarrow \pi^- \pi^0$ [4]. Immediately, discoveries of similar phenomena in π^- [5] and antiprotons [6] followed.

2. Metastable Atomcules $\bar{p}\text{He}^+$

The longevity of negative hadrons was first suggested by Condo [7], who proposed an exotic atom $X^-e^-\text{He}^{++}$ to explain some anomalous decay phenomena of negative kaons and pions in liquid helium bubble chambers. Following Condo's suggestion Russell [8] studied this system theoretically and showed that the antiprotonic helium atoms may have long-lived states. Historical accounts on this subject is seen in Ref.[9].

The key reasons for the metastability of $\bar{p}\text{He}^+$ are the following:

- i) It is a neutral atom with one electron, which does not polarize neighbouring helium atoms and does not penetrate into neighbouring helium atoms due to the Pauli principle.
- ii) The $e^- - \bar{p}$ interaction removes the degeneracy of different- l states of the same

n quantum number. This contributes to a suppression of Stark mixing, which is usually the main cause for fast nuclear absorption.

- iii) The level spacing is very small compared with the ionization energy (I_0) around 25 eV. The typical energy for the dominant $E1$ transitions is around 2 eV, much smaller than I_0 . This very large ionization energy helps to suppress the Auger process, and the transition from very large- l states proceeds via a slow radiative process with a typical lifetime of 1 μ s.

Fig.2 Structure of $\bar{p}\text{He}^+$ atoms, calculated by Ohtsuki, taken from Ref. [13].

After the discovery of long-lived antiprotons more theoretical studies have advanced. One is by Yamazaki and Ohtsuki [10], who took into accounts configuration mixings in atomic wavefunctions. The calculated structure of $\bar{p}\text{He}^+$ is shown in Fig.2.

The metastable states of $\bar{p}\text{He}^+$ are described mainly by the electronic $1s$ orbital and an antiprotonic (n, l) orbital which are mutually shielded. They pointed out that the configuration mixing of np orbitals gives a substantial reduction (by a factor of 3) of the $E1$ transition rate of $\bar{p}$ from (n, l) to $(n-1, l-1)$, in a way similar to the Arima-Horie mechanism for the reduction of nuclear magnetic moments [11]. We expect large (n, l) states to be metastable. In the region of $n = n_0 = 38$, states with $l \geq 35$ are metastable, while those with $l < 34$ proceed to ionized states ($\bar{p}\text{He}^{++}$) via fast Auger transitions of $\Delta l \leq 3$, which immediately annihilate due to the Stark mixing.

Since the $\bar{p}$ moves much more slowly than the electron, this three-body system can be described by using the Born-Oppenheimer approximation on a two-center object, $\bar{p}$ and He^{++} , as calculated comprehensively by Shimamura [11]. They also produce a similar level structure and radiative transition rates, but do not predict the Auger transition rates.

The $\bar{p}\text{He}^+$ atom is a very peculiar object, which may be called "atomcule". It may be understood in terms of the already existing concepts such as

- i) A *peculiar He atom*, in which one of the electrons is replaced by $\bar{p}$. It is a slowly decaying object.
- ii) A *peculiar H atom*, in which an extended object $\bar{p}^-\text{He}^{++}$ constitutes a "proton".
- iii) A *peculiar diatomic molecule* with two nuclei, the charge being +2 and -1.

How can we understand the phenomena of long-lived antiprotons? To prove or disprove the atomcule model we have made various experiments.

3. Delayed Annihilation Time Spectra of Antiprotons

Typical delayed annihilation time spectra (DATS) are shown in Fig.3. One is in ^4He and the other in ^3He . Both were taken in 1993 under the condition of about 10 K and 0.5 bar, which we know produces the longest trapping time. DATS's are understood as a cumulative effect of antiproton cascades through metastable states. They are informative, reflecting the formation, structure and decay of those states but only in an integral way. So far, there is no quantitative explanation of DATS. They may also be affected by the surrounding medium, namely, density, temperature, presence of impurities, etc.

