



Technical developments toward antiprotonic atoms for nuclear structure studies of radioactive nuclei

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Abstract

Aiming at nuclear structure studies, a future experiment to form antiprotonic radioactive nuclear ions (RI) is discussed. A cloud of antiprotons trapped in a Penning trap will be used as target and singly ionized slow RI beams as projectiles. Among several experimentally observable phenomena, it is intended to measure the ratio of the plus and minus pions produced in an annihilation process to deduce the different distributions of protons and neutrons at the surface of the nuclei. Several technical developments are required to perform such experiments: the accumulation of antiprotons, a portable trap for antiprotons, and slow RI beams. The status of the development to obtain slow RI beams using an rf ion guide is presented here.

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1. Introduction

Exotic atoms play important roles in nuclear structure studies. Muonic X-ray measurements, for instance, provided reliable root-mean-square radii of nuclei. However, so far, those experiments are, limited to stable nuclei. Antiprotonic atoms would be excellent probes for nuclear structure studies, in particular for the different peripheral distribution of protons and neutrons in a nucleus. Jastrzebski et al. have performed pioneering work

on this subject [1]. We propose to extend it to radioactive nuclei as a possible future experiment at the slow radioactive nuclear ion (RI)-beam facility of the RIKEN RI-beam factory (RIBF). Since the number of RI atoms are limited and their lifetime is short, it is impossible to use a conventional experimental configuration in which fixed target atoms are irradiated by antiproton beams. Thus we propose to use a cloud of trapped antiprotons as a target and use slow radioactive ions as projectiles provided by an on-line RI-beam facility.

So far, trapped antiprotons are only available at the CERN antiproton decelerator (AD) facility, while CERN ISOLDE provides intense RI beams. There are two possibilities to perform the proposed experiment at CERN. One is at AD, where 5×10^6 antiprotons are already trapped [2]. In this

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case one must build a beam transport line from ISOLDE to AD to provide RI beams on-line. The other possibility is at ISOLDE, in which case, one must develop a portable trap to transport a trapped antiproton target from AD to ISOLDE. The trapping lifetime should be as long as possible, since it takes at least a few hours of manipulations if loading and unloading procedures are included. Furthermore, it would be advantageous to trap antiprotons for more than 10 days due to a background problem discussed later. Although a portable trap for antiprotons is not realized yet, antiprotons have been trapped for months in a Penning trap [3] and a portable trap have carried electrons 5000 km [4].

Assuming such a portable trap is available in the near future, we propose to perform the antiprotonic RI atom experiments at RIKEN RIBF. A great advantage of the RIKEN RIBF, as compared to the CERN ISOLDE, would be that the number of available nuclides is larger. Since the production and separation of radioactive nuclei at the RIBF is *in-flight* without any chemical process, a wide variety of radioactive nuclides are obtained with less restrictions on lifetimes and chemical properties of the nuclides. However, the ion energy is typically 100 MeV per nucleon, and the beam quality is not adequate for slow RI-beam experiments. Slow RI beams with a small emittance are on the other hand essential to form antiprotonic atoms. We have worked on technical developments to obtain slow or trapped RI ions provided by the RIKEN RIBF by using a large gas-catcher cell, an rf ion-guide and a beam guide that also includes rf multi-pole fields for beam cooling and bunching [5–8].

2. Antiprotonic radioactive nuclear atoms

The production rate of \bar{p} -RI atoms is $R = \sigma_{\bar{p}A} N_{\bar{p}} I_{RI}$, where $\sigma_{\bar{p}A}$ is the \bar{p} -atom formation cross section, $N_{\bar{p}}$ is the surface density of \bar{p} target and I_{RI} is the intensity of RI beams. The cross section $\sigma_{\bar{p}A}$ for neutral heavy atoms are theoretically estimated by Cohen [9]. A typical value is $13 \times 10^{-16} \text{ cm}^2$ for Ar atoms when the relative energy is 0.1 atomic units. This energy corresponds

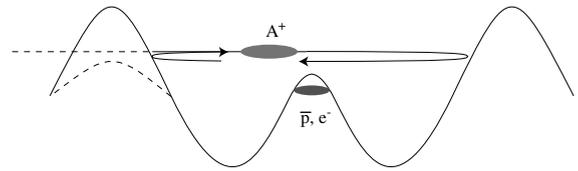


Fig. 1. Nested trap for simultaneous trapping of antiprotons and RI ions.

