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Antiparticle excitation of atomic inner shells

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Antiparticles are shown to produce inner-shell vacancies in atoms with cross sections that can be orders of magnitude larger than those for particles at the same incident velocity. This phenomenon occurs for projectile velocities which are low compared with the orbital velocity of the electrons. The disparity in vacancy production manifests itself through differences in the characteristic x-ray yields induced by particles and antiparticles. The principle of a self-calibrating detector for antiparticle-induced x-ray emission is given.

I. INTRODUCTION

Inner-shell excitation is a powerful dynamic tool for the study of electronic states of atoms. This method is particularly instructive for collisions with heavy charged particles which have atomic number Z_1, much less than the target atomic number Z_2.[1-4] Under these conditions the projectile acts as a point charge devoid of atomic structure.[2] It is the purpose of this paper to demonstrate that the change in sign of the projectile interaction with the atom causes large differences between the probabilities of inner-shell excitation by particles and by antiparticles. Antiparticles penetrate atoms more deeply and hence excite with higher probability than do particles under otherwise equal conditions. Other, more subtle, effects magnify this trend. Recent work,[5] addressing other aspects, also explores particle-anti-particle differences in atomic collisions.

There is an acute need for quantitative analysis of antiparticle-atom interactions now that antiproton beams are becoming available. Many ancillary scientific problems related to high-energy atomic physics will emerge in the wake of colliding particle-antiparticle beam research. The present study might pertain as well to observational tools needed to answer the pressing question[6] of the presence of antimatter in the universe, and our present view of cosmology.

II. INNERSHELL EXCITATION BY PARTICLES AND ANTIPARTICLES

Consider a proton approaching a target atom with velocity v_1 comparable to the mean orbital velocity of the target K-shell electron v_{2K}. (It is an easy matter to extend the following treatment to other particles and antiparticles heavier than the electron and to L and M shells, but for definiteness and simplicity we concentrate on protons and K-shell excitation.) Penetration into the domain of the K shell induces three major effects: (1) The trajectory is deflected away from the target nucleus so that $R_0 > b$, as sketched in Fig. 1, where R_0 is the distance of closest approach for impact parameter b. This reduces the amount of ionization. (2) The proton excites K-shell electrons with a probability which is influenced by the binding effect: The electrons to be excited act under the influence of a central charge of roughly $Z_1 + Z_2$ during the process of excitation. Since the low velocity limit of the ionization cross section in inversely proportional to the ninth power of the binding energy, the shift from Z_2 to $Z_1 + Z_2$ further reduces the cross section by about a factor of $(1 + Z_1/Z_2)^{-18}$. (3) During the collision the proton is slowed significantly

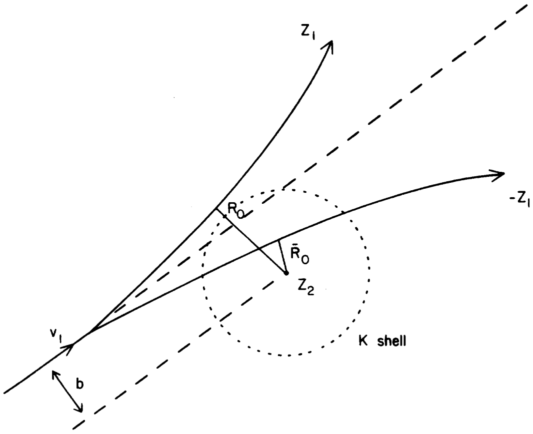

FIG. 1. A schematic classical picture of the trajectories of a particle (p) with nuclear charge $+Z_1$ and an antiparticle ($\bar{p}$) of charge $-Z_1$ in the field of a target atom with nuclear charge Z_2. At equal impact parameters b and low velocities v_1, the distances of closest approach, R_0 and $\bar{R}_0$, and the projectile velocities there differ significantly. This can cause antiparticles to ionize inner shells with much larger probabilities than particles, as illustrated in Fig. 2.

in the proximity of the target nucleus and, in addition, loses the energy necessary to ionize the K shell, if ionization occurs. Since in the low velocity regime the ionization cross section is proportional to $(v_1/v_{2K})^8$, these changes cause additional drastic reductions in the probability of ionization by protons.

