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Exotic atoms in superintense laser fields

Applications in atomic, nuclear, and particle physics

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Abstract. The interaction of very strong laser fields with hydrogenlike atomic systems is analyzed theoretically. It is shown that the usual magnetic field-induced limitations for efficient recollisions can be overcome by employing exotic atoms rather than ordinary ones. In this way not only high-harmonic radiation in the MeV regime could be produced, but also laser-induced nuclear effects and particle reactions come into the reach of near-future laser facilities.

1 Introduction

Studies on exotic atoms have made important contributions to our understanding of the fundamental laws of physics. Purely leptonic systems like positronium are free from nuclear uncertainties and thus allow for high-precision tests of quantum electrodynamics [1,2]. Investigations of very compact systems like muonic [2,3] or pionic atoms [4,5] probe electromagnetic forces at short distances, nuclear properties, and the strong interaction. A particularly interesting feature of hydrogenlike exotic atoms is that the mass ratio of the two binding partners is much larger than in ordinary atoms or ions (where the electron-nucleus mass ratio is $m_e/m_{\rm nuc} \leq 10^{-3}$), and in certain cases amounts to unity. This implies according to Newton's law, that the dynamic response to an external force field of each of the atomic constituents is rather similar. In this paper we consider dynamic processes that can occur in exotic atoms when they are exposed to strong laser fields. Although all exotic atoms have finite lifetimes, some of them can be considered stable on the typical time scale $\sim 10^{-15}$–10^{-10} sec of high-intensity laser pulses.

During the last two decades experiments on intense laser-atom interactions have revealed various nonlinear phenomena such as above-threshold ionization and high-harmonic generation [6–9]. These processes find an intuitive explanation in terms of the three-step model of laser-driven recollisions. According to this semi-classical model, after laser-induced tunneling ionization (first step) and free propagation in the field (second step), an atomic electron may be driven back to its parent ion by the oscillating electric field where it then recollides (third step). The nonlinear processes mentioned above correspond to different exit channels of this collision. The highest collision energy attained so far is about 1 keV in helium [10]. Higher collision energies are desirable but difficult to achieve because of the increasing influence of the laser's magnetic-field component [7]. In fact, when the electron energy approaches the relativistic domain it is forced by the magnetic field into forward direction while the heavy nucleus is staying behind so that both particles miss each other at the recollision event. For this reason, recollisions are largely suppressed in optical laser fields above $\sim 10^{16}$ W/cm^2 intensity. In exotic atoms the situation is different because of the more similar or even equal masses of the particles involved. Some consequences of this circumstance for atomic, nuclear, and particle physics applications are elaborated in the following for positronium, muonic atoms, and hadronic atoms.

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2 Positronium atoms

The first exotic atom that has been produced was positronium (Ps) in 1951 [1,2]. It consists of an electron (e^-) and its anti-particle, the positron (e^+). The ground-state of Ps has a binding energy of 6.8 eV and exists in two spin configurations. In para-Ps the electron and positron spins are antiparallel and form a $^1S_0$ spin-singulett state; its lifetime is limited to 0.125 nsec due to e^+e^- annihilation into two photons. Contrary to that, ortho-Ps is a $^3S_1$ spin-triplett with the particle spins oriented parallelly; it decays into three photons with a lifetime of 142 nsec. The hyperfine splitting between the para- and ortho-states amounts to less than 1 meV. In a statistical mixture of Ps atoms the longer-lived ortho state has an abundance of 75%. The positrons required for Ps production usually stem from a radioactive source (e.g., ^{22}Na). After moderation, large amounts of positrons can efficiently be accumulated by advanced trapping techniques today [11]. Via subsequent electron capture from a target material, high Ps densities $n \approx 10^{15}\,\mathrm{cm}^{-3}$ have been achieved, and even higher densities ($n \geq 10^{18}\,\mathrm{cm}^{-3}$) are envisaged for generation of a Ps Bose-Einstein condensate or a 511-keV annihilation laser [12]. Very recently, high Ps densities have for the first time led to the production of Ps_2 molecules [13].

