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Protonium atoms generation at antiprotons channeling in a LiH crystal

N.V. Maksyuta [a], V.I. Vysotskii [a,*], S.B. Dabagov [b,c,d]

[a] Taras Shevchenko Kyiv National University, Kyiv, Ukraine
[b] INFN – Lab. Naz. di Frascati, Frascati, Italy
[c] PN Lebedev Physical Institute, Moscow, Russia
[d] NR Nuclear University MEPhI, Moscow, Russia

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ABSTRACT

The possibility of formation of moving exotic protonium atoms at channeling of antiprotons in an ionic crystal of lithium hydride is proposed and investigated. For this purpose the probability of proton capture by moving antiprotons channeling in crystallographic H^-–(1 1 1) planes and H^-–(1 1 0) axes in ionic LiH crystal was calculated. It has been shown that the process of formation of moving exotic pp^- protonium atoms regarding antiprotons velocities has a resonance character depending on quantum states of these protonium atoms. It was shown that at the capture to higher quantum states the magnitude of resonance peaks increases and the resonance velocities decreases.

1. Introduction

It is well known that for investigation of the fundamental symmetries of nature (in particular, CPT-symmetry), for creation of elementary particles annihilation theory and also at studying various gravitation phenomena, different exotic micro objects are often used. Protonium atoms pp^- are also among such exotic objects. A traditional method for obtaining pp^- protonium atoms is based on a mixing of protons and antiprotons in special traps-"nests" beforehand cooled to a low temperature [1]. Other methods of protonium atoms creation have been discussed in many papers (e.g., [2,3]).

In this paper we propose to use the effect of antiproton channeling in LiH crystal. The crystal is a natural trap, or, in other words, natural reservoir of protons, oscillating in the crystal lattice around their equilibrium positions. Calculation of the probability to capture these intracrystalline protons into different quantum states of moving protonium atoms carried out on the basis of non-stationary perturbation theory. The basis for creation of these atoms is antiprotons channeling along crystallographic directions, in which protons are most densely packed. Indeed, these directions are along the main H^-–(1 1 1) planes and the main H^-–[1 1 0] axes.

2. On the probability of LiH protons trapping by channeled antiprotons

At first let's discuss in brief the physics of the process of antiproton channeling in H^-–(1 1 1) and H^-–[1 1 0] LiH crystals.

At antiproton motion in LiH crystal it undergoes the action of electrostatic fields of Li^+ and H^- ions which one-particle potentials may be written down by the following way (e.g., [4]):

$$\varphi_{\pm}(r) = e[2(Z^*_{\pm}/a_0 + 1/r)\exp(-2Z^*_{\pm}r/a_0) \pm 1/r], \quad (1)$$

where $Z^*_{\pm} = Z_{\pm} - 5/16$, $Z_{\pm}$ are the atom numbers of Li^+ and H^- ions, correspondingly, a_0 is the Bohr radius. After potential (1) averaging over the planes and axes (see, for example, [5,6]), taking into account thermal oscillations (at T = 300 K Li^+ and H^- ions oscillate nearby their equilibrium positions with $u_+ \approx 0,1A$ and $u_- \approx 0,27A$ amplitudes, correspondingly, [7]), we find the interaction potentials of a channeled antiproton with the (1 1 1) planes and [1 1 0] axes. The averaging methods of Coulomb one-particle potentials (the second components of Eq. (1)) in both planar and axial cases are discussed in [4,7–9].

In Fig. 1a, the 2D-plot of antiprotons interaction potential with (1 1 1) planes in LiH crystal is presented. In Fig. 1b there is the 3D-plot of antiproton interaction potential with [1 1 0] axes in LiH crystal presented in relative Cartesian coordinates. Besides, Fig. 1c presents the schematic geometry of motion by setting instant positions of proton (p) and antiproton (p^-) by $\vec{r}'$ and $\vec{r} = \vec{\rho} + \vec{e}_z vt$ radius-vectors, where v is the antiproton velocity.

* Corresponding author.
E-mail address: vivysotskii@gmail.com (V.I. Vysotskii).

