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Joint Letter of Intent to the CERN SPSC and the CERN INTC

Probing the density tail of radioactive nuclei with antiprotons

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Executive Summary

We propose an experiment to determine the proton and neutron content of the radial density tail in short-lived nuclei. The objectives are to (i) to evidence new proton and neutron halos, (ii) to understand the development of neutron skins in medium-mass nuclei, (iii) to provide a new observable that characterises the density tail of short-lived nuclei.

We propose an original approach based on the use of trapped antiprotons to study the structure of short-lived nuclei via nucleon annihilation.

The antiprotons will be provided by the ELENA low-energy ring. We aim at storing 10^9 antiprotons in a dedicated Penning-Malmberg trap. The trap will be conceived to allow extra high vacuum of 10^{-17} mbar, and therefore a half-life of the stored antiproton cloud of weeks.

The stored and cooled down antiprotons will be transported to the ISOLDE facility.

Short-lived nuclei produced at ISOLDE will be introduced at low energy in the trap. They will overlap with the antiprotons in a nested trap. Antiproton capture will occur with cross sections of the order of 10^6 barns. The formed antiprotonic atom will decay via X-ray and conversion electron emission. When reaching the tail of the nuclear density, the captured antiproton will annihilate with a nucleon at a density of typically few percents of the saturation density. The annihilation will occur with a proton or a neutron with probabilities proportional to the respective proton and neutron densities at the annihilation site.

The annihilation will result in the emission of pions. The electric charge is conserved in the process. Neutron (proton) annihilation will lead to a total sum of the pion charges equal to -1 (0). Emitted pions will be measured with an efficiency higher than 90%. The curvature of the charged pions in the magnetic field of the solenoid constituting the penning trap will sign the charge of each pion.

The ratio of proton to neutron annihilations will be obtained from the experiment after corrections of final state interactions. This ratio is sensitive to the composition of the nuclear density tail and will be the observable used to to characterise halos and skins.

A planning covering 5 years seems feasible to reach the first measurements with short-lived isotopes.

1 Motivation and physics cases

The occurrence of neutron halos was discovered in the light-mass region of the nuclear landscape at the limit of nuclear existence, *i.e.* at the neutron drip line [1]. Halo nuclei exhibit a spatially extended wave function well beyond the core of the nucleus and represent a unique quantum phenomenon [2,3] where the nucleon probability density lies mostly in the region forbidden by classical mechanics. While only *s-wave* halos have been observed so far, *p-wave* neutron halos have also been recently claimed to appear in very neutron rich Ne, Mg isotopes from breakup cross sections [4,5]. For medium mass nuclei, the appearance of a halo is predicted by several models [6-8] but controversial [9,10]. The role of deformation has not been treated so far and no data support the existence of the phenomenon. Neutron skins, corresponding to a neutron density higher than the proton density at the surface of the nucleus, have been evidenced in stable nuclei and thick neutron skins, *i.e.* thicker than 0.25 fm, were observed in light neutron rich nuclei. Microscopic models predict the development of thick neutron skins in very neutron rich medium mass nuclei but no experimental evidence exists so far. Such thick neutron skins would be a unique occurrence of low-density pure neutron matter in the laboratory.

The nature of the neutron skin region in nuclei may not be as simple as described by mean field approaches. Spatial correlations including alpha clustering are predicted to take place at sub-saturation densities and therefore at the nuclear surface [11]. It is expected that clustering and the formation of inhomogeneous matter at low densities modifies the proton density in the tail of the nuclear density and therefore the symmetry energy as compared to calculations assuming a uniform uncorrelated spatial distribution of constituents [12]. Recently *ab initio* calculations have been extended to medium mass nuclei but show the need for more data. Calculated binding energies and matter radii of stable nuclei show a systematic discrepancy compared to experiment when the coupling constants of the perturbative expansion of the input two- and three-body interactions up to the next-to-next-to-next leading order are fixed to scattering data and three-body nuclei, showing limitations to the most recent ab initio theories [13].