Due to a constituent mass ratio of one, Ps atoms are particularly suited for realization of laser-driven recollisions at high field strengths [14]. After ionization (see also [15,16]), the electron and positron oscillate in opposite directions along the laser electric field and experience an *identical* magnetic drift motion, which largely reduces the detrimental impact of the latter. This allows for recollisions and recombination into a bound state at arbitrary laser intensity and frequency. Via high-harmonic generation from Ps atoms coherent, hard x-rays well above 1 keV can therefore be produced. For example, a cutoff energy of 50 keV can be reached by interaction with an intense, long-wavelength laser beam ($I \approx 10^{13}\,\mathrm{W/cm}^2, \lambda \approx 100\,\mu\mathrm{m}$) [14]. We note that in view of the latest progress in Ps accumulation mentioned above [12,13], the predictions in Ref. [14] regarding achievable x-ray yields may be considered as conservative estimates as they were based on target densities of $n \sim 10^8\,\mathrm{cm}^{-3}$ only.

By increasing the laser intensity into the relativistic domain, high-energy e^+e^- collisions can be obtained by laser-driving Ps atoms which might even lead to particle reactions like muon ($\mu^+\mu^-$) or pion ($\pi^+\pi^-$) pair creation [17,18]. The minimum field intensity to ignite these processes amounts to about $10^{23}\,\mathrm{W/cm}^2$ in the near-infrared frequency range. At such high intensities, the laser magnetic field has another harmful effect on the recollision efficiency which is caused by a combination of relativistic and quantum phenomena: Since the electron and positron are accelerated to relativistic longitudinal speeds, the time until they recollide becomes very long due to relativistic time dilation; as a consequence, the particle wave packets considerably spread before recollision due to quantum mechanical dispersion which dilutes their current densities and, thus, the reaction rates. This problem can be avoided, however, when instead of a single laser pulse, two counterpropagating laser beams are employed [19,20]. Then the wave-packet spreading is greatly reduced and higher collision luminosities are attained. In this field configuration, laser-driven muon or pion pair creation from Ps atoms could be realized by present-day technology [18,20].

3 Muonic atoms

The first x-ray spectroscopy of muonic atoms was carried out in 1953 [3]. A muonic atom consists of a muon bound to a nucleus (and possibly additional electrons). The muon is the unstable heavy brother of the electron ($m_\mu/m_e \approx 207$); it decays via $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$ into electron and neutrinos with a lifetime of 2.2 μsec which also limits the lifetime of muonic atoms. Muons can be produced only indirectly via pion creation, where the latter are generated in high-energy proton-proton (pp) collisions and subsequently decay into muons according to $\pi^- \to \mu^- + \bar{\nu}_\mu$. The muons are decelerated and then captured by target atoms, typically into a high-lying orbit from where they cascade down to the ground state. In the ground state of muonic hydrogen, the muon is bound by 2.5 keV at a Bohr radius of 285 fm, and experiences an electric field strength of $1.8 \times 10^{14}\,\mathrm{V/cm}$ corresponding to the intensity $4.2 \times 10^{25}\,\mathrm{W/cm}^2$. Today, large-scale muon facilities like TRIUMF (Vancouver, Canada) [21] are specialized in the production of muons

and muonic atoms. New developments aim at the generation of radioactive muonic atoms for performing spectroscopic studies on unstable nuclear isotopes [22]. Muonic atoms also play an important role as catalysts for nuclear fusion [23].

Due to the small Bohr radius of the bound muon, the muonic wave function has an appreciable overlap with the binding nucleus. For this reason muonic atoms represent traditional tools for nuclear spectroscopy via precise measurements of the transition energies between stationary muonic levels. This way, information on the nuclear size, deformation, or surface thickness can be obtained. When muonic atoms are exposed to external laser fields, the problem becomes explicitly time-dependent and the muon a *dynamic* probe of nuclear structure features. Against this background we have calculated high-harmonic generation from strongly laser-driven muonic hydrogen ($p\mu^-$) and deuterium ($d\mu^-$), and found isotope signatures in the radiation spectra [24]. For light nuclei and moderate laser parameters this process can be described by nonrelativistic quantum dynamics. Due to the large muon mass, the magnetic-field induced drift is suppressed. Moreover, the nucleus cannot be considered as infinitely heavy, so that the motion of both binding partners must be taken into account. The calculation is facilitated by the fact, that the 2-body problem separates into relative and center-of-mass coordinates when the laser field is treated as purely time-dependent (dipole approximation). The center-of-mass moves freely since the total charge of hydrogen isotopes is zero. The relative motion is governed by the usual Schrödinger equation