to an Ar beam energy of 112 eV in the \bar{p} rest frame. However, there are no reliable estimates for $\sigma_{\bar{p}A}$ for singly ionized heavy ions. At this point we would assume, $\sigma_{\bar{p}A} \simeq 10^{-16} \text{ cm}^2$. The number of trapped \bar{p} so far achieved by ASACUSA [2] is 5×10^6 . If we assume that they are confined to 1 mm^2 , the target density is $N_{\bar{p}} = 5 \times 10^8 \text{ cm}^{-2}$. The intensity of RI beams is generally very weak, especially for nuclides far from stability. To compensate for such low intensities, we propose a nested trap configuration (Fig. 1). Slow RI ions are bunch-injected in a nested trap, where \bar{p} and electrons are preloaded at the central part of the trap. The RI ions pass through the \bar{p} cloud for $5 \times 10^5 \text{ s}^{-1}$ if the relative energy is 0.1 atomic units and the trap length is 4 cm. Since we are mainly interested in very short-lived nuclei, we plan to use a short measurement cycle, for instance 10 ms, in which only 10 RI ions are involved when the RI-beam intensity is 10^3 s^{-1} . The estimated event number per cycle is $10^{-16} \times 5 \cdot 10^8 \times 10 \times 5 \cdot 10^3 = 2.5 \times 10^{-3}$. Thus the average event rate is 0.25 s^{-1} , if we continuously repeat the measurement cycle. This rate, one event per four seconds, is a feasible number if the detection efficiency is sufficiently high and the background is reasonably low.

An antiprotonic atom emits Auger electrons and X-rays during a cascaded decay of the antiproton into a certain atomic level, where an annihilation occurs. These X-rays already show nuclear size effects [10]. The highlight of this study should be that the annihilation occurs with a nucleon at the surface of the nucleus and that one can distinguish whether the nucleon is a proton or a neutron by the following phenomena. One is that $\bar{p}n$ and $\bar{p}p$ annihilations produce charged pions with a net charge of -1 and 0 , respectively. This is a phenomenon that already Bugg et al. used in an investigation for natural C, Ti, Ta, Pb in a

hydrogen bubble chamber [11]. The other is the fact that the *cold* residual nucleus A_Z becomes ${}^{A-1}_{N-1}Z$ and ${}^{A-1}_NZ$, as consequences of $\bar{p}n$ and $\bar{p}p$ annihilations, respectively. Here a *cold* residue means that the residual nucleus becomes a nucleus of $A - 1$ without further excitation. From such *cold* residues the Warsaw group detected γ -rays and in this way identified the produced nuclides in their investigation of several stable isotopes [12].

We conclude that the most feasible method is the observation of π^\pm if we consider the detection efficiency and the estimated event rate, since the detection efficiencies for X-rays or γ -rays are, in general, much lower than those for π^\pm . Also, the pion event is independent of the final state of the residual nucleus which is a critical problem in the radiochemical detection method. A proposed experimental setup is shown in Fig. 2. A cloud of antiprotons are stored in the central part of a Penning trap and bunched slow RI ions are repeatedly injected into a nested trap to irradiate the antiproton target. The annihilated π^\pm are detected by stacked position sensitive detectors. The charges of π^\pm can here be identified by the direction of their deflection in a magnetic field. Since all the charged pions in one event cannot be detected because their detection efficiencies are not unity, one cannot determine the net charge of each event. However, one can compare the total detected π^\pm numbers throughout a measurement, in order to deduce the abundance of protons and neutrons. A simulation result is shown in Fig. 3.

The background rate is also a major concern. The charge exchange reactions in the material of the vacuum chamber and the detectors may cause misidentifications of the polarities of the pions.

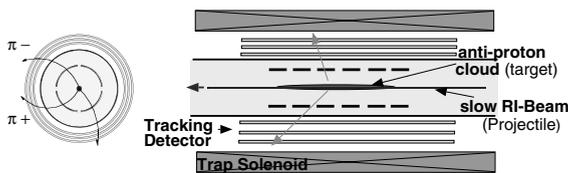


Fig. 2. Proposed experimental setup for antiprotonic radioactive nuclear atom.

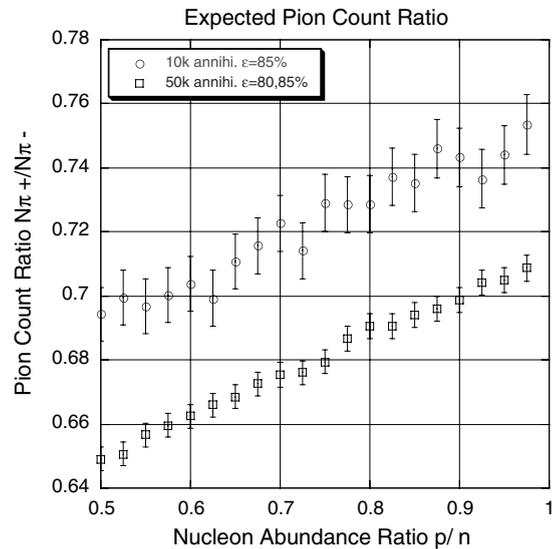


Fig. 3. The simulated ratio of detected pion numbers as function of the abundance of protons and neutrons. Circles indicate the case of 10^4 annihilations with an 85% overall pion detection efficiency, while boxes indicate the case of 5×10^4 annihilations with an 80% detection efficiency for π^+ and 85% for π^- . Error bars indicate statistical errors including a 10% background event rate.

