Production of beams of polarized nuclei and photons in ion–electron and ion–laser-photon collisions

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A method is proposed for producing beams of polarized nuclei and photons with intensities above 10^4 particles per second in ion storage rings. There would not be any substantial losses.

This study was motivated by the need to produce relativistic ions, not completely stripped of electrons, for certain experiments proposed in Refs. 1–5. It has been shown that the formation of hydrogen-like ions through electron capture by nuclei in electron-cooling devices leads to the formation of beams of not only quasimonochromatic polarized photons but also polarized nuclei, both nonrelativistic and relativistic.

Let us imagine that a straight section of a nonrelativistic ion storage ring (STR, ASTRID, etc.) or a relativistic one (SPS, RHIC, TEVATRON, etc.) is broken up into three segments S_1, S_2, and S_3 (Fig. 1). In segment S_1, the circulating beam I of completely stripped ions is accompanied by electrons e as in electron cooling devices (Ref. 6, for example). If the electrons are somehow polarized, then the interaction between the magnetic moment of a captured electron and that of the nucleus will cause some of the nuclei of the hydrogen-like ions which form to be polarized in precisely the same manner as in the Zavoĭskiĭ method,[7] in which ions passing through ferromagnetic foils acquire a polarization by capturing polarized electrons. In addition, the characteristic radiation emitted during the filling of vacant K shells forms a quasimonochromatic beam of vacuum-UV and x radiation.[4,8] In segment S_2, these partially polarized ions interact with a laser beam L_1 so that a new beam of polarized quasimonochromatic photons can be produced by the method of Refs. 1–5. The ions then either continue to circulate in the ring without any significant loss after their complete stripping in segment S_3 by another laser beam L_2 or are dumped from the ring without any further ionization in segment S_3.

Moving on to some quantitative estimates, we first note that the rate (R_1) at which these hydrogen-like ions and polarized nuclei are formed in segment S_1 is given by[6,8]

$$R_1=\alpha_r \eta N_i n_e \gamma^{-2}, \tag{1}$$

where N_i is a number, $\gamma=E/M_i c^2=[1-(V_i/c)^2]^{-1/2}$ is the Lorentz factor of the ions in the ring, n_e is the density of electrons, $\eta=S_1/S_R$ is the ratio of the "cooling length" to the total length of the storage ring, S_R, and

$$\alpha_r=9.83\pi^2\alpha^3 c\lambda_e^2 Z^2 (mc^2/kT_{\mathrm{tr}})^{1/2}=9.3\times10^{-13}\,Z^2(kT_{\mathrm{tr}})^{-1/2}\ (\mathrm{cm}^3/\mathrm{s}) \tag{2}$$

is a recombination coefficient. The product of the transverse temperature T_{tr} and the Boltzmann constant k in the last expression is expressed in eV.

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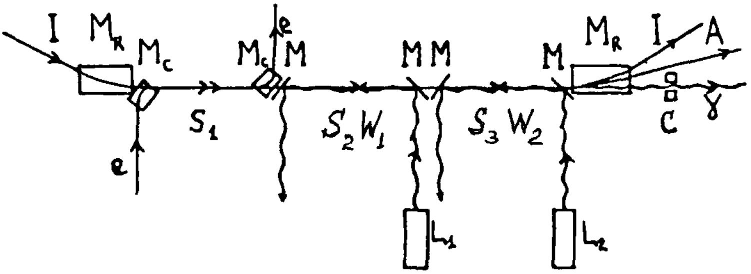

FIG. 1. The experimental apparatus. *I*—Beam of completely polarized ions; M_R—magnets of storage ring; M_c and *e*—magnets and electron beam of electron cooling system; *M*—mirrors; $L_{1,2}$—laser beams; *A*—dumped beam of hydrogen-like ions with polarized nuclei; *C*—collimator; γ—quasimonochromatic beams of γ rays.

The degree of polarization of the nuclei, P_n, and that of the electrons, P_e (if the latter are somehow polarized) are related by an equation [see Eq. (2.8) in Ref. 9] which takes the following simple form in the capture of electrons in *K* shells:

$$P_n = \frac{2(I_n+1)}{3(2I_n+1)} P_e, \tag{3}$$

which has a maximum $P_{\text{nucl}} = P_e/2$ if the spin of the nuclei is $I_n = 1/2$.

In segment S_2 we can organize a head-on collision of these hydrogen-like ions with polarized laser photons and produce beams of quasimonochromatic and polarized photons, in the following way.[1-5] The Doppler effect will raise the energy of the photons in the rest frame of the ions to $\omega_1' = 2\gamma\omega_1$, where ω_1 is the energy of the photons in the lab frame. If the values of γ and ω_1 are such that the condition $\omega_1' = \omega_{if}$ holds, where ω_{if} is the energy of an allowed transition between two energy levels of the hydrogen-like ion, then there will be a resonant scattering of laser photons by the hydrogen-like ions formed in S_1, with energies up to $\omega_{2\text{max}} = 4\gamma^2\omega_1$ for the scattered photons in the lab frame.[1] The cross section for this process is large, given by

$$\sigma_{rs} = \lambda_{if}^2 A_{if}/8\pi\Delta\nu = \lambda_{if}^2 \Gamma_{if}/4\omega_{if}(\Delta\gamma/\gamma), \tag{4}$$

where λ_{if}, A_{if}, and Γ_{if} are the wavelength, Einstein coefficient, and width of the $i \to f$ transition, and $\Delta\nu$ is the frequency width of the laser photons in the rest frame of the ions resulting from the energy spread $\Delta\gamma$ of the ions in the storage ring.