Antiprotons and the annihilation process from nucleon- and nucleus-antiproton collisions have been studied at CERN in the past at the Low Energy Antiproton Ring (LEAR) and the the Antiproton Decelerator (AD). The unique sensitivity of low-energy antiprotons to the very surface of nuclei was demonstrated [14]. However, as of today, no facility provides antiprotons to be used as probes for unstable nuclei. Indeed, the use of antiprotons with unstable nuclei requires two large scales machines (one for the antiproton production and one for radioactive-ion beams (RIB)) connected together, or a way to bring antiprotons to a RIB facility. There is no RIB-antiproton collider today. The proposed experiment aims at bringing stored antiprotons from ELENA to the ISOLDE RIB facility. Its results may provide the necessary inputs to advocate for an antiproton-radioactive ion collider.

The first objectives of the experiment are to (i) to evidence new proton and neutron halos, (ii) to understand the development of neutron skins in medium-mass nuclei, (iii) to provide a new observable that characterises the density tail of radioactive nuclei. The determination of thick neutron skins and/or halos will give precious information on the nuclear many-body problem and the equation of state of neutron rich nuclear matter at low density. Envisioned core physics cases are given in Table I.

Case	Location	Beam(s)	Objectives
1	CERN/AD ELENA	^{4}He, ^{7}Li, ^{16}O, ^{40}Ar from ion source	1) Validation of the method 2) Study of absorption / charge exchange 3) benchmark with previous work 4) final state population (if gamma array financed / developed)
2	CERN/ISOLDE	^{6,8}He, ^{9,11}Li	1) neutron skins and/or halos as a function of isospin along key isotopic chains. Comparison with other previous work and other techniques. 2) ^{6}He, ^{9}Li (high statistics): study of charge exchange and absorption and compare to stable isotopes (^{4}He, ^{7}Li) for comprehensive study
3	CERN/ISOLDE	^{8}B,^{17,18}Ne	1) Search for proton halos
4	CERN/ISOLDE	$^{26\text{-}31}$Ne, $^{28\text{-}33}$Mg	1) Neutron skin in light isotopic chains 2) Search for (p-wave) neutron halos
5	CERN/ISOLDE	$^{104\text{-}138}$Sn	1) Neutron skin in unstable medium mass ions 2) Final state population (if gamma detection included)

Table I. Examples of foreseen first physics cases at ISOLDE.

2 Overall scheme

We propose to develop a nomad device to store a large number of antiprotons (10^9), and to maximise the capture yield from trapped nuclei and to detect radiations following the annihilations. The experimental scheme is composed of two phases: (1) the filling of the device with antiprotons at ELENA, (2) the collision of these antiprotons with slow exotic nuclei will take place at the ISOLDE facility.

The annihilation probability of an individual nucleus with stored antiprotons is estimated to reach 10^6 barns at 100 eV relative energy [15]. Antiprotons annihilate with both protons and neutrons. The quasi-totality of decay channels are composed of energetic pions with conservation of the initial charge and momentum of the antiproton-nucleon system. The dominant annihilation channels are $\pi^+\pi^-\pi^0\pi^0\pi^0$ (23%), $\pi^+\pi^-\pi^+\pi^-\pi^0$ (20%), $\pi^+\pi^-\pi^+\pi^-\pi^0\ \pi^0$ (17%), $\pi^+\pi^-\pi^0\pi^0$ (9%) for antiproton proton annihilation and $\pi^-\pi^-\pi^+ k\pi^0$ (k>1, 40%), $\pi^- k\pi^0$ (k>1, 17%), $\pi^-\pi^-\pi^-\pi^+\pi^+\ \pi^0$ (12%) for antiproton neutron annihilation. We will measure the net charge of emitted pions to determine if a proton or a neutron was annihilated. The concept was first introduced at Brookhaven [16] and investigated for RIBs by Wada and Yamazaki [17].