However the charge exchange reaction probability should be less than 1%. Absorptions of π^\pm simply corresponds to a loss of detection efficiency, which is a negligible effect (Fig. 3). The dominant background π^\pm come from annihilations with residual impurity atoms, since $10^7 \bar{p}$ in a trap with a storage lifetime of 10 days already annihilate with a rate of 0.1 s^{-1} . The development of a \bar{p} trap with an extremely long storage lifetime is thus essential also because of this background issue. It should be noted, however, that the residual gas at cryogenic temperature is almost purely H_2 , i.e. such a reaction does not produce recoil nuclei. If one can detect a recoil nucleus coincident with pions, one can clearly identify a true event.

A great advantage of RI-beam experiments is that one can frequently change the nuclides while preserving the other experimental conditions. Thus one can compare the ratio of the numbers of detected π^- and π^+ within an isobar or isotone. This makes the analysis simple as compared to a discussion of the absolute values of the ratios.

3. Slow RI beams from a projectile fragment separator

A new accelerator complex (the RIBF) is under construction at RIKEN that consists of a linear accelerator, a series of four cyclotrons, and a projectile fragment separator [13,14]. It will provide a wide variety of energetic RI beams. A slow RI-beam facility is planned as part of the RIBF using the energetic RI beams and the rf ion guide technique. The high energy beam (~ 100 MeV per nucleon) is passed through a degrader and then stopped and thermalized in a large He gas cell (~ 100 Torr). The high ionization potential of He guarantees that most ions end up in the singly ionized state. Using the ion charge as a handle, one can apply dc electric fields to pull the RI ions to a cathode electrode located at an exit hole, while rf-fields keep the ions away from the surface of the electrode. A six-pole rf ion-beam guide (SPIG) then transports the slow ions toward an UHV region, where the ion trap and other low energy devices are located. This SPIG also features cooling and bunching capabilities [7,8].

On-line tests of the rf ion guide setup have been performed at the existing facility RIPS which provides a 70-MeV per nucleon ^8Li ion beam with a typical intensity of $\sim 10^6$ atoms/s. An overall efficiency as function of the primary beam intensity is shown in Fig. 4. This overall efficiency here is defined as the number of slow ^8Li ions detected by their delayed α -rays divided by the total intensity of the energetic ^8Li beam provided by RIPS. In total we achieved an overall efficiency of $\sim 1\%$ when the intensity of the incoming beams was weak.

To estimate the efficiency of the present experiment, it is necessary to understand that the energy spread behind the degrader is as wide as 100 MeV even though a wedge shaped degrader is employed at an energy dispersive focal point (mono-energetic degrader). Thus only a fraction of the incoming beam can be stopped in the He gas. An energy distribution measurement and a range calculation showed that only 6.4% of the incoming ^8Li ions stop in the gas cell, while 68% stop in the degrader and 25% pass through the gas cell. Assuming that the effective volume is within 30 cm of

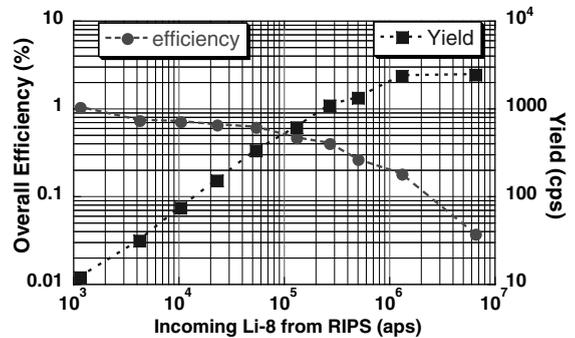


Fig. 4. Overall efficiency and yield of slow ^8Li ions as function of the incoming ^8Li beam intensity. A maximum efficiency of 1% was obtained when the intensity was weak.

the exit, only a 1% fraction can be stopped in this volume. So that we can say that most ^8Li ions, stopped in the effective volume, were extracted as a slow ion beam. With an increased intensity I_0 of the injected beam, the collection efficiency decreases as $1/\sqrt{I_0}$ because of recombination effects [15].

4. Conclusion

We propose an experiment to form antiprotonic radioactive nuclear atoms for nuclear structure studies, especially to determine the different distributions of protons and neutrons at the surface of the nucleus. In order to realize such an experiment, the following developments are required: (1) trap as many antiprotons as possible, (2) achieve a long storage time (~ 10 days) for antiprotons in a portable trap, (3) produce slow RI beams of various radioactive nuclides, (4) build an efficient charged pion tracking detector system, (5) develop a theory of antiprotonic atom annihilation and their effect from the nuclear structure. Among those, a new project for a slow RI-beam facility is under progress at RIKEN. The key development for the project is a portable trap for antiprotons. If such a portable trap cannot be realized, it would be necessary to provide both slow RI beams and slow antiprotons, simultaneously. Constructing a beam line from ISOLDE to AD at CERN or the GSI future facility [16] would be candidates for such an experiment.

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