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Charge asymmetry in alignment of atoms excited by protons and antiprotons

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Abstract. The multichannel diffraction approximation is used to consider excitation of lithium atom by proton and antiproton impact. The sign-of-charge effect in the alignment of produced $1s^23d$ excited state and in the linear polarization of the subsequent spontaneous $1s^23d \to 1s^22p$ radiation is expected to be considerable.

PACS. 34.10.+x General theories and models of atomic and molecular collisions and interactions – 34.50.Pi State-to-state scattering analyses

1 Introduction

Current developing of the FAIR program at GSI promises to supply atomic physics with unique possibilities to continue famous LEAR studies [1–3] to investigate antiproton-matter interactions in the low- and intermediate-energy region. The question of sign-of-charge asymmetry in ionization and excitation of atoms by protons and antiprotons can take an important place in corresponding future measurements. In this connection we come back to our suggestions [4,5] on an expected proton-antiproton asymmetry effect in alignment of produced atomic excited states and, hence, in polarization (and angular anisotropy) parameters of their electromagnetic radiation. Calculations in [4,5], as well as those presented below, show that alignment parameters of the excited states are expected to be as sensitive and, in some cases, even more sensitive to the sign of charge of the bombarding particle as corresponding excitation cross sections themselves. However, being free of necessity to perform absolute measurements of corresponding proton and antiproton excitation cross sections, the investigation of alignment has an important advantage from the experimental point of view.

Our calculations [4,5], in accordance with the dominating general tendency in theoretical studies on antiproton-atom collisions (see, e.g. [6,7]), concerned excitation of noble gas atoms. Now we turn to the case of so-called *quasi one-electron* atoms and begin with $1s^22s \to 1s^23d$ optically forbidden excitation in atomic lithium. In two cases mentioned above target atoms have quite different excitation spectra. This concerns, in particular, the location of their strongest dipole-excited states, which are expected to be the main intermediate point in atomic multi-step excitation transitions, such as two-step excitation processes $1s^2 : {}^1\mathrm{S} \to 1s3d : {}^1\mathrm{D}$ via $1s2p : {}^1\mathrm{P}$ in helium, and $1s^22s : {}^2\mathrm{S} \to 1s^23d : {}^2\mathrm{D}$ via $1s^22p : {}^2\mathrm{P}$ in lithium atoms. The parallel antiproton and proton scattering studies on the variety of targets can serve to develop the general theory of multi-step excitations in atoms in collisions with heavy particles to wider extend.

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2 Theory

As in [4,5], we base our calculation on the multichannel diffraction approximation by Feshbach and Hüfner [8], which was successfully used in atomic physics to describe the alignment effect in electron-atom inelastic collisions [9]. The partial amplitude of inelastic scattering $\boldsymbol{k}_1 \to \boldsymbol{k}_n$ of a projectile of mass m_p with a target excitation $|1\rangle \to |n\rangle$ is

$$F_n(\boldsymbol{k}_n, \boldsymbol{k}_1) = -\frac{m_\mathrm{p}}{2\pi\hbar^2} \sum_{n'=1}^{N} \int d\boldsymbol{b} e^{i\boldsymbol{q}\cdot\boldsymbol{b}} \times \int_{-\infty}^{+\infty} dz\, e^{i(k_{n'}-k_n)z} V_{nn'}(\boldsymbol{b}, z) u_{n'}(\boldsymbol{b}, z). \quad (1)$$

Here $|n\rangle = |1\rangle$ specifies the target ground state among the whole set $|n\rangle = |1\rangle, |2\rangle, ..., |N\rangle$ of its states taken for consideration. Vector $\boldsymbol{b}$ stands for the impact parameter of the incoming proton or antiproton, and z is their longitudinal coordinate. At high velocity of the incoming particle and small polar scattering angle θ, the transferred momentum $\boldsymbol{q} = \boldsymbol{k}_n - \boldsymbol{k}_1$ is almost perpendicular to the initial velocity of the beam and enters the scalar product $\boldsymbol{q} \cdot \boldsymbol{b}$ as a two-dimension vector. The $(N \times N)$-matrix $V_{nn'}(\boldsymbol{b}, z)$ represents the multi-channel projectile-target interaction operator. Generally, the channel functions $u_n(\boldsymbol{b}, z)$ are determined by the system of coupled integral equations

$$u_n(\boldsymbol{r}) = e^{i\boldsymbol{k}_1\cdot\boldsymbol{r}}\delta_{n1} + \sum_{n'} \int G_n^{(+)}(E, \boldsymbol{r}, \boldsymbol{r}')V_{nn'}(\boldsymbol{r}')u_{n'}(\boldsymbol{r}')d\boldsymbol{r}',$$

which, when using the Green functions within the eikonal approximation

$$G_n^{(+)}(E, \boldsymbol{r}, \boldsymbol{r}') \approx -\frac{im_{\rm p}}{\hbar^2 k_n} e^{ik_n(z-z')}\delta(\boldsymbol{b} - \boldsymbol{b}')\Theta(z - z'),$$

is transformed, at fixed $\boldsymbol{b}$, into a system of one-dimension coupled equations over z.