In the case of collisions performed at antiproton-ion relative energy of about 200 eV at which the capture cross section is of the order of 10^{-16} cm^{-2}, and assuming an antiproton

cloud “thickness” of 10^8 cm^{-2} (density of about 10^3 antiprotons / mm^3), the yield of annihilations of short lived nuclei is rather high. Indeed, for a 3-cm long antiproton bunch, every ion at 200 eV will “cross” the cloud 2 10^4 times when trapped for 10 ms. By assuming nuclei produced at 1000 s^{-1} transmitted to PUMA from RFQ bunches at 10 ms cycles (mean value of 10 ions / bunch), the corresponding annihilation rate to be measured will be 10 per minute in this case. The gain of PUMA is therefore twofold: *(i)* a specific probe directly sensitive to the proton to neutron density ratio at the nuclear surface, *(ii)* access to neutron skin information at beam rates as low as a few tens of Hertz.
The design and conception of the extra-high vacuum trap requires exceptionally low background from spurious annihilations. A vacuum of 10^{-17} mb corresponds to a residual gas density of 10^{-4} atom / mm^3.

3 Production of antiprotons and trapping

Antiprotons can be stored in traps in high vacuum to avoid losses by annihilation on nuclei of the residual gas. The statistical lifetime of antiprotons due to residual-gas annihilation in a 10^{-10} mb vacuum of butane is typically 1 hour. PUMA aims at building such a trap for long time storage of several weeks (vacuum better than 10^{-15} mbar), the typical time necessary to fill in the trap, dismount, transport, re-install and perform collisions with slow radioactive ions. Stored antiprotons will be transmitted by bunches to the collision trap through a transmission line. Antiprotons will be confined by a 4T magnetic field and electrical potentials from cylindrical electrodes, as in traditional Malmberg-Penning traps.

The ASACUSA collaboration managed to slow down and store bunches of antiprotons with an efficiency of 4%, 50 times larger than before. 1.2 x 10^6 antiprotons per AD cycle were stored in the trap for 10 minutes or more. In case of a 100% trapping efficiency, the storage of 10^9 antiprotons would therefore cost 10^3 AD cycles of 2 minutes each corresponding to about a one-day run at the AD when a routine operation is reached. Transportable traps have been built in the past [18]. The PUMA storage trap should also have a size compatible with transportation to RIB facilities, minimised energy consumption (superconducting) and very low He loss allowing a conservation time beyond a few weeks to several months. High vacuum of the order of 10^{-16} mbar (we target 10^{-17} mbar) are therefore required. The main challenge of the system is to obtain extremely high vacuum for long storage of antimatter. Such a regime has already been reached for a small number of antiparticles, for example in the BASE experiment [19] in which an « infinite » lifetime for trapped antiprotons has been reached with a sealed trap with cryo-pumping at very low temperature [20]. Our trap will be inside a cryostat at 4 K and sealed by a thin entrance window.

We will build a “double-zone” trap: a *storage zone* dedicated to the storage of a large amount of antiprotons, and a *collision zone* dedicated to the interaction of antiprotons and unstable ions. The transfer of charges from one trap to another has been developed [21,22]. Both zones will be at the same extreme high vacuum and cryogenic temperatures. Two separated zones offer essential flexibility in the manipulation of the antiproton cloud to be used as a target in terms of electron cooling, length, radius and amount of antiprotons in the collision zone. The trap will be designed so that the antiproton density will not exceed 10^7/ cm^3. The total trap length is defined to be 700 mm to allow two trapping zones with enough spatial separation. Non destructive feedback will be used as diagnostic. A sketch of the device is provided in Fig. 1.

4 Extreme vacuum and sealing window

The trap at extra high vacuum will be separated from a “normal” high vacuum region by a Si_3N_4 15 nm-thick membrane commercially available in small dimensions (5×5 mm^2). Thicknesses down to 10 nm with proper size are available. A high transmission of antiprotons can be achieved through such a thin window, the energy loss of 4 keV protons in a 24 nm Bi crystal membrane is about 1.2 keV. Energy loss of very low-energy ions, protons and antiprotons in solid foils has been studied and reproduced by calculations. For antiprotons, the transmission is estimated to be better than 90 %.