Consider now an antiproton approaching a target atom under the same conditions. As Fig. 1 indicates, the trajectory of the antiproton is bent towards the target nucleus by the mutual Coulomb attraction. This has the consequences that: (1) $R_0 < b$ which increases the ionization probability. (2) The electronic binding energy is reduced and causes a further increase in the ionization cross section by a factor of about $(1-Z_1/Z_2)^{-18}$. (3) The attraction increases the projectile velocity near the nucleus and this again increases the cross section drastically.

For a proper description of the effect of the projectile interaction with the target nucleus we follow methods outlined elsewhere.[7] We express the cross sections for particles and antiparticles in the same form but find that they can have vastly different values.

As in our previous work,[3,4] the K-shell ionization cross section for particles in the perturbed stationary-state (PSS) approximation can be expressed in terms of the plane-wave Born approximation (PWBA) as

$$\sigma_K(p;Z_1)=\sigma_K^{\text{PSS}}=C_K(\pi d q_0 \zeta_K)\,\sigma_K^{\text{PWBA}}(\eta_K;\zeta_K\theta_K) \ . \tag{1}$$

The corresponding cross section for antiparticles becomes

$$\sigma_K(\bar{p};Z_1)=\sigma_K(p;-Z_1) \ , \tag{2}$$

where Z_1 is always positive and p and $\bar{p}$ denote particle and antiparticle. The projectile velocity variable in the cross section is $\eta_K=(v_1/v_{2K})^2$, where v_{2K} is the target K-shell orbital velocity. The factor C_K gives the effect on the ionization cross section of the Coulomb deflection of the projectile trajectory by the target nucleus. The distance of closest head-on approach is denoted by $2d$, and $\hbar q_0$ is the minimum momentum transfer for ionization. The binding and polarization effects are given by two functions, g and h, respectively, which are described elsewhere[3,4] and appear in the factors

$$\zeta_K=1+\frac{2}{\theta_K}\frac{Z_1}{Z_{2K}}(g-h)$$

and

$$\bar{\zeta}_K=1-\frac{2}{\theta_K}\frac{Z_1}{Z_{2K}}(g-h) \ , \tag{3}$$

so that $\zeta_K+\bar{\zeta}_K=2$. Here $Z_{2K}=Z_2-0.3$ takes into account the inner atomic screening and θ_{2K} is the reduced K-shell ionization energy.[2] We note the important result that the antiparticle Coulomb-deflection factor $\bar{C}_K$ is much larger than the particle-deflection factor in that

$$\bar{C}_K(x)=9\int_1^{T_M}\frac{e^{+xt}}{t^{10}}\,dt \ , \tag{4}$$

while for particles,

$$C_K(x)=\int_1^{T_M}\frac{e^{-xt}}{t^{10}}\,dt \simeq 9E_{10}(x) \ , \tag{5}$$

where $E_{10}(x)$ is the exponential integral of order 10. The upper limit corresponds to the maximum energy transfer T_M to the K-shell electrons. In practice, the integration for $\bar{C}_K$ is terminated when or before the integrand reaches its minimum. This procedure is justified by the vanishingly small probability for large energy transfers.

As an illustration, Fig. 2 displays the ratio of the K-shell excitations cross section of aluminum $(Z_2=13)$ for antiprotons and protons. The absolute cross section for protons is contained in Figs. 5 and 7 of Ref. 2. We see an enormous increase of this ratio, by orders of magnitude, at low velocities $v_1 < v_{2K}$. At higher velocities, where Coulomb-deflection effects subside, the influence of the binding effect still remains. At even higher velocities the ratio drops below unity because the polarization of the target-electron orbit by the projectile dominates other ef-