We present these equations in their final form for the case of calculations for atomic states taken in the L-S coupling scheme. With the azimuthal angle φ dependence of $u_n(\boldsymbol{b}, z)$ and $V_{nn'}(\boldsymbol{b}, z)$ taken in the explicit form

$$u_n(\boldsymbol{b}, z) = e^{i(M_1-M_n)\varphi}e^{ik_n z}\chi_n(b, z),$$
$$V_{nn'}(\boldsymbol{b}, z) = e^{i(M_{n'}-M_n)\varphi}V_{nn'}(b, z),$$

the system of coupled equations for the channel functions reads:

$$\chi_n(b, z) = \delta_{n1} - \frac{im_{\rm p}}{\hbar^2 k_n} \sum_{n'=1}^{N} \int_{-\infty}^{z} dz' \times e^{i(k_{n'}-k_n)z'}V_{nn'}(b, z')\chi_{n'}(b, z'). \quad (2)$$

So the amplitude (1) and, correspondingly, the integrated cross-section of $|1\rangle \to |n\rangle$ excitation are calculated as

$$F_n(\boldsymbol{k}_n, \boldsymbol{k}_1) = e^{i(M_1-M_n)\varphi}\frac{k_n}{2\pi i}\int d\boldsymbol{b}e^{i\boldsymbol{q}\cdot\boldsymbol{b}}\left[\chi_n(b, \infty) - \delta_{n1}\right],$$

and

$$\sigma_n = 2\pi\frac{k_n}{k_1}\int_0^\infty |\chi_n(b, \infty) - \delta_{n1}|^2 b\, db. \quad (3)$$

Within the L-S coupling approach alignment of excited state with orbital momentum L, induced by the proton-atom and antiproton-atom collisions, is described by statistical tensors $\rho_{kq}(L, L)$, representing its orbital momentum density matrix [10], which diagonal elements are proportional to the population cross sections of the sublevels with different orbital momentum projections M. We take the quantization axis along the incoming beam direction. In the case when the scattered particle is not detected and the target atom in its ground state is not polarized, the general symmetry arguments reduce the total set of parameters $\rho_{kq}(L, L)$ to those with index $q = 0$. For dipole transitions from excited state, the angular distribution and the linear polarization of emitted radiation are determined by the only one reduced statistical tensor $A_{20}(L, L) = \rho_{20}(L, L)/\rho_{00}(L, L)$ (*the alignment parameter*). When the total spin of atom S is not zero, the effective alignment parameter $A_{20}({}^{2S+1}L, {}^{2S+1}L) = f_2({}^{2S+1}L)A_{20}(L, L)$, averaged over total angular momentum $\boldsymbol{J} = \boldsymbol{L} + \boldsymbol{S}$ of the atom, should be used. Its value is less than $A_{20}(L, L)$ due to depolarization caused by the in-atom spin-orbit interaction. Generally, their ratio is referred as a fine-structure *disalignment factor*

$$f_k({}^{2S+1}L) = \frac{\sum_J (2J+1)^2 \begin{Bmatrix} J & J & k \\ L & L & S \end{Bmatrix}^2}{\sum_J (2J+1)^2 \begin{Bmatrix} J & J & 0 \\ L & L & S \end{Bmatrix}^2}.$$

Linear polarization of the radiation emitted in $L_i \to L_f$ decay, when measured perpendicular to the incident beam direction, is given by the formula

$$P_{\rm L}(L_i \to L_f) = \frac{3\alpha_2^\gamma(L_i \to L_f)A_{20}({}^{2S+1}L_i, {}^{2S+1}L_i)}{\alpha_2^\gamma(L_i \to L_f)A_{20}({}^{2S+1}L_i, {}^{2S+1}L_i) - 2},$$

where $\alpha_2^\gamma(L_i \to L_f)$ is *the anisotropy parameter* [10]. For the case of $1s^2 3d : {}^2\text{D} \to 1s^2 2p : {}^2\text{P}$ transition under consideration one obtains $\alpha_2^\gamma = \sqrt{7}/2\sqrt{10}$,

$$A_{20}(2, 2) = \frac{\sqrt{10}}{\sqrt{7}}\frac{2\sigma_2 - \sigma_1 - \sigma_0}{2\sigma_2 + 2\sigma_1 + \sigma_0}, \quad (4)$$

$f_2({}^2\text{D}) = 19/25$ and, as a result,

$$P_{\rm L}({}^2\text{D} \to {}^2\text{P}) = \frac{57(\sigma_0 + \sigma_1 - 2\sigma_2)}{119\sigma_0 + 219\sigma_1 + 162\sigma_2}, \quad (5)$$

where σ_M is the integrated cross-section of excitation of ^{2}D sublevel with definite orbital momentum projection M (here, due to the symmetry properties, $\sigma_M = \sigma_{-M}$).