Both antiprotons and, in a second phase, ions, should go through the entrance window with minimal loss. This implies a minimum kinetic energy at the exit of the thin entrance window to minimise angular and energy straggling, as well as losses from interactions. On the other hand, the antiprotons and ions have to be trapped downstream of the entrance window, requiring a very low kinetic energy. We foresee tuning the kinetic energy of antiprotons and ions before entering the trap so that their kinetic energy at the exit of the window is about 1 to 10 keV. Their kinetic energy will then be slowed down by a decelerating electric potential inside the trap using a pulse drift tube. The amplitude of the decelerating barrier will be adjusted to reach a final kinetic energy of few hundreds of eV.

From Monte-Carlo simulations, the transmission through a 15 nm entrance window was estimated to be 90 % for ^{11}Li at 4 keV with an energy loss of 1.4 keV and an energy straggling of 0.7 keV (standard deviation) after the window. Note that the magnetic field of the trap will focus the incoming ions into the antiproton trap. After passing through the entrance window, the charge state distribution also depends on the ion’s atomic charge. The foreseen window thickness corresponds to the order of a hundred of mean free paths for charge exchange. Therefore the final charge state of ions should depend on atomic processes occurring in the window and on the ion velocity at the exit of the window. Incoming ions will be singly charged. At 4 keV exit kinetic energy, 40% Mg ions exit the entrance window with charge +1, others are mostly neutralised which are then lost for trapping.

5 Solenoid

The solenoid should have a size compatible with transportation to ISOLDE and minimum energy consumption (superconducting). It will also be designed with reduced external field (active shielding) in agreement with regulations and the constraints in amplitude and derivative of B imposed by surrounding experiments at ELENA. The solenoid will have the following characteristics (preliminary): length of 1 meter, internal bore diameter of 300 mm, field homogeneity better than 0.1% in the trap area. The above dimensions have been defined according to simulations for tracking efficiency of emitted pions, momentum sensitivity from the curvature of antiprotons in the B field and spatial separation of the collision and storage zones. To fulfill the above characteristics, we are considering a home-made design composed of 12 coils with a peak field of 6.6 T and a total mass of conductor of 400 kg.

6 Production of Radioactive Isotopes

Radioactive ions will be produced at ISOLDE from the interaction of protons from the PS booster and production target. Different ions sources have been developed at ISOLDE and allow the extraction of a large range of elements.

The low-energy branch of ISOLDE will be used. Produced low-energy ions will cooled and bunched by the ISCOOL RFQ cooler and buncher. They will then be delivered at a kinetic energy of few keV to the experiment. It is planned that the experiments take place at ISOLDE beam lines LA1 or LA2.

7 Detection and analysis

The capture of the antiproton by an ion is followed by the decay of the antiproton to lower orbitals, through X-ray and Auger electron emissions. The hadronic system always remains positively charged and trapped. Contrary to accelerated-beam experiments, the reaction channel after annihilation in PUMA cannot be selected by identifying the heavy-ion residue. This will be done by tracking these energetic pions by use of their curvature in the magnetic field of the solenoid. In the case of sequential annihilations within few microseconds, the association of pions will be done by vertex reconstruction and timing from fast detectors.

Different detection systems are required for the collision zone and the storage zone. A cylindrical detection system will be placed around the collision trap, inside the solenoid's bore. The purpose of this system is: (1) to trigger on prongs, (2) to determine the vertex position of the annihilation, (3) to extract information on the type of annihilation process by defining the total charge of emitted mesons after the annihilation, (4) to measure gamma rays emitted from the de-excitation of nuclear excited states formed by annihilation.

The vacuum tube will be surrounded by a time projection chamber with an internal diameter of 100 mm, an external diameter of 250 mm and a length of 300 mm. The vertex resolution is simulated to be less than 4 mm FWHM. Optimised pad geometry will be defined according to simulations at different magnetic fields. About 5000 channels are foreseen for the TPC. A third detection layer composed of a scintillator array for low-energy gamma detection is foreseen.

The observable from the measurement will be a two-dimension matrix composed of the total charge of detected pions and the multiplicity of detected charged pions. The redundancy of the information contained in this matrix will allow to correct from pion-nucleus final state interactions. The methodology and accuracy was first described in [17]. The development of a refined method and the demonstration of the sensitivity from microscopic calculations are ongoing and will be released in the near future.