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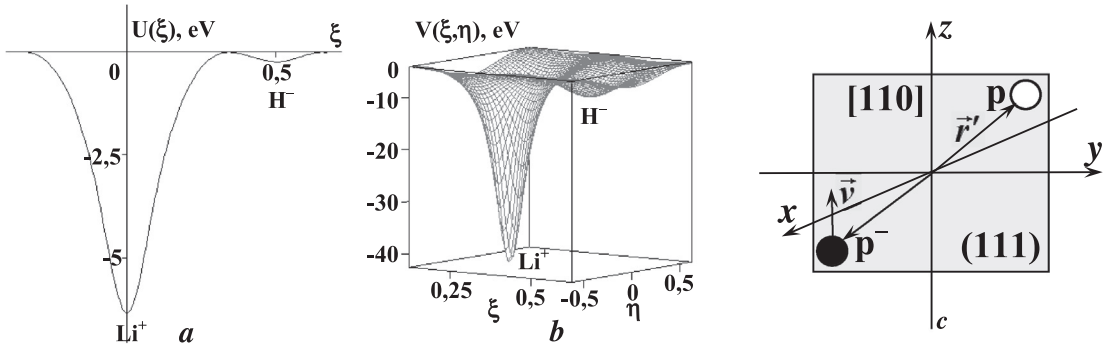

Fig. 1. The antiproton interaction potential in LiH crystal: (a) – with the main charged (1 1 1) planes in the form of 2D-plot, $\xi = x/a_x$ is relative Cartesian coordinate, $a_x = a/\sqrt{3}$ – the distance between (1 1 1) planes, a – the constant of LiH crystal lattice; (b) – with the main charged [1 1 0] axes in the form of 3D-plot, $\xi = x/a\sqrt{2}$, $\eta = y/a$ is relative Cartesian coordinates; (c) – the schematic presentation in a laboratory Cartesian coordinate system a proton p and a channeling antiproton p–oscillating in a lattice of LiH crystal.

As seen from Fig. 1a, b, the depths of the potential wells in H^-–(1 1 1) planes and H^-–[1 1 0] axes equal to $U_0 \approx 0,25$ eV and $V_0 \approx 2,5$ eV, correspondingly, and are small (see also [10,11]). However, for antiprotons moving at $v \approx (0,5 \div 2) \cdot 10^8$ cm/c velocity, the Lindhard angles $\theta_L^{pl;ax} \approx \sqrt{2(U_0;V_0)/mv^2} \approx (1 \div 5) \cdot 10^{-2}$ rad (e.g., [5,12,13]) that leads to the possibility of effective antiprotons population of the bound transverse states. Here m is the antiproton (proton) mass. Taking advantage of one-dimensional oscillation approximation for planar channels, we calculate one bound state with $\varepsilon_0 \approx 0,1$ eV energy and $\psi_0(x) = (2\alpha/\pi)^{1/4} \exp(-\alpha x^2)$ wave function, where $\alpha \approx 25$ Å^{-2}. Using two-dimensional oscillation approximation for axial channels one can find two energy levels for this well. At antiproton channeling at zero angle regarding [1 1 0] axes only a lower level with $\varepsilon_0 \approx 1$ eV energy and $\psi_0(\rho) = (2\beta/\pi)^{1/2} \exp(-\beta\rho^2)$ wave function, where $\beta \approx 100$ Å^{-2}, is populated.

The moving antiproton at the expense of a perturbation interaction potential $W(\vec{r},\vec{r}') = -e\varphi_-(|\vec{r}-\vec{r}'|)$ can, with a certain probability, capture a proton in one of quantum states of a protonium atom $\psi_{nlm}(r,\theta,\varphi)$ on the energy level $E_n = -e^2/2a_1n^2 = -12,47\ \text{keV}/n^2$, where $a_1 = 2\hbar^2/me^2$. Proton initial state in a crystal is described by the wave function $\psi'(\vec{r}') = (2\pi u_-^2)^{-3/4} \exp(-r'^2/4u_-^2)$, while a bound energy ε' (so-called cohesive energy [14]) does not exceed 10 eV which is much smaller than the proton bound energy with an antiproton of a protonium atom formed (up to large n values). This condition allows taking into consideration just ε_0 energy of antiproton channeling.