$$i\hbar\frac{\partial}{\partial t}\psi\left(x,t\right)=\left\{-\frac{\hbar^2}{2m_r}\frac{\partial^2}{\partial x^2}-exE(t)+V_{\text{nuc}}\left(x\right)\right\}\psi\left(x,t\right) \tag{1}$$

for a hydrogen atom in a laser field $E(t) = E_0 \sin(\omega t)$, except that m_r is the reduced mass of the effective 1-body problem. By numerical solution of Eq. (1), the dipole acceleration and the spectrum of radiated frequencies are obtained, which reveals signatures of the finite nuclear mass and size [24]. The influence of the nuclear mass can directly be infered from Eq. (1). In a strong laser field, the harmonic cutoff position is determined by the ponderomotive energy which amounts to $U_p = e^2E_0^2/(4\omega^2 m_r)$ in the present case and is the larger the smaller the reduced mass is. Under suitable conditions, the cutoff energy from muonic hydrogen is therefore larger by about 5% than that from muonic deuterium, which is in accordance with the relative difference of the reduced masses. As regards finite nuclear size effects, it is found that the harmonic plateau height is larger for muonic hydrogen than muonic deuterium. The reason is that a smaller nuclear radius ($R_p \approx 0.875\,\text{fm}$ versus $R_d \approx 2.139\,\text{fm}$) increases the steepness of the potential near the origin, leading to more violent acceleration and thus to enhanced harmonic emission. This demonstrates that muonic atoms in strong laser fields can, in principle, be utilized to dynamically gain structure information on nuclear ground-state properties. Moreover, coherent γ-ray harmonics of about 0.5 MeV can be obtained from muonic hydrogen in a superintense VUV laser field ($I \approx 10^{23}\,\text{W/cm}^2$ at $\hbar\omega \approx 27\,\text{eV}$) which could be utilized to induce photonuclear reactions [24].

Concluding this section, we note that laser-induced modifications in muon-catalyzed fusion of deuterium molecules ($dd\mu^-$) at $I \sim 10^{22}\,\text{W/cm}^2$ have also been calculated recently [25].

4 Hadronic atoms

Pionic atoms were the first species of exotic atoms where effects of the strong interaction could be determined quantitatively [4]. The pion has a similar mass as the muon ($m_\pi/m_e \approx 273$) so that the energy levels in pionic and muonic atoms are in principle similar. But pionic spectral lines are broadened by the influence of the strong force since the pion can be absorbed by the nucleons of the binding nucleus. This limits the lifetime of light pionic and, in general, hadronic atoms to typical values of $\sim 10^{-15}$ sec. During recent years high-precision lifetime measurements have been conducted on pionic hydrogen at PSI (Villigen, Switzerland) [26] and on pionium ($\pi^+\pi^-$) at CERN (Geneva, Switzerland) [27] in order to test fundamental symmetries of quantum chromodynamics. Another interesting type of hadronic atoms involves antiprotons, e.g. antiprotonic hydrogen ("protonium") or helium [5,28].

In contrast to muonic atoms or positronium, hadronic atoms cannot be considered as stable in the laser field as their lifetime is on the order of an optical cycle. At first sight, this seems to exclude investigations of their interaction with strong laser fields. A possibility to overcome this problem could be the application of a relativistic atomic beam with Lorentz factor $\gamma \sim 10$ instead of a fixed target [29]. Then, due to time dilation, the lifetime of the atoms is increased by a factor γ. Alternatively, high-lying Rydberg states of hadronic atoms could be employed having lifetimes in the μsec range [28]. Though technically challenging, by these or similar methods the coupling of hadronic atoms to intense laser fields could, in principle, be studied at high (lab-frame) laser frequencies $\sim$1 keV and/or intensities $\sim 10^{22}$–10^{26} W/cm^2.

5 Conclusion

Due to a more favorable mass ratio of the constituent particles, exotic atoms offer promising perspectives for superintense laser interaction studies. Via high-harmonic generation from positronium or muonic atoms, coherent x-rays or even γ-rays could be produced. Moreover, with the help of intense laser fields the traditional spectroscopy of muonic atoms could be extended towards dynamical analyses of nuclear structure, whereas strongly laser-driven positronium provides interesting prospects for coherently controlled particle collisions and reactions. Similar studies are conceivable with strongly interacting particles in hadronic atoms, despite their short lifetimes on the femtosecond scale. All these processes come into experimental reach by upcoming high-power laser facilities like the Extreme-Light Infrastructure (ELI) [30].

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