Medium energy antiproton absorption,  
a tool to study neutron halo nuclei

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Abstract

A novel method is proposed to measure the difference of neutron and proton density distributions of nuclei far off stability by medium energy antiproton absorption. The radioactive nuclei are produced by projectile fragmentation at medium energies (400–800) A MeV, separated and stored in a medium energy storage ring. The antiprotons are produced with 30 GeV protons, accumulated, cooled, decelerated and stored at energies of about 5 MeV in a small storage ring. The medium energy radioactive beams are brought to head on collisions with the low energy antiproton beam in an interaction section of both rings. The coasting radioactive beam and the reaction products from the collisions with the antiprotons are observed with the Schottky noise frequency analysis method, which allows to separate all reaction products and measure their production rates as well as the loss rate of the primary beam. From these observations, the total and partial reaction cross sections may be determined, even with a small number of rare ion species in the ring. An analysis of the total and partial reaction cross sections will allow to determine both $\langle r_p^2 \rangle$ as well as $\langle r_n^2 \rangle$ for nuclei far off the stability.

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1. Motivation

There is great interest in the nuclear structure community to study nuclei far off stability. Especially neutron rich nuclei are in the focus because they are relevant for the rapid neutron capture path of the nuclear synthesis. These nuclei are expected to develop neutron halos around a proton core with low density and large spatial extension. At low densities strong pairing correlations, smearing out the population of the states at the Fermi edge, and a reduction of the spin orbit force are expected. The consequence is a drastic change of the shell structure of such neutron rich nuclei.

2. Methods for studies of neutron halos

We have roughly speaking two methods to synthesize neutron rich nuclei, the so called "iso-
tope online” (ISOL) and fragmentation method.

In the ISOL method radioactive nuclei are produced in spallation reactions or fission of heavy nuclei by beams of medium energy protons and neutrons or in a high flux of thermal neutrons from a reactor. The produced nuclei diffuse out of a target at high temperature, are ionized and separated on line by an isotope separator.

For the fragmentation method, heavy ions are accelerated to medium energies, 100–1000 A MeV, and are used to bombard a target of light nuclei, such as hydrogen or more practical beryllium. The fragmentation products are emitted in forward direction with a small angular and momentum spread and can be isotopically separated by combined magnetic field and energy less separation techniques [1]. The separated isotopes can efficiently be accumulated in a storage ring and cooled with stochastic and electron cooling. Using an internal cluster jet target of hydrogen or noble gas, nuclear reactions may be studied with high luminosity in so called inverse reaction kinematics, with the heavy products emitted into forward direction. Such reaction studies have been already performed with external targets. Total reaction cross section measurements with target of light nuclei have been extensively used to measure interaction radii, pioneered by Tanihata and his group [2]. In this way light neutron halo nuclei, such as $^{11}$Li were discovered and studied in detail [3]. Further more, proton elastic scattering in inverse kinematics has been used to study nucleon distributions in neutron rich nuclei, such as $^{6}$He and $^{8}$He [4].

Knock out reactions combined with studies of the momentum distributions of the recoil nuclei are used for a measurement of the momentum wavefunctions of the knock out nucleons [5].

These experiments may be favorably transferred into storage rings, using thin targets and making use of the high circulating currents. But the point of this contribution is, that even antiprotons may be used as targets to study total reaction cross sections, absorption on neutrons and protons, including recoil momentum measurements.

3. Antiproton absorption

Strong interaction shifts and widths of X-ray transitions in antiprotonic atoms have been recently measured at CERN, [6] and have been used to study neutron density distributions at the nuclear surface. In addition the yields of A-1 isobars with one neutron and one proton being removed by antiproton absorption have been measured using radiochemical methods [7]. The results are used to extract the differences of the neutron and proton meansquare radii in stable nuclei. These methods used up till now are not directly applicable to radioactive nuclei, but developments are under way, reported at this conference by Wada [8], to overcome the problems using trapping methods.

We propose here storage ring and collider techniques for the study of total reaction cross sections and A-1 yield measurements following the absorption of antiprotons by neutrons and protons in radioactive nuclei. Furthermore momentum distributions of knock out residues may be studied using similar techniques as those performed with external proton targets. Actually all techniques may be developed now at the ESR at GSI Darmstadt using an existing hydrogen cluster target, Schottky mass spectrometry techniques and recoil spectrometry using the first 60° magnet following the target [9].