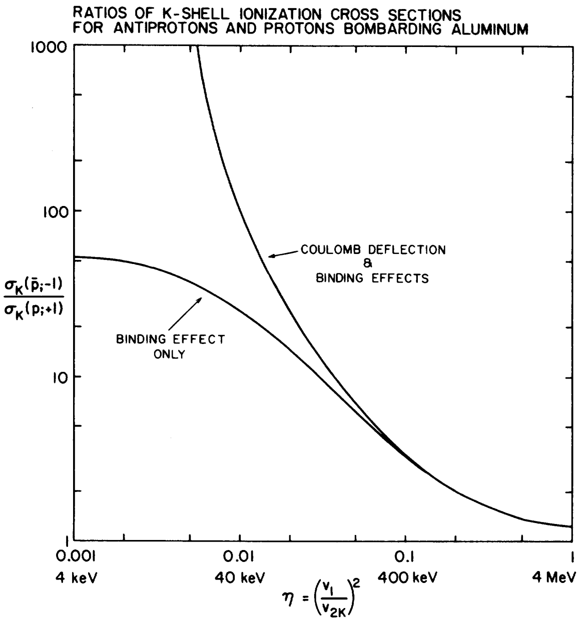

FIG. 2. Calculated cross-section ratios for antiprotons (−1) and protons (+1) ionizing aluminum K shells as a function of projectile velocity v_1 (in units of the aluminum K-shell orbital velocity v_{2K}) or projectile energy. The absolute $\sigma_K(p;+1)$ cross sections are reported in Refs. 2 and 3. When $(v_1/v_{2K})^2>0.1$, the large Coulomb-deflection effect wanes, and only the binding effect contributes to the antiparticle enhancement of inner-shell excitation.

fects on the cross section.[3] Significant differences between antiparticles and particles vanish when the cross sections have passed their maximum values at projectile velocities $v_1 >> v_{2K}$ where the Z_1^2 dependence of the cross sections obtains.

III. DISCUSSION

Antiparticles excite inner shells of atoms with probabilities that can be orders of magnitude larger than the excitation probabilities of particles at equal velocities when they are less then the inner-shell orbital electron velocities. The different inner-shell excitation probabilities of particles and antiparticles can influence experiments which bombard atoms with antiprotons. New programs are emerging which are centered on the antiproton storage ring at CERN which aim at elucidating atomic structure and quantum electrodynamic effects through interactions of antiprotons with atoms. The beam energies envisioned at present, 0.1–2 GeV, are too high for such an atomic effect to contribute. When energies on the order of 1 MeV are obtained, the enhanced production of x rays by antiprotons becomes observable. If the antiprotons were first moderated, for example, through about 25 cm of aluminum, considerable energy straggling would occur. Still comparison of x-ray data produced by similarly moderated protons will show the predicted enhancement effect for antiprotons.

To address the need to distinguish matter from antimatter, one could construct a detector of antiparticle-induced x-ray emission (APIXE) which is based on the following principle. Two targets are exposed: one of them has low Z_2 and responds equally to antiparticles and particles in a bombarding energy range in which a second target of high Z_2 gives a distinctive x-ray yield. (See Fig. 2.) For reasons given in Sec. II, and illustrated in Fig. 2, detailed sample calculations show such a detector is feasible in space experiments only if there are substantial low-energy antiproton components in the particle spectrum encountered.

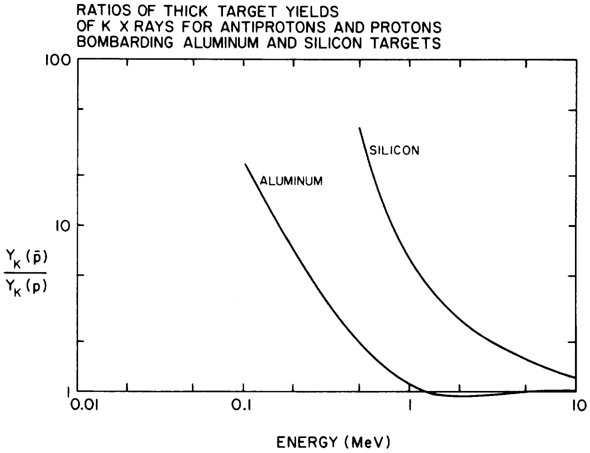

FIG. 3. Response of a self-calibrating APIXE detector. A low-Z_2 material shows little difference between antiparticle and particle production of x rays, in contrast to the response of a high-Z_2 material for projectiles at a given energy. Comparison of high-Z_2 and low-Z_2 x-ray production therefore is a measure of the antiparticle component in a mixed low-energy particle-antiparticle flux.

Antiparticle enhancement of inner-shell excitation can be observed at energies in the MeV range and below. If such a component were to be present in the interplanetary particle background, a simple self-calibrating antiparticle-induced x-ray emission detector could be constructed on the basis of these considerations (Fig. 3). It could ascertain, through direct observation, the density of antiparticles in outerspace and would thereby, help us decide among cosmological theories.

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