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Quasi-Stable Exotic Atoms/Nuclei as Resonance States

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Abstract A review is made of recent theoretical and experimental studies concerning exotic atoms and nuclei with anomalous quasi-stabilities, which are characterized as special types of resonance states embedded in the continuum. They are i) metastable antiprotonic helium atom-molecules $\bar{p}\text{He}^+$, ii) deeply-bound π^- states in heavy nuclei and 3) theoretically proposed nuclear $\bar{K}$ bound states. The narrow decay widths make it possible to perform various high resolution experiments, which yield rich information on the fundamental properties of the antiproton, three-body atomic structure, QED, the pion nucleus interaction, and the kaon nucleus interaction.

1 Introduction

The high resolution spectroscopy of atomic and nuclear systems is a key to understanding the structure and dynamics of matter and the underlying fundamental interactions. In general, because the natural width of a relevant state limits the ultimate precision of the spectroscopy involving the state, high resolution spectroscopy requires that the lifetimes of the relevant states be sufficiently long. Since antiprotons, negative pions and kaons are subject to strong nuclear absorption, exotic atoms and nuclei with such hadrons as constituents are believed to have widths that are too broad.

In 1991, the anomalous longevity of antiprotons in liquid helium was discovered [1, 2], contrary to the usual belief that exotic hadronic atoms are subject to prompt nuclear absorption. The discovery has stimulated high resolution laser resonance spectroscopy of the metastable states and has clarified the mechanism for the metastability [3, 4, 5, 6]. In 1996 deeply bound π^- states were discovered [7, 8] following theoretical predictions [9, 10]. Furthermore, very deeply bound $\bar{K}$ in few body nuclear systems have been predicted to be discrete states, and experimental methods are being pursued [11, 12]. The present paper reviews those recent developments.

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2 Antiprotonic Helium Atomcule [Observed]

The uppermost states of large quantum numbers (n, l) of the Coulomb three-body system, $\bar{p}\text{He}^+ \equiv \bar{p} + e + \text{He}^{2+}$, are metastable states because the transition energies are small (~ 2 eV) compared with the ionization energy (~ 25 eV) and thus the Auger decays are suppressed [14, 15]. The structure of $\bar{p}\text{He}^+$ is shown in Fig. 1. This system has a dual character, namely, as a two-body exotic atom and as a peculiar diatomic molecule, because the $\bar{p}$ is circulating slowly in a localized orbit. Thus, it is often called *Antiprotonic Helium Atom-Molecule*, or in short *Atomcule*. The metastable states have principal quantum numbers close to

$$n_0 = \sqrt{\frac{M^*}{m_e}} \sim 38 \quad (1)$$

with M^* being the reduced mass, and are populated in the $\bar{p}$ capture by ^4He .

Although they are highly excited discrete bound states embedded in the continuum, they are quasi-stable, even against collisional quenching. The key for the quasi-stability is the large angular momentum of the $\bar{p}$. The main decay mode, the radiative process $(n, l) \rightarrow (n-1, l-1)$, has lifetimes of typically $1.5 \mu\text{s}$ [16, 17], which permit high-resolution laser spectroscopy [3, 4, 5, 6, 18, 19]. The observed transition energies have been compared with recent theoretical calculations which include relativistic and QED corrections [20, 21, 22, 23, 24, 25, 26]. Excellent agreements between theory and experiment, as shown in Fig. 2, indicate that the mass and charge of $\bar{p}$ are the same as those of the proton (except for the sign) within 6×10^{-8} precision [19].

The hyperfine structure of this three-body system due to the coupling of the orbital and spin moments of $\bar{p}$ and the electron spin has been theoretically studied [27], and a doublet structure has been found in a laser resonance transition [28]. The predicted quadruplet structure (Fig. 3) will soon be investigated by the combination of a microwave resonance and two lasers [29].

The Auger transition rates have been calculated [30, 31, 32]. Some particular laser transition has revealed the presence of an anomalously short lived state [33] due to the coupling of an electronically excited state, as predicted [32]. The interactions of $\bar{p}\text{He}^+$ with the surrounding He atoms [18, 34] as well as H_2 molecules and others [35, 36, 37, 38] have also been studied experimentally. Theoretical explanations for these phenomena have been made [39, 40].

