A NEW TUNEABLE AND PULSED VACUUM-ULTRAVIOLET
AND X-RAY LINE SOURCE

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ABSTRACT

It is proposed to use the radiation emitted in electron capture by ions occurring in electron cooling of stored stable particle beams as a tuneable photon source for vacuum-ultraviolet (VUV) and X-ray spectroscopy. By choosing a suitable ion beam and storage energy, photon energies from the VUV to the X-ray region can be obtained. The photon line width can be made smaller than 0.2 eV and its energy can be tuned in steps smaller than 10^{-4} . The photon source can be continuous or pulsed with pulse durations of 100 ns and less and repetition rates of 1 MHz and more. With present electron cooling systems and storage-ring configurations, about 10^8 - 10^{12} photons can be produced into a 4π solid angle. The corresponding intensities for observation in a solid angle of 1 msr range from 10^4 in the VUV to more than 10^8 in the X-ray region.

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1. INTRODUCTION

The phase-space cooling of ion beams by high-quality electron beams has advanced considerably in recent years [1]. The virtue of this technique is to increase the phase-space density of a stored ion beam by several orders of magnitude without any losses in very short times. This is achieved by intersecting a circulating ion beam over a fraction of the storage ring with an electron beam of equal velocity. The electron beam has small transverse velocity components and is extremely monochromatic. In the thermodynamic sense it is a cold beam, characterized by a transverse and longitudinal temperature which corresponds to the mean transverse and longitudinal velocity spread of the electrons in the particle rest frame (PRF) -- a system in which the average longitudinal electron (ion) velocity vanishes. Controversely the ion beam is a hot beam. Through repeated interactions of the circulating ions with the electrons, heat from the hot ion beam is transferred to the continuously renewed electron beam. The ion beam is cooled, i.e. its beam dimensions, divergence, and momentum spread shrink until thermal equilibrium between both beams is reached. Under ideal conditions this entails the frozen beam having a velocity spread $\bar{v}_i$ in either direction by a factor of $\sqrt{m/m_i}$ smaller than the electron beam velocity $\bar{v}_e$ (m = mass of the electron, m_i = mass of the ion).

Electron cooling experiments on protons were begun in Novosibirsk [2] and continued at CERN [3] and Fermilab [4]. Cooling of antiprotons and H^- -ion beams will be attempted at LEAR in the near future [5]. It turned out that electron-proton recombination serves as an excellent diagnostic tool [2,3,6] in electron cooling of proton beams. No attention has, however, yet been paid to the radiation emitted in recombination of the cooling electrons with positive ions:

This process is, however, a powerful source of monochromatic photons tuneable over a wide range of energy.

2. RECOMBINATION CROSS-SECTION

The cross-section for radiative electron capture can be found in the literature. For our purpose it is sufficient to consider the formula given by Bethe and Salpeter [7] for the capture into an atomic level of main quantum number n :

$$\sigma_n = 1.96\pi^2\alpha\lambda_e^2 \frac{R_y^2}{n(R_y + n^2T_e)T_e} \quad (1)$$

where

α : fine structure constant,

λ_e : electron Compton wavelength = 3.86×10^{-11} cm,

R_y : ground-state binding energy of one electron attached to an ion = $(m/2)(Z\alpha)^2c^2$,

T_e : electron energy.

The recombination coefficient α_r is obtained by averaging the recombination cross-section over the electron velocity distribution:

$$\alpha_r = \langle \sigma \cdot v_e \rangle .$$

In thermal equilibrium only the electron velocity distribution matters since

$$\bar{v}_i = \sqrt{\frac{m}{m_i}} \bar{v}_e .$$

For small electron velocities $R_y \gg T_e$, a Maxwellian electron velocity distribution in the transverse plane characterized by a transverse electron temperature $T_\perp = (m/2)\bar{v}_\perp^2$ and narrow longitudinal velocity distribution $T_\parallel \ll T_\perp$ (flattened distribution), one obtains

$$\alpha_{r,n=1} = 9.83\pi^2\alpha^3c\lambda_e^2 Z^2 \sqrt{\frac{mc^2}{T_\perp}} . \quad (2)$$

The recombination coefficient multiplied by the electron density n_e , the number of circulating ions N_i , and the fraction η of the overlap region to the whole ring circumference, give the absolute recombination rate in the PRF. The rate R observed in the laboratory is lower by a factor of $\gamma^2 = (1 - \beta^2)^{-1}$:

$$R = \alpha_r n_e N_i \eta \gamma^{-2} . \quad (3)$$

All atomic (ionic) levels are reached; however, the population of the ground state is strongly favoured, as is obvious from Eq. (1).