If the transverse dimensions of the ion beam and the laser beam are the same, then the scattering rate R_2 is related to R_1 by

$$R_2/R_1 = \sigma_{rs}\, n_{\text{ph}}\, S_2(V_i + V_{\text{ph}})/V_i, \tag{5}$$

where n_{ph} is the density of laser photons. It follows from (5) that in order to achieve the maximum value $R_2 = R_1$ it is necessary to have a laser photon density

$$n_{\mathrm{ph}}^{rs} > \frac{1}{S_2 \sigma_{rs}} \frac{V_i}{V_i + V_{\mathrm{ph}}}. \tag{6}$$

In segment S_3 we can attempt to produce completely stripped nuclei again, arranging a head-on collision of new laser photons with hydrogen-like ions. For this K ionization we would need photons with energies ω_2 satisfying the condition $\omega_2' = 2\gamma\omega_2 > I$, where $I = me^4Z^2/2h^2$ is the ionization potential of the ground level of the hydrogen-like ion.[10] When ω_2' is close to I, the cross section for this photoelectric effect is given by the Stobbe formula, which can be written as follows[10] in the limit $\omega_2' \to I$:

$$\sigma_k \simeq 6.44 \times 10^{-18}/Z^2 (\mathrm{cm}^2). \tag{7}$$

The ionization rate R_3 is given by (5), if we replace σ_{rs} by σ_k and S_2 by S_3. In order to return the completely stripped ions to the ring without losses, we need the laser photon density in (6) with the replacements specified above, $n_{\mathrm{ph}}^{\mathrm{str}}$.

To illustrate the results found above, we consider storage rings for completely stripped O^{8+} ions. Substituting the typical values $kT_{\mathrm{tr}} = 0.2$ eV, $n_e = 10^9$ cm^{-3}, $\eta = 0.05$, and $N_i = 10^8$ and 5×10^{10} ions for a nonrelativistic ion storage ring ($\gamma \simeq 1$) and for a relativistic one ($\gamma \simeq 100$) into (1) and (2), we find $R_1 \simeq 6.6 \times 10^5$ and 3.3×10^4 hydrogen-like ions (or polarized nuclei) per second. These ions, i.e., O VII ions, have an allowed transition $1s^{2\,1}S_0 \to 1s2p\,^1P_1$ with $\omega_{12} = 571.3$ eV, $\Gamma_{12} = 1.364 \times 10^{-2}$ eV, and $A_{12} = 2.072 \times 10^{13}$ s. Setting $S_1 = S_2 = S_3 = 10^2$ cm and $\Delta\gamma/\gamma = 10^{-3}$, we find $\sigma_{rs} = 5.37 \times 10^{-16}$ cm^2 and $\sigma_k = 1 \times 10^{-19}$ cm^2 from (4) and (7). According to (6), we would need photons with densities $n_{\mathrm{ph}}^{rs} = 1.86 \times 10^{12}$ and 10^{14} cm^{-3} for total scattering, and $n_{\mathrm{ph}}^{\mathrm{str}} = 10^{15}$ and 5×10^{16} cm^{-3} for complete stripping of the ions. At the moment, such photon densities can be achieved over distances $S_2 = S_3 = 10^2$ cm only from pulsed lasers, in view of the bunch structure of ion beams. The RHIC,[11] for example, will have 57 bunches 0.8 ns long separated by 224 ns. There will be 10^9 ions in a bunch. In the case of relativistic ions, argon lasers with $\omega_1 = 2.4$ eV provide the necessary "tuning" for resonant scattering with $\gamma = 119$. In the case of nonrelativistic ions, it would be reasonable to produce only polarized nuclei.

We note in conclusion that the basic result of this study—the method proposed for producing polarized nuclei, including protons and deuterons—may find applications in existing and future storage rings, even if resonant scattering and the possible buildup and preservation of the number and polarization of the nuclei do not occur.

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[1] K. A. Ispirian and A. T. Margarian, Phys. Lett. A **44**, 377 (1973).

[2] N. G. Basov, A. N. Oraevskiĭ, and B. N. Chichkov, Zh. Eksp. Teor. Fiz. **89**, 66 (1985) [Sov. Phys. JETP **62**, 37 (1985)].

[3] S. M. Darbinian, K. A. Ispiryan, and D. B. Saakyan, JETP Lett. **44**, 6 (1986); Izd. Akad. Nauk Arm. SSR, Fiz. **23**, 65 (1988).

[4] K. A. Ispiryan and K. A. Ispiryan, Preprint ErFI-891(42)-86, Erevan Physics Institute, 1986; Izv. Akad. Nauk Arm. SSR, Fiz. **22**, 284 (1987).

[5] S. A. Bogacz, Preprint FERMILAB-Conf-90-247, 1990.

[6] H. Poth, Preprint CERN-EP/90-04, 1990.

[7] E. K. Zavoĭskiĭ, Zh. Eksp. Teor. Fiz. **32**, 408 (1957) [Sov. Phys. JETP **5**, 338 (1957)].
[8] H. Poth and A. Wolf, Phys. Lett. A **94**, 135 (1983).
[9] V. A. Djrbashian, Nucl. Phys. A **103**, 177 (1967).
[10] V. B. Berestetskiĭ, E. M. Lifshitz, and L. P. Pitaevskiĭ, *Quantum Electrodynamics* (Pergamon, Oxford, 1982).
[11] S. Ozaki, *Conf. Record of the 1991 IEEE Particle Accelerator Conf.*, Vol. 5 (San Francisco, Calif., 1991), p. 2901.

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