High-luminosity colliding beams of *x* rays and relativistic ions or antiprotons: production of relativistic antihydrogen atoms

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The development of x-ray-relativistic-ion (xRI) or $x\bar{p}$ colliders is proposed. An estimate is derived for the cross section of the reaction $\gamma+\bar{p} \rightarrow \bar{H}+e$ resulting from the capture of some of the positrons from the reaction $\gamma+\bar{p} \rightarrow \bar{p}+e^{+}+e^{-}$. An $x\bar{p}$ collider would constitute an antihydrogen factory.

1. By organizing a continuous collision of intense beams of relativistic ions or $\bar{p}$'s with synchrotron-radiation photons, one can study nearly all the photonuclear processes discussed in Ref. 2 for nuclei at rest and synchrotron radiation, as in collisions of relativistic ions with laser photons.[1] Intense beams of relativistic ions and $\bar{p}$'s are presently available at many storage rings. The photon energy ω in the laboratory frame of reference increases in the rest frame of the ion, where it is $\omega^{*}=2\gamma\omega$, where $\gamma_L=E/M=1/(1-\beta^2)^{-1/2}$ is the Lorentz factor of the ion ($\hbar=c=1$). At $\gamma_L=10^3$, for example, photons with ω values of several keV can excite nuclear levels (in the MeV range) or can produce e^+e^- pairs if $\omega>\omega_{\rm thr}=2m_e/\gamma_L$.

The synchronized beam of synchrotron radiation to be sent to the interaction point of the storage ring can be sent first through a monochromator to narrow the spectrum to an interval $\Delta\omega$. Alternatively, a beam with a "white" spectrum can be used. The choice would depend on the cross section for the process, $\sigma_{x{\rm RI}(\bar{p})}(\omega)$. As an example we consider the Tevatron $\bar{p}$ beam with $N_p=7\times10^{10}$ $\bar{p}$'s in a bunch, a collision frequency $f=0.3$ MHz, and a cross section $S_{\bar{p}}=4\times10^{-5}$ cm^2 at the interaction point.[3] We assume that this beam collides with either a monochromatized ($\Delta\omega/\omega=0.1\%$) or white beam from a third-generation synchrotron-radiation source[4] with a constant brightness $B\approx\text{const}\approx10^{17}$ photons/(s · mm^2 · mrad^2), with a relative bandwidth (BW) of 0.1% in the region $\omega \approx$ 0.1–10 keV, with $S_{\rm SR}=1$ mm^2, with a distance $R=10$ m from the source of the synchrotron radiation to the interaction point. For an $x\bar{p}$ collider we then find a total luminosity $L\approx7\times10^{27}$ cm$^{-2}\cdot$s^{-1} and a differential luminosity $dL/d\omega\approx7\times10^{30}/\omega$ cm$^{-2}\cdot$s$^{-1}\cdot$keV^{-1}. If we were working with a monochromatized beam of synchrotron radiation with $\Delta\omega/\omega=0.1\%$, for example, we would then be able to detect processes with $\sigma\approx1$ μb $\dot{N}_{\rm prop}\approx25$ h^{-1}. The luminosity of an xRI collider based on the SPS and the LEP synchrotron radiation would be sufficient for studying reactions[2] with large cross sections, e.g., the excitation of giant resonance of nuclei, with a very good energy resolution. There would be no interference with other experiments in progress.

2. Antihydrogen $\bar{H}=(\bar{p}e^+)$—the simplest atom of the antiworld—has yet to be

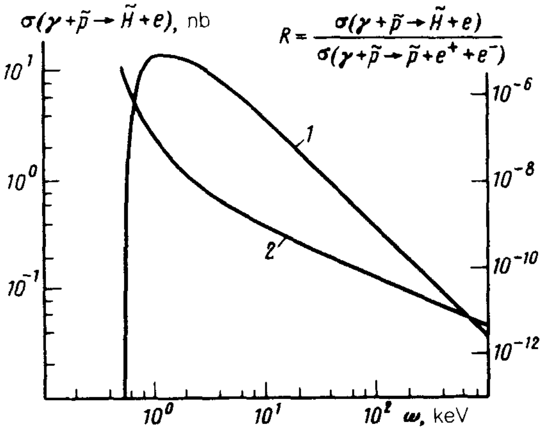

FIG. 1. The integral cross section for $\bar{H}$ production (curve 1, in nanobarns) and the ratio $R=\sigma(\gamma+\tilde{p} \to \bar{H}+e)/\sigma(\gamma+\tilde{p} \to \tilde{p}+e^+e^-)$.

observed, despite a major effort to observe it.[5] This atom would make it possible to test several fundamental laws of physics, and it would find widespread applications. It can be shown that a fairly large number of $\bar{H}$ atoms could be produced at $x\bar{p}$ colliders as the result of recombination of $\bar{p}$'s with those e^+'s of the e^+e^- pairs produced which have velocities close to the $\bar{p}$ velocities in the proper frame of the antiproton. In a crude approximation (but one sufficient for our estimates), the total cross section $\sigma(\gamma+\bar{p}\to\bar{H}+e)$ for the production of antihydrogen can be found by integrating the differential (with respect to the kinetic energy of the positron, T^*) cross section $d\sigma(\gamma+\bar{p} \to \bar{p}+e^+ +e)/dT^*$, without corrections,[6] from zero to the binding energy of the hydrogen atom.

Figure 1 shows $\sigma(\gamma\bar{p}\to\bar{H}e)$ and its ratio to the total cross section for the production of e^+e^- pairs as a function of ω in the case $\gamma_L=10^3$. It is easy to find the dependence for other values of γ_L, since σ depends on only ω^*. Evaluating the integral $\dot{N}=\int (dL/d\omega)\sigma(\omega)d\omega$ numerically again, we find $\dot{N}_{\text{prop}}\approx 10^2\ \text{h}^{-1}$ for the $x\bar{p}$ collider considered above. This figure would make it possible to measure not only the cross section for the production of $\bar{H}$ and e^+e^- but also the Lamb shift of antihydrogen, by (for example) one of the methods discussed in Ref. 7, but with a larger statistical base.

The development of xRI and $x\bar{p}$ colliders would not require the several years of prepatory studies necessary in the cases of e^+e^-, $e^-\gamma$, $\gamma\gamma$, and γp colliders.[8,9] The relativistic $\bar{H}$ beams produced at $\bar{H}$ factories which could be developed from existing $\bar{p}$ accelerators and fourth-generation sources of synchrotron radiation, with $B\approx(10^{20}\text{–}10^{22})$ photons/[s · mm^2 · mrad^2 · (0.1% BW)] (Ref. 4) would make it possible to test CPT[7] and other laws of the antiworld. When $\bar{p}$ storage rings with energies above 100 TeV become available in the future, $\bar{H}$ beams could be produced in collisions of such $\bar{p}$'s with laser photons with energies of a few electron volts.[1]

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