3. PHOTON ENERGIES

The photon energy E^* in the PRF is determined by the binding energy of the atomic (ionic) state into which the electron is captured and $T_{\perp}$. In the lab. frame, however, its energy is shifted owing to the Doppler effect:

$$E^{\text{lab}} = E^* / (1 - \beta \cos \theta_{\text{lab}}) \gamma, \quad (4)$$

where θ_{lab} is the angle between the ion-beam direction and the direction of the emitted photon. Owing to this effect, the photon energy can be tuned over a wide range by varying either the velocity of the particle beams or the observation angle. The velocity can be tuned by changing the electron energy with a resolution of at least 10^{-4} . High-energy photons (X-rays) can be produced by capturing electrons by fully stripped ions.

For instance, electron capture by a proton into the hydrogen ground state produces a photon line of $911 \text{ \AA}$ in the PRF. If the system moves with $v = 0.8c$ this line is observed in the lab. frame along the direction of the proton trajectory ($\theta = 0^\circ$) with a wavelength of $304 \text{ \AA}$. Observed in the backward direction its wavelength is at $2733 \text{ \AA}$. Correspondingly, in the case of electron capture by a fully stripped Ca ion, an X-ray of 4.0 keV is emitted in the PRF and observed with energy 12.0 keV and 1.3 keV in the forward and backward directions, respectively, in the lab. frame.

4. PHOTON LINE WIDTH

The line width of the emitted photons in the PRF is given by the ratio of the transverse energy of the electrons ($T_{\perp} \leq 0.2 \text{ eV}$) to the atomic level binding energy. This yields, for electron capture in the ground state of a hydrogen-like atom formed from a fully stripped ion,

$$\frac{\Delta E}{E} \leq \frac{0.2 \text{ eV}}{E} = \frac{1.5 \times 10^{-2}}{Z^2}, \quad (5)$$

where Z is the charge of the stripped ion. In addition the energy is smeared out in the lab. system owing to the Doppler effect:

$$\frac{|\Delta E^{\text{Dop}}|}{E_{\text{lab}}} = \frac{\Delta\Omega}{1/\beta - \cos \theta_{\text{lab}}} . \quad (6)$$

The variation is the smallest in forward and backward emission.

5. POLARIZATION AND INTENSITY DISTRIBUTION

Theory [7] predicts strong linear polarization of the recombination radiation if the direction of relative motion between electrons and ions before capture is well defined. On capture into the ground state of a hydrogen-like atom, the radiation is 100% linearly polarized along this direction and has a $\sin^2$ angular intensity distribution around it. On capture into higher excited states, the degree of polarization decreases gradually.

For the proposed photon source, however, the polarization is determined by the properties of the electron beam through the average over its velocity distribution in the PRF. The presence of a magnetic guiding field parallel to the beam, forcing the electrons to fast cyclotron motion in the transverse plane, leads to a cylindrical symmetry of this distribution around the beam axis; therefore, the photon radiation emitted in forward or backward direction will be unpolarized. As a consequence of the flattened velocity distribution, the described polarization properties of recombination radiation will nevertheless appear in the averaged angular intensity distribution. Forward and backward photon emission will be enhanced to the extent in which transverse directions of electron motion in the PRF are favoured, and some polarization will occur for off-beam-axis observation.

6. ENHANCEMENT OF FORWARD PHOTON EMISSION BY TRANSFORMATION OF THE SOLID ANGLE

The forward emission of photons as observed in the lab. frame is enhanced with respect to the PRF owing to the transformation of the solid angle:

$$d\Omega^{\text{lab}} = \gamma^2 (1 - \beta \cos \theta_{\text{lab}})^2 d\Omega^* . \quad (7)$$

This means that a given solid angle in the PRF is compressed in the lab. system by a factor of $f = (1 + \beta)/(1 - \beta)$ in the forward direction. Correspondingly the backward lab. solid angle is blown up by the same factor.