3 Deeply Bound Pionic States [Predicted and Observed]

The presence of narrow deeply bound $1s$ and $2p$ states of π^- in heavy nuclei was predicted [9, 41] and their production in $(d, ^3\text{He})$ reactions was proposed [10]. Although, in general, deeply bound hadronic states cannot exist as discrete states because of the strong nuclear absorption, the predicted narrowness of the pionic states is due to a halo like structure which is accommodated jointly by a strong Coulomb attraction and a strong repulsive interaction, as shown in Fig. 4. They are a kind of Coulomb-assisted bound states [42]. The highly reduced

overlapping of the π^- with the nucleus is the key to narrowing the absorption width

The deeply bound π^- states in ^{207}Pb with pionic atom quantum numbers (nl), for instance, are regarded as resonance states in the continuum of ^{207}Tl at around 135 MeV excitation. They are characterized as a kind of Gamow Teller resonances ($\Delta S = \Delta T = 1$) with nuclear quantum numbers (J^π)

$$J = l, \quad \pi = (-1)^{l+1} \quad (2)$$

The first successful experiment was carried out at GSI using a 600-MeV deuteron beam on a ^{208}Pb target [7, 8, 43, 44]. The predicted two peaks (1s and 2p states) were identified. The second experiment was focussed on a ^{206}Pb target to observe a clearly separated 1s peak [45], as shown in Fig. 6. Since the π^- binding energies of the 1s states depend on the local (s-wave) part of the strong interaction potential, the combination of empirical 1s binding energies in a variety of nuclei with different (N, Z) values will yield the isoscalar interaction parameter (b_0) and the isovector parameter (b_1) separately.

Restoration of the chiral order parameter (the pion decay constant, f_π) in the nuclear medium is theoretically expected, and has been discussed in terms of medium-modified masses of hadrons ($N, \rho, \omega, \dots$) [46, 47]. So far, however, no clear experimental evidence exists because of the intrinsic difficulties in an in-medium-mass determination [48]. It has been emphasized only very recently that the isovector parameter (b_1) in the pion-nucleus potential plays an important role in connection with f_π [49, 50]. Fig. 7 from [49] shows theoretical relations between the isoscalar (b_0) and isovector (b_1) parameters for various values of the local potential strength V_0 in the cases of ^{115}Sn (broken lines), ^{123}Sn (dotted lines) and ^{205}Pb (solid lines). The free πN values (FREE) and effective values (EFF) after the double scattering corrections are indicated. The experimental zone (26.1 ± 2.5 MeV, shaded) of ^{205}Pb from a recent experiment [45] is shown. The circles A and B correspond to two assertions: A) $b_1 = b_1^{\text{free}}$ and B) change of b_1 , and subsequent change of b_0 due to double scattering (shown by a broken curve), respectively. The in-medium scale of the pion decay constant $f_\pi^{*2}/f_\pi^2 = b_1^{\text{free}}/b_1$ is shown in the upper part. More recently, analyses including the 1s states of light pionic atoms and taking into account the neutron skin effect in ^{205}Pb have been done [51], in which the circle B is preferred, indicating an enhanced b_1 (a reduced f_π) according to the theoretical expectation by Weise [50].

4 Nuclear $\bar{K}$ Bound States [Predicted]

Very recently definite knowledge concerning the strong interaction shift of the kaonic hydrogen atom has been obtained from a KpX experiment at KEK [52, 53], which results in a negative “repulsive-type” shift of $(-323 \pm 63 \pm 11) + i(407 \pm 208 \pm 100)$ eV for the 1s orbit. Asserting that the $\Lambda(1405)$ resonance is an $I = 0$ bound state of $\bar{K} + p$, Akaishi and Yamazaki [11, 12, 13] constructed the $\bar{K}N$ interactions and applied them to few-body nuclear systems by the G-matrix method. The possible existence of deeply bound nuclear states of $\bar{K}$ is

predicted. Here, the key mechanism for reducing the decay width is that the energy level lies below the main decay channel ($\Sigma + \pi$) due to a strong attraction between the K^- and the surrounding protons, which are contracted around the K^- . The local nuclear density becomes very high and helps to lower the energy level furthermore.