Let's consider one more the main question concerning antiproton dynamics. To make protonium atoms generation effective, the length of antiproton dechanneling should be quite big (in comparison with a crystal thickness). For the case of a planar channeling total probability for a proton to leave the ε_0 level due to antiproton interaction with a nucleus sub-system of H^-–(1 1 1) crystallographic plane is defined by the following:

$$\Gamma_0 \approx \frac{e^2}{\pi S_{pl}\hbar^2 c}\int_{-\infty}^{\infty} dx_i f(x_i)\int_0^{\infty} dq\{|V_q|_{00}^2 - |(V_q)_{00}|^2\}, \qquad (2)$$

obtained in [5] for the inequality $\langle x^2\rangle_0 \ll u_-^2$. Here $S_{pl} = a^2\sqrt{3}/4$ is the area for one ion H^-; $V_q = \int d\vec{\rho}\varphi_-(|\vec{r}-\vec{r}_i|)\exp(i\vec{q}\vec{\rho})$ is the two-dimensional Fourier component of one-particle potential numerically matched in such a way to make the potential well in H^-–(1 1 1) planes calculated by its help the same as in Fig. 1a; $f(x_i) = \exp(-x_i^2/2u_-^2)/\sqrt{2\pi u_-^2}$ is the function of H^- ions deviation from equilibrium position in the model of isotropic thermal deviations. The calculation by Eq. (2) gives the value $\Gamma_0 \approx 3 \cdot 10^{12}c^{-1}$. It corresponds to the length of antiproton dechanneling $z_0 = c/\Gamma_0 \approx 10^{-2}$ cm, which is quite enough to realize an effective catch of protons by antiprotons in thin crystals. Besides, the dechanneling length for generating electro-neutral protonium atoms should be much more since the atoms move in the regions with low nucleus density (obviously, the electron sub-system of a crystal lattice LiH leads to negligible braking of protonium atoms).

3. Probability of LiH proton trapping by channeled antiproton

Calculation of the capture probability for a proton into the basic state of $\psi_{100}(r)$ antiproton, can be done in the laboratory Cartesian coordinate system (see Fig. 1c) within the approach of non-stationary theory of perturbations [15]:

$$P_1(v) = \frac{1}{\hbar^2}\left|\int_{-\infty}^{\infty} W_{10}(v,t)\exp(i\Omega_1 t)dt\right|^2. \qquad (3)$$

Here $W_{10}(t)$ is the matrix element of interaction perturbation potential $W(\vec{r},\vec{r}')$ for the transition between initial and final states, $\Omega_1 = (E_1 - \varepsilon' - \varepsilon_0 - mv^2/4)/\hbar \approx (E_1 - mv^2/4)/\hbar$ is the frequency of transition between these states. The initial wave functions of the system "proton plus antiproton" in a planar channeling regime or in the regime of an axial channeling can be written down in the following:

$$\Psi_0(\vec{r},\vec{r}',t) = \frac{\psi'(\vec{r}')}{\sqrt{2\pi\hbar}}\left\{\frac{\psi_0(x)}{\sqrt{S_{pl}}},\psi_0(\rho)\right\}\exp\left[-\frac{i}{\hbar}\left\{(\varepsilon'+\varepsilon_0)t - mv_z z + \frac{mv_z^2 t}{2}\right\}\right] \qquad (4)$$

The final wave functions (when protonium atom pp^- is formed) in both planar and axial cases are presented in the following form:

$$\Psi_1(\vec{r},\vec{r}',t) = \frac{1}{\sqrt{2\pi^2 a_1^3\hbar}}\left\{\frac{\exp[ip_x x/\hbar]}{\sqrt[4]{a_x^2 S_{pl}}},\frac{\exp[i\vec{p}_\perp\vec{\rho}/\hbar]}{\sqrt{S_{ax}}}\right\} \times \exp\left[\frac{i}{\hbar}\left(2mv'_z z - mv_z'^2 t - \varepsilon_1\right) - \frac{|\vec{r}-\vec{r}'|}{a_1}\right], \qquad (5)$$

where $\vec{v}_z = v\vec{e}_z$, $\vec{v}'_z \simeq \vec{v}_z/2$ are the antiproton and protonium velocities, correspondingly; a_x is the distance between (1 1 1) planes in LiH crystal; $S_{ax} = a^2/2\sqrt{2}$ is the quantization area for the axis H^-–[110]. It is supposed here that the neutral protonium atom in a crystal volume is free in the case of planar channeling as well as axial channeling.

Using Eqs. (3)(5) the partial amplitude $A_1(\rho,v)$ for a capture probability of oscillating proton into a basic state $\psi_{100}(r)$ of channeled antiproton can be calculated integrating the expressions by

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