7. PULSED PHOTON EMISSION

If the circulating ion beam is bunched, or the cooling electron beam is pulsed, or both operations are applied, only then are photons emitted when both beams overlap in space and time. Bunching with a certain harmonic n of the revolution frequency f_{rev} and a bunching factor b would produce a photon pulse of duration b/nf_{rev} with a repetition rate nf_{rev} . For instance, a revolution frequency of 1 MHz and a bunching factor of 0.1 would yield in the single-bunch operation a photon pulse of 100 ns duration every 1 μ s. A coasting ion beam and a continuous electron flow would, of course, deliver a continuous photon beam.

8. INDUCED RADIATIVE CAPTURE

It has recently been emphasized that radiative capture in electron cooling can be stimulated by the presence of a radiation field [6]. This is achieved, for instance, by shooting a laser beam antiparallel to the particle trajectories into the cooling region. Profit can be taken from the Doppler effect to boost the laser frequency to higher values. Photon gains of several orders of magnitude might be achieved during the laser pulse duration [6].

Owing to the limited frequency band of high-power lasers only higher atomic (ionic) levels can be populated. Since, however, the radiative transition probability in highly stripped ions is large, the excited ion would be rapidly de-excited and produce a photon line spectrum of particular intensity distribution.

9. RECOVERY OF IONS AFTER ELECTRON CAPTURE

After electron capture the charge of the ion is reduced by one unit. This entails the ion following a different trajectory in the guiding magnetic field of

the storage ring. Since the beam is frozen its orbit can be separated from the rest of the ion beam. This may allow the captured electron to be stripped off by means of a stripping foil or other techniques and the ion to be recuperated.

10. HIGHER ENERGIES

The proposed technique of generating photons is not limited to non-relativistic electron cooling ($\gamma \lesssim 2$). In relativistic electron cooling a stored ion beam is cooled by a circulating electron beam which cools itself by synchrotron radiation emission. In this case ($\gamma \gtrsim 100$), the Doppler shift is much larger and the photon energies can be boosted to high values. However, the recombination rate is reduced by a factor of γ^2 and probably only a small fraction of the ion storage ring can be overlapped with the electron beam. This might be partially compensated by the gain resulting from the much smaller beam dimensions and hence the higher particle densities.

11. PHOTON INTENSITIES

The achievable photon intensities can be calculated from eq. (3) by inserting eq. (2). The most intensive line corresponds to the electron capture into the atomic ground state. For simplicity we consider here only spontaneous electron capture by a fully stripped ion. Using the Laslett limit [8] we estimate the maximum number of ions which can be stored in a ring:

$$N_i = \frac{A}{Z^2} \frac{2}{r_p} \pi \epsilon \beta^2 \gamma^3 \Delta Q \quad (8)$$

where

A : atomic number of the ion,

ϵ : beam emittance (rad·m),

r_p : classical proton radius = 1.53×10^{-18} m,

ΔQ : tune shift due to space charge.

Inserting Eq. (8) in Eq. (3) we find for the intensity of the photons emitted when electrons are captured by fully stripped ions (into the level $n = 1$):

$$R_{\gamma, n=1} = 19.65 \pi^2 \alpha^3 c \frac{\lambda_e^2}{r_p} \sqrt{\frac{mc^2}{T_{\perp}}} n_e A \pi \epsilon \beta^2 \gamma \Delta Q \eta . \quad (9)$$

Inserting typical values: $T_{\perp} = 0.2$ eV, $n_e = 10^9$ cm⁻³, $\pi \epsilon = 5 \times 10^{-5}$ rad·m, $\Delta Q = 0.2$, $\eta = 0.05$, Eq. (9) reduces to

$$R_{\gamma, n=1} = 5.5 \times 10^9 A \beta^2 \gamma \text{ (s}^{-1}\text{)} .$$

The number of photons emitted per second into a forward solid angle of 1 msr would then be

$$R_{\gamma, n=1}^{(1 \text{ msr})} = 4.4 \times 10^5 A \beta^2 \gamma^3 (1 + \beta)^2 .$$

Bearing in mind that the photons are monochromatic, that their energies can be tuned with high accuracy, that the photon source can be pulsed, and that a wide dynamic range of energies can be covered, these photon intensities are very encouraging.

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