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CASCADE OF EXOTIC HELIUM ATOMS

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ABSTRACT

The cascade of $\mu^-4\text{He}$, $\bar{p}^-4\text{He}$, $\bar{p}^-3\text{He}$ and its pressure dependence has been calculated over the whole pressure range from 1×10^{-2} atm to 1×10^3 atm. The calculation does not use any free parameter. The results agree reasonably well with experimental data.

1. CASCADE MODEL

Exotic He atoms are formed by replacing an electron with an exotic particle (μ^- , π^- , K^- , $\bar{p}$). The capture probability is large when the overlap of the wave functions of an electron and an exotic particle is optimal. Here we assume that the exotic particle E^- is captured into orbits with principal quantum number

$$n = (m_E/m_e)^{1/2},$$

where m_E and m_e are the reduced masses of the exotic particle and the electron in the He system. The second electron is ejected via internal Auger effect and an $(E^- \alpha)^+$ ion is formed. The subsequent cascade of the $(E^- \alpha)^+$ ion is determined by the subtle balance of pressure-dependent and pressure-independent processes:

i) Radiative transitions

$$(E^- \alpha)_{n\ell}^+ \rightarrow (E^- \alpha)_{n'\ell'}^+ + \gamma; \quad \Gamma_{\text{rad}} \propto (\Delta E)^3$$

(n = principal quantum number, ℓ = orbital angular momentum).

The radiative transitions are pressure-independent and exactly calculable.

ii) External Auger effect

In a collision between an $(E^- \alpha)^+$ ion and a He atom the electronic 1S level of the $(E^- \alpha)^+$ is partially occupied by a He electron. This electron can be ejected, leading to de-excitation of the ion:

$$(E^- \alpha)_{n\ell}^+ + \text{He} \rightarrow (E^- \alpha)_{n'\ell'}^+ + \text{He}^+ + e^-; \quad \Gamma_A \propto (\Delta E)^{-1/2}.$$

iii) Stark mixing

The electron densities seen by an $(E^- \alpha)^+$ ion in a collision lead to high electric fields. The external electric fields disturb the spherical symmetry of the Coulomb potential and therefore the orbital angular momentum ℓ is not conserved:

$$(E^- \alpha)_{n\ell}^+ + \text{He} \rightarrow (E^- \alpha)_{n'\ell'}^+ + \text{He}.$$

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In addition to these effects, possible particle decays and strong interaction level shifts and widths must be considered. In the case of muonic helium, the 2S level is metastable and the two-photon decay has to be taken into account:

$$(\mu^- \alpha)_{2S}^+ \rightarrow (\mu^- \alpha)_{1S}^+ + 2\gamma; \quad \Gamma_{2P} = 1.18 \times 10^5 \text{ s}^{-1}.$$

2. CASCADE CALCULATIONS

The cascade calculations were made in three steps:

2.1 Collision processes

The collisional processes between exotic He ions and He atoms were investigated numerically. Thirty He atoms and the exotic He ion were confined in a sphere of radius r_{He} defining the average He density. The classical trajectories of all 31 particles (93 second-order differential equations) were calculated using the known He-He¹⁾ and H⁺-He potentials²⁾ to approximate the $(E\alpha)^+$ -He potential. The calculations were done at He densities corresponding to 175 atm, 350 atm, 750 atm, and 1000 atm of He pressure.

Because of the minimum in the $(E^- \alpha)^+$ -He potential, the formation of a molecular ion is possible³⁾:

The results of the Monte Carlo simulations were:

- i) collision rate between ion and He atoms;
- ii) molecular ion formation rate;
- iii) integrated electron density per collision;
- iv) pressure-dependent distribution of the electric fields seen by the ion.