3 Results and discussion

We perform our calculations in the basis of 13 orbital $2s$, $2p$, $3s$, $3p$ and $3d$ states of the upper electron in Li atom by solving the system (2) numerically and integrating corresponding differential cross-sections over b according to (3). The alignment parameter $A_{20}(2, 2)$ of $3d$ state and linear polarization of radiation emitted in its decay are then evaluated from (4) and (5) correspondingly. Calculations are performed for the energy range 100 keV – 1 MeV of incoming proton and antiproton which should be reliable enough due to the general requirements of the multichannel diffraction approximation [8].

Figure 1 shows the pronounced sign-of-charge effect in alignment of the excited $3d$ state, produced in proton-lithium (solid line) and antiproton-lithium (broken line) collisions. At beam energy below 1 MeV, $A_{20}(2, 2)$ is larger for the antiproton impact than for the proton one. This difference vanishes at energies above 1 MeV where the one-step excitation amplitude prevails over the whole sum

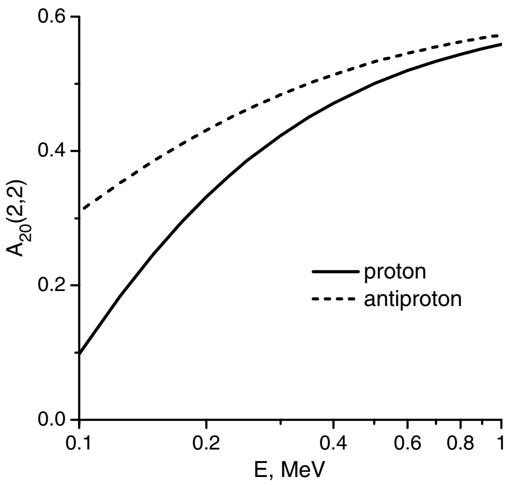

Fig. 1. Alignment parameter $A_{20}(2, 2)$ of Li atom $3d$ state excited by proton (solid line) and antiproton (broken line).

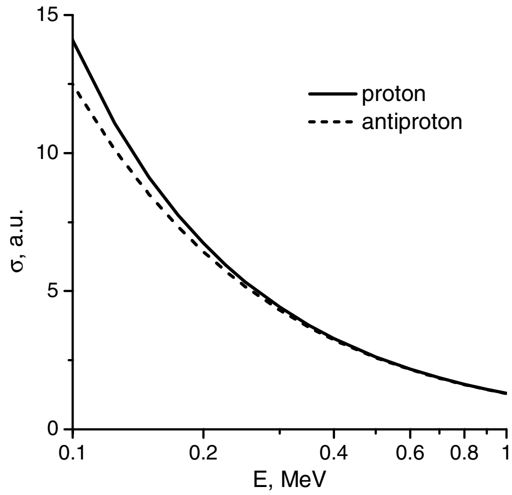

Fig. 2. Proton (solid line) and antiproton (broken line) impact excitation cross-section of $3d$ level (summed over angular momentum projections) of the upper electron of Li atom.

of other terms in the amplitude. The analysis shows that no single two-step or multi-step scattering mechanism can be recognized as the main origin of the charge asymmetry. Actually, all the variety of two-step processes, like $2s \to 3d$ excitation via intermediate $2p$ and $3p$ states and the reorientation of the atomic angular momentum in final $3d$ state, must be appreciated as equally important in the interference of their amplitudes with the amplitude of direct $2s \to 3d$ transition. As Figure 2 shows, all these mechanisms lead also to the charge asymmetry effect in the integrated $1s^22s : {}^2\mathrm{S} \to 1s^23d : {}^2\mathrm{D}$ excitation cross-section.

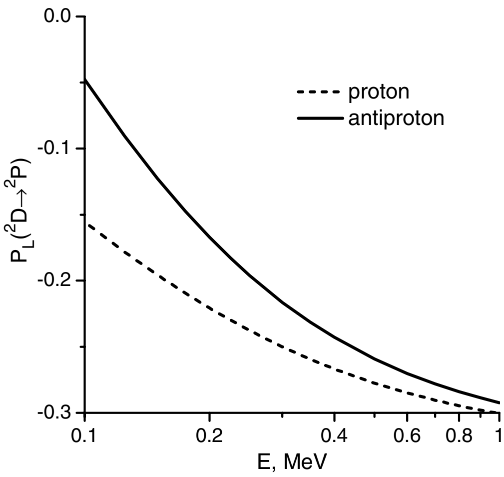

Fig. 3. Linear polarization of the decay radiation from $3d$ state excited by proton (solid line) and antiproton (broken line).

The linear polarization (5) of the radiation emitted in $1s^23d : {}^2\mathrm{D} \to 1s^22p : {}^2\mathrm{P}$ decay with account for the spin-orbital disalignment is presented in Figure 3. The difference between the proton case (solid line) and the antiproton one (broken line) looks considerable enough for experimental observation. The clear sign-of-charge effect in the polarization occurs for projectile energies below 1 MeV and become stronger when going to lower energies.

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