Antiprotonic Radioactive Atom for Nuclear Structure Studies

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Antiprotonic atom would be a new probe for nuclear structure studies, especially for the different peripheral distribution of protons and neutrons in a nucleus, which is in particular interesting for nuclei far from stability. Exotic properties of nuclei, such as halo and skin, have been investigated in such unstable nuclei.

Antiprotonic atoms have been studied exclusively for stable nuclei with various experimental methods. Antiprotonic atoms were produced by irradiating an antiproton beam on a fixed target material. When an antiproton is captured in an electronic orbital of an atom, it decays to lower levels by radiating auger electrons and X-rays. The lowest X-ray transition level and the shift indicate the matter radius of the nucleus [1]. At a certain level where a sizeable overlapping of the wavefunctions of the antiproton and the nucleons, an annihilation process between the antiproton and a nucleon of the nucleus occurs. The highlight of these studies should be that the annihilation dominantly occurs with a nucleon at the surface of the nucleus where the matter density is as small as 1/1000 of the center and that one can distinguish whether the vanished nucleon is a proton or a neutron by the following phenomena. One is that pbar-n and pbar-p annihilations produce charged pions with a net charge of -1 and 0, respectively. Bugg et al. used a bubble chamber to detect charged pions and identified the annihilated nucleons [2]. The other is the fact that the "cold" residual nucleus becomes ${}^{A-1}_{N-1}Z$ and ${}^{A-1}_{N}(Z-1)$ from the parent nucleus ${}^{A}_{N}Z$, as consequences of pbar-n and pbar-p annihilations, respectively. Warsaw group detected γ-rays from the residues in radio chemical way to identify the cold residues [3].

We proposed a future experiment aiming at investigations of the different abundance of protons and neutrons at the surface of nuclei far from stability by forming antiprotonic radioactive nuclear atoms in a nested Penning trap [4]. Here a cloud of antipronts are trapped in the central part of the trap as a target and slow radioactive ions are bunch injected in the outer well of the trap. If we assume a target density of 5×10^6 antiprotons in 1 mm^2, a slow RI-beam intensity of 10^3 s^{-1}, and a short measurement cycle of 10 ms for short-lived nuclei, an antiprotonic atoms production rate of 1 s^{-1} is expected. Charged pions radiated from the produced antiprotonic atoms are detected by multi-layer position sensitive detectors and the polarity of the charge is identified by the deflection direction in the magnetic field. Even if the detection efficiency is not unity, the annihilated nucleon can be identified statistically simply by accumulating the number of π^+ and π^- events throughout a measurement. If we assume a pion detection efficiency of 50% and a background event rate of 10%, 5×10^5 antiprotonic atoms enable us to determine the relative abundance ratio $\rho_\mathrm{n}/\rho_\mathrm{p}$ with an accuracy of 5%.

Measurements of X-rays from antiprotonic atoms enable us not only to determine the matter radii of the nuclei but also to identify the mean atomic level where annihilation has occurred. However, it is rather hard to realize a sufficiently high detection efficiency for MeV photons in the possible geometry of the experimental setup. This function would be a future option.

The statistical pion detection method would be a universal method. As long as the intensity of the slow radioactive ion beam is sufficiently high, any nuclides including drip-line nuclides can be experimental objects. Note that the "cold residues" of them are particle unbound.

[1] Trzcinska et al., Phys. Rev. Lett. 87 (2001) 82501.
[2] Bugg et al., Phys. Rev. Lett. 31 (1973) 475.
[3] Jastrzebski et al., Nucl. Phys. A588 (1993) 405c.
[4] M. Wada and Y. Yamazaki, Nucl. Instr. Meth. B214 (2004) 196.