2.2 Calculation of radiative, Auger, and Stark mixing rates

The external Auger rates were calculated by multiplying the internal Auger rates⁴⁾ with the electron density taken from the Monte Carlo simulations. The interaction of an external electric field $\vec{E}$ with an induced electric dipole moment $\vec{\mu}$ leads to a matrix element for Stark mixing transition of

$$M = \langle n_f \ell_f m_f | \vec{\mu} \cdot \vec{E}(t) | n_i \ell_i m_i \rangle.$$

During a collision the electric field changes adiabatically with respect to the precession of the electric dipole moment; hence the magnetic quantum number is conserved and only $\Delta \ell = \pm 1$ transitions are allowed. But during the collision time, several transitions may occur successively, allowing $\Delta \ell = \pm 2, \pm 3, \dots$ transitions. The Stark transition probabilities $P_{Si}(n_i \ell_i m_i \rightarrow n_f \ell_f m_i)$ for a transition from level $|n_i \ell_i m_i\rangle$ to a level $|n_f \ell_f m_i\rangle$ ($\ell_f = 0, \dots, \ell_i - 1, \ell_i + 1, \dots, n_i - 1$) were calculated for five impact parameters. The known pressure dependence of the impact parameters' distribution allowed the Stark mixing probabilities and their pressure dependence to be calculated.

2.3 The cascade

The cascade calculations of an $(E^- \alpha)^+$ system started with a principal quantum number:

$$n_c = (m_E^2 / m_e^2)^{1/2}.$$

A statistical distribution of the ℓ -quantum number was chosen.

Depopulation of a level n occurred

- i) during the free flight through vacuum by radiative transitions, nuclear capture, and particle decay;
- ii) during collisions with He atoms by external Auger transitions and Stark mixing [in addition to the processes under (i)].

Flight and collisions are repeated until the residual population of a level n is below 10^{-3} . The calculation started at $n = n_c$ and proceeded to $n = n_c - 1, n_c - 2, \dots, 2$. The formation of molecular ions is introduced by an exponential increase of the collision rate and the electron density with a time constant given by the mean molecular ion formation time. Collision rate and electron densities saturate at the values experienced in a molecular ion. A more detailed description of the cascade model can be found in Ref. 5.

3. RESULTS

Cascade calculations have been performed for μ - ^4He , $\bar{p}$ - ^4He , and $\bar{p}$ - ^3He at densities corresponding to pressures from 1×10^{-2} atm to 1×10^3 atm. Selected results, intensities of radiative transitions, the population, and the lifetime of the metastable muonic 2S level are shown in the following figures and compared with experimental data. In order to demonstrate the stability of the results, cascade calculations for muonic helium were made with two extreme (pressure-independent) Stark mixing rates and with the molecular ion formation switched off. The results⁶⁻¹⁰⁾ are shown in Figs. 1a-d as dotted curves. These are, of course, not the true errors but extreme values. In Figs. 2 and 3 the results¹¹⁻¹⁴⁾ for $\bar{p}$ - ^4He are shown for three different 3d widths ($\Gamma_{3d} = 2.4 \pm 0.5$ meV). The results on $\bar{p}$ - ^3He show similar agreement with the data.

4. CONCLUSIONS

The cascade of exotic He and its pressure dependence has been calculated without the use of any free parameter for electromagnetic processes. The calculated X-ray intensities agree reasonably well with the measured intensities over the whole density range. It could be shown that the lifetime of the metastable muonic 2S level decreases rapidly with increasing pressure. At pressures between 7 atm and 50 atm the lifetime is less than 1/100 of the lifetime in vacuum. This is in striking contrast with the results of the CERN experiments^{6,7,15)} but in agreement with recent SIN data^{8,9)}.

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Fig. 1: X-ray intensities (a, b), 2S population (c), and 2S lifetime (d) of muonic ^4He ($\circ$ = Ref. 8; Δ = Ref. 9; $\square$ = Ref. 10; $\blacktriangle$ = Ref. 6; $\circ$ = Ref. 7; $\downarrow$ = Ref. 8)

Fig. 2: Absolute X-ray intensities of antiprotonic ${}^4\text{He}$ (.... $\Gamma_{3d} = 1.9$ meV; — $\Gamma_{3d} = 2.4$ meV; - - - $\Gamma_{3d} = 2.9$ meV; Δ = Ref. 11; $\square$ = Ref. 12; $\diamond$ = Ref. 13; $\circ$ = Ref. 14)

Fig. 3 : Relative X-ray intensities of antiprotonic ${}^4\text{He}$ (.... $\Gamma_{3d} = 1.9$ meV; — $\Gamma_{3d} = 2.4$ meV; - - - $\Gamma_{3d} = 2.9$ meV; Δ = Ref. 11; $\square$ = Ref. 12; $\diamond$ = Ref. 13; $\circ$ = Ref. 14)