8 Milestones

A long-term shutdown of the facility is expected at CERN from December 2018 to end of 2020 for LHC upgrades. We aim at a full operation and installation at ELENA at the end of 2020.

1) Simulations, design and completion of the technical development
2) Assembly and validation at TU Darmstadt:
    - trapping with protons and light ions
    - trapping with positrons, vacuum better than 10^{-16} mbar
    - transportation of positrons over 1 km, storage over 1 week
3) Validation of ion-insertion procedure at CERN/ISOLDE
4) Installation at CERN/ELENA and antiproton storage
5) Physics program at ELENA and ISOLDE

Part of step 2) may also be performed at CERN.

Additional context information

The described experiment was proposed to the European Research Council by a member of the collaboration and was allocated a grant for most of the developments detailed in this letter of intent. The ERC project is named PUMA (antiProton Unstable Matter Annihilation) [23].

The trap, a key part of the proposed device, will be conceived and built in collaboration with the Max Planck Institute of Heidelberg.

An official agreement was made with the GBAR collaboration in 2015 to host PUMA at the GBAR « beam dump » location and allow the storage of antiprotons. With the present Letter of Intent, we aim at accessing an independent beam line in future, if made available.

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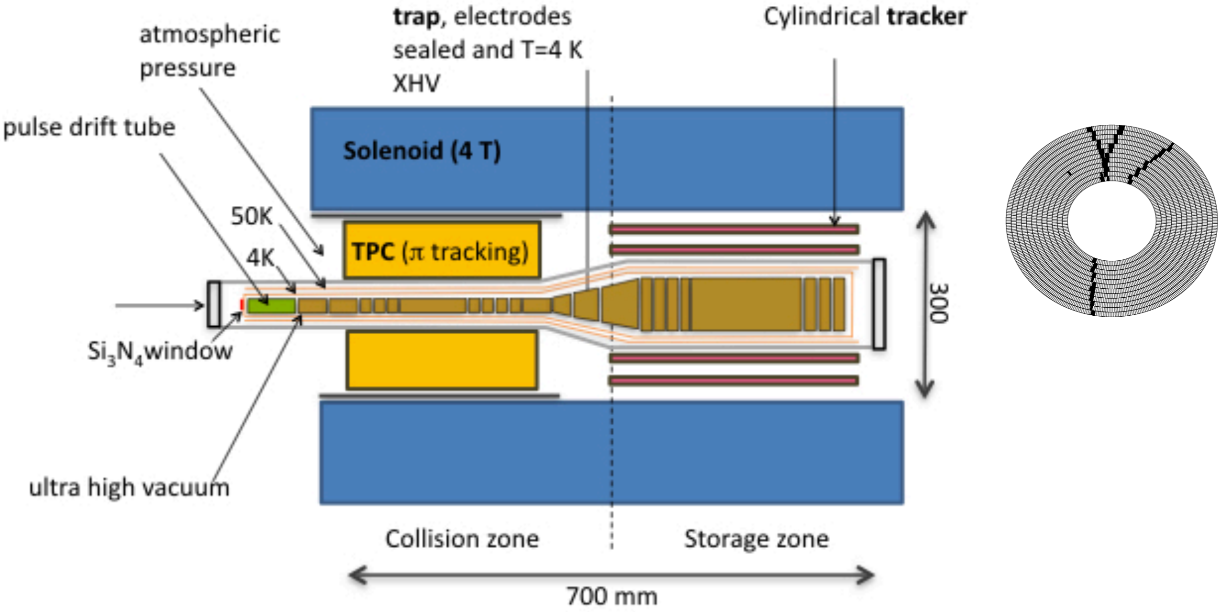

Figure 1. (Left) Sketch of the apparatus to be designed and build for the proposed experiment. (right) Simulation of antiproton-proton annihilation resulting into the emission of 4 charged pions, detected in the time-projection chamber. The projection of charges onto the detection plane is shown. In this example, the total sum of detected charges is zero.