Although we cannot account for the spectral shape of DATS, the two data on ^4He and ^3He show a spectacular isotope effect. One is the resemblance of the spectra: if the time scale of DATS of ^3He is enlarged by a factor of 1.14 it can be perfectly overlaid on DATS of ^4He . From this observation we obtain an isotope ratio of the overall trapping time as

$$\frac{\tau(\bar{p}^4\text{He}^+)}{\tau(\bar{p}^3\text{He}^+)} = 1.14 \pm 0.01. \quad (2)$$

On the other hand, Yamazaki and Ohtsuki [10] predicted the isotope ratio to be given by a simple estimate

$$\frac{\tau(\bar{p}^4\text{He}^+)}{\tau(\bar{p}^3\text{He}^+)} = \left[\frac{M^*(\bar{p}^4\text{He})}{M^*(\bar{p}^3\text{He})} \right]^2 = 1.13 \quad (3)$$

based on the atomic model. The isotope effect is essentially the effect of the reduced mass which gives the energy scale. The observed value is found to be in excellent agreement with the above estimate [13]. This gives a support to the atomic model, but in an indirect way.

Fig.3 DATS in ^4He and ^3He in low temperature (~ 5 K) and low pressure (~ 0.3 bar) gas phase.

4. Laser Resonance Spectroscopy

To obtain a direct evidence and thus to proceed to atomic spectroscopy for this atomcule we challenged a new effort: laser spectroscopy. Laser spectroscopy was conceived because the transition energies of the metastable states are typically 2

eV, in the visible light region. However, to detect the induced resonance transition is generally difficult, since it contributes only to equalize the populations of two relevant metastable states which are a small part of the whole metastable stansitions. Morita *et al.* [15] proposed a way to induce a resonant transition from a metastable state to a neighbouring ($\Delta l = 1$) short-lived state. In this case, the resonance can be signaled as a spike in a time spectrum when a pulsed laser is used. Such combinations exist in the border region between the metastable region and the short-lived region.

Morita *et al.* [16] succeeded in observing a resonant transition from the (39,35) metastable state to the (38,34) short-lived state, as shown in Fig.4. This observation proved in a definite way the validity of the atomic model. The resonant laser wavelength was 597.26 nm, in excellent agreement with the calculated values based on the atomic approach [10] as well as on the molecular approach [12].

Fig.4 Laser resonance measurements by Morita *et al.* [16].

5. New Knowledge about Initial Stage

Furthermore, Hayano *et al.* [17] measured the time dependence of the laser spike intensity by changing the laser ignition time. They used two successive laser pulses of the same wavelength, the first one to empty the (39,35) state and the second one

to measure the growing population from the upper states, as shown in Fig.5. From detailed analyses of the single- and double-pulse laser results they succeeded in deducing the decay rate and the initial population of the (39,35) state. The relevant level scheme is given in Fig.6. The decay rate obtained, $0.72 \pm 0.02 \mu\text{s}^{-1}$, is much slower than the "single-particle" estimate neglecting the correlation between the e^- and the $\bar{p}$, but in excellent agreement with the theoretical value based on the configuration mixing [10] and on the molecular approach [12].

The initial population of the (39,35) state turned out to be 7% of total delay fraction, and that of the upper state (40,36) decreases to 4%. This means that the metastable state with $n = 39$ has a substantial population, while the higher- n states have less population. This is the first direct proof of the long-held belief that exotic atoms are formed with the initial principal quantum number as given by eq.(1). There is no rigorous theory for the initial population $P(n, l)$.

Fig.5 Time dependence of laser resonance spikes in double-pulse laser experiments by Hayano *et al.* [17].

Yamazaki and Ohtsuki [10] presented a simple formula for the l distribution

$$P(l) = (2l + 1) \ln(l_{\max}/l) \quad (4)$$

where $l_{\max}$ is the upper limit of possible angular momenta brought in the capture of $\bar{p}$ by He. The $l_{\max}$ is essentially given by the $\bar{p}$ momentum and the atomic radius at the capture, order of 40. The experimental DATS is consistent with $l_{\max} \sim 39$.

6. Future Scope

The high precision laser spectroscopy can be extended to further studies of this interesting atomcule. It may yield a gateway to fundamental physics involving $\bar{p}$. The metastable $\bar{p}\text{He}^+$ atomcule can also be used for the synthesis of antihydrogens, as discussed in Ref. [18].

Fig.6 Level scheme of the $\nu = 3$ sequence, as established by a double-pulse laser resonance experiment by Hayano *et al.* [17].

Acknowledgement

The author would like to thank his collaborators, in particular, Drs. R.S. Hayano, N. Morita, K. Ohtsuki and J. Eades for the discussions. The present work is supported by the Grants-in-Aid for Specially Promoted Research and for International Scientific Research of the Japanese Ministry of Education, Science and Culture.

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