The nuclear ground states of K^- in ^3He and ^4He are predicted to be discrete states with binding energies of 108 MeV and 86 MeV and widths of 20 MeV and 34 MeV, respectively. The formation of the $T = 0$ $K^- \otimes ^3\text{He} + \bar{K}^0 \otimes ^3\text{H}$ state in the $^4\text{He}(\text{stopped } K^-, n)$ reaction has been proposed and its branching ratio calculated. An experimental study of this formation process is proposed [54].

A general diagram involving exotic particles as nuclear constituents is shown in Fig. 9. The K^- bound states as well as π^- bound states are indicated.

5 Concluding Remarks

The three cases of unusual quasi stabilities of exotic atoms/nuclei explained above may belong to *Feshbach resonances*. They are bound states accommodated by their potentials with the nuclei, but are embedded in the continuum. The coupling with the continuum (and other decay channels) is diminished by special mechanisms individually. To form those quasi-stable states we need suitable entrance channels. In the antiprotonic helium atom/nucleus it is simply stopping of low energy antiprotons in a helium medium. In the deeply bound π^- cases it is a “pion transfer” reaction. In the deeply bound K^- case there is no method yet that is experimentally established, though theoretically proposed [11, 12, 13, 55]. This extremely interesting frontier should be investigated furthermore.

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Figure 1. (a) Structure of the $\bar{p}\text{He}^+$ atomcule, where the $\bar{p}$ with large- (n, l) quantum numbers circulates in a localized orbit around the He^{2+} nucleus, while the electron occupies a distributed $1s$ state (b) Level scheme of large- (n, l) states of the $\bar{p}\text{He}^+$ atomcule. The solid bars indicate radiation dominated metastable states, while the broken lines are for Auger-dominated short lived states, which proceed to the ionized $\bar{p}\text{He}^{++}$ states shown by dotted lines. From Ref. [2]

Figure 2. (Left) New laser resonance profiles and their density shifts in $\bar{p}^4\text{He}^+$, observed in the first year (2000) of the Antiproton Decelerator of CERN. (Right) New comparison between the experimental (filled circles with errors) and theoretical (squares [26] and triangles [24]) values for six transitions frequencies in $\bar{p}^4\text{He}^+$. From Hori *et al* [19]

Figure 3. Hyperfine splitting of $\bar{p}\text{He}^{-1}$ states due to the magnetic interactions among the $\bar{p}$ (spin and orbital) and the electron spin [27]. The dominant splitting is due to the coupling of the electron spin with the $\bar{p}$ orbital moment, and a finer splitting is due to the coupling of the $\bar{p}$ spin. Laser transitions $(n, L) \rightarrow (n', L')$ constitute a doublet with frequencies f_- and f_+ . Two microwave transitions are possible within a quadruplet with frequencies ν_{HF}^+ and ν_{HF}^- .

Figure 4. (Upper) π^- ^{207}Pb potential and (Lower) π^- densities in the 1s and 2p states; solid curves with the strong interaction and broken curves with the Coulomb interaction only

Figure 5. Nuclear excitation spectrum in a pion-transfer reaction $^{208}\text{Pb}(d, ^3\text{He})$, revealing deeply bound π^- states in ^{207}Pb . From the first successful experiment at GSI [7]

Figure 6. Cross section versus excitation energy of the $^{206}\text{Pb}(d, ^3\text{He})$ reaction measured at $T_d = 604$ MeV. From Geissel *et al* [45]

Figure 7. Theoretical relations between the isoscalar (b_0) and isovector (b_1) parameters and comparison with experimental information. See text. From Kienle and Yamazaki [49]

Figure 8. Calculated $\bar{K}N$ and $\bar{K}$ -nucleus potentials and the bound levels, $\Lambda(1405)$, ${}^3_{\bar{K}}\text{H}$ and ${}^4_{\bar{K}}\text{H}$ for the $\bar{K}p$, $\bar{K}-{}^3\text{He}$ and $\bar{K}-{}^4\text{He}$ systems, respectively. The nuclear shrinkage effects are taken into account. From Akaishi and Yamazaki [11, 12, 13]

Figure 9. General diagram for hadron-nucleus bound states