4. Collider technique for the study of antiproton–RI-beam collisions

It is proposed to use the future GSI accelerator facility [10,11] for beams of ions and antiprotons to produce neutron rich nuclei with fragmentation reactions at energies between $E/A = 400–800$ MeV and collide them with low energy antiprotons ($E \approx 5$ MeV) produced by 30 GeV protons cooled, decelerated, stored in a low energy storage ring and brought to collision with the RI beams.

Fig. 1 contains those parts of the facility which are foreseen for the production, accumulation, and deceleration of antiprotons which are produced by 30 GeV protons accelerated in the synchrotron with 100 Tm bending power. The collector ring
(CR) serves to cool the antiprotons stochastically, the accumulator ring RESR accumulates the antiprotons and provides final cooling, while the NESR may serve for deceleration of the antiprotons. The CR may also be used for accumulation of RI beams and the NESR for experiments with RI beams.

Fig. 2 shows the RI part of the proposed low energy antiproton ion collider. The CR accumulates and cools exotic nuclei produced in a fragmentation target and separated with the super-FRS. They are transferred to the NESR, with electron cooling, and Schottky pick up plates for Schottky noise frequency mass spectroscopy. The cooled antiprotons are transferred via the RESR, not shown in Fig. 2, into the NESR, decelerated, cooled and finally transferred to the small p–A collider ring with energies of about 5 MeV. They are the target for the RI beams circulating in the opposite direction in the NESR. The RI beam is continuously renewed with each SIS 100 cycle, whereas the antiprotons are kept until they are used up in the small collider ring.

The kinematics of 400–800 A MeV ions colliding with 5 MeV antiprotons is such that most of the...
reaction products following the absorption of an antiproton remains within the radial and momentum acceptance of the NESR. It is this property, which we make use of for a simple analysis method of the recoil nuclei relics. But it is also possible to detect the reaction products with position sensitive PID detectors after the first bending magnet of the NESR behind the interaction region.

The luminosity of the collider in a coasting beam mode is estimated to be about $3 \times 10^{25}$ cm$^{-2}$ s$^{-1}$, with $10^9$ ions circulating with a frequency of $2 \times 10^6$ s$^{-1}$, $10^{12}$ antiprotons in the small collider ring, a ratio of $10^{-1}$ for the interaction zone and the ring circumference, and an area of 1 mm$^2$ for the interaction zone. So total cross sections, which are expected to be in order of barns, can be easily measured, also for much smaller number of ions ($10^3$). Small numbers are attractive because then the coating ions form ordered strings [12].

5. Isobar detection by Schottky spectroscopy

In analogy to the radiochemical method one can determine the yields of the reaction products, especially the isobars with $(A-1)$ by Schottky noise frequency measurements of the coasting beam and its products, either in the synchronous mode (with the ring operated at the transition energy $\gamma = \gamma_\nu$) or with electron cooling, depending on the lifetime of the products [14].

In order to illustrate the power of this tool Fig. 4 shows a Schottky frequency spectrum of a 350 MeV/A $^{187}$Re$^{75+}$ beam with $10^8$ particles traversing an argon jet target with a density of $3 \times 10^{12}$ cm$^{-2}$ in the ESR. The circulation frequency is normalized on $^{187}$Re ($\sim 1.5$ MHz) and the measuring time is about 200 s [15].

Note that one can observe next to the intense primary beam the neutron knock out products $^{186}$Re$^{75+}$, $^{185}$Re$^{75+}$, with very small intensities as narrow lines at higher frequencies because of the lower $m/q$ ratio. $^{185}$W$^{74+}$ appears at lower frequency, not on scale is the one proton knock out

![Fig. 3. Total antiproton absorption cross section for Ni-isotopes as function of $A$ show a simple $A^{2/3}$ dependence at bombarding energies between 50 and 450 MeV [13].](image)

![Fig. 4. Schottky noise power spectrum as function of the relative revolution frequency, normalized to the revolution frequency of a $^{187}$Re$^{75+}$ primary beam coasting in the ESR for 200 s through an argon gas jet target with $3 \times 10^{12}$ argon atoms/cm$^2$. Note the narrow side lines with small numbers of ions, which can be assigned to projectile fragments produced in the intersecting argon gas jet target. By replacing the argon target with antiprotons at 5 MeV in a small collider ring, all absorption products could be detected in the Schottky spectrum.](image)
product $^{186}$W$^{74+}$. Note that all reaction products with $Z$ and $A$ close to the primary beam can be identified and their cross section can be measured, even with very small number of nuclei being produced.

In the case of antiproton absorption this would allow a rather detailed study of the complicated absorption process including contribution from pion reabsorption.

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References