

ANTIPROTONIC ATOMS AS A TOOL TO STUDY THE NUCLEAR PERIPHERY*

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The nuclear periphery was studied using antiprotons. Two experimental methods were applied: analysis of the antiproton annihilation residues one mass unit lighter than the target mass by nuclear spectroscopy and the measurement of strong interaction effects on antiprotonic level widths and shifts. 26 isotopes from a wide range of mass numbers ($40 < A < 238$) were investigated. Neutron density distributions and difference of neutron and proton root-mean-square radii for these isotopes were deduced.

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1. Experimental methods

Antiprotons are a good probe for the investigation of the nuclear surface as the \bar{p} -nucleus interaction has a peripheral character. Thanks to the strong antiproton–nucleus interaction even a small overlap between the antiprotonic and nuclear wave functions is sufficient to lead to annihilation. The life time of the lowest levels available for the antiproton in the atom is then reduced and the levels become wider. They are also shifted in relation to the purely electromagnetic energy.

To a first approximation the strong \bar{p} -nucleus interaction potential is proportional to the nuclear matter density [1–3]. Therefore, the widths and shifts of the last levels, which depend on this potential, can give information on the density at the nuclear periphery where annihilation takes place or — more precisely — at a distance of about $c_{\text{ch}} + 1.5$ fm (c_{ch} — the charge half-density radius) according to calculations [4]. The widths of the levels can be deduced from the shapes of the lines in the antiprotonic X-ray spectrum (for the last available level, the so-called “lower” level) or from the intensity balance (for the “upper” level — the last but one level).

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The antiprotonic cascade in the atom ends with the annihilation of the \bar{p} with one of the peripheral nucleons (a proton or a neutron) leading to a nucleus with mass number one unit smaller than the target mass A_t (a nucleus with proton number $Z_t - 1$ or with neutron number $N_t - 1$, respectively). If both of these products are radioactive their relative yields can be determined with standard nuclear-spectroscopy methods. These yields are directly related to the proton and neutron densities at the annihilation site. The yields are transformed to the halo factor, f_{halo} defined by [5]

$$f_{\text{halo}} = \frac{N(\bar{p}n)}{N(\bar{p}p)} \frac{Z}{N} \frac{\text{Im}(a_p)}{\text{Im}(a_n)}, \quad (1)$$

where the first term is the yield ratio of the products $A_t - 1$, the second term is the normalization factor and the third term — the ratio of the imaginary parts of the antiproton–nucleon scattering amplitudes — expresses the ratio of annihilation probability on a proton to that on a neutron. According to the latest potential models [2, 3], confirmed by experimental consideration [6], the neutron and proton scattering lengths are the same. The halo factor defined above is proportional to the neutron-to-proton density ratio ρ_n/ρ_p at the “cold” [7, 8] annihilation site. The maximum of the cold annihilation probability is at a radius 2.5 fm larger than the charge half-density radius [4].

2. Results

The PS209 experiment resulted in the determination of 44 level shifts and 62 level widths for 34 isotopes over a wide range of masses (see Fig. 1). The data were obtained with very good precision and extended the systematics of earlier measurements [9]. The halo factor was deduced for 19 isotopes [7, 8, 10].

Details of the data analysis were reported in several articles (*eg.* [11–17]). Comparison of the f_{halo} data with the results of the experiments determining the difference of the neutron and proton root mean square radii (Δr_{np}) indicates that the excess of neutrons is distributed in a form of the halo rather than a skin (neutron and proton distributions differ by the surface thickness and not by the half density radius [11]). The neutron distributions were determined for several isotopes. In the analysis, a spherical symmetry and a two-parameter Fermi (2pF) distribution was assumed for both neutrons and protons. The proton densities were adopted from literature (from compilations [18, 19]). At the beginning the simple optical potential of the antiproton–nucleus interaction of the form [20] $V_{\text{opt}} = \bar{a}(\rho_p + \rho_n)$ was used (\bar{a} — the antiproton scattering length, ρ_p and ρ_n — the densities of protons and neutrons, respectively). Later ([17]) the new available optical potentials — [2, 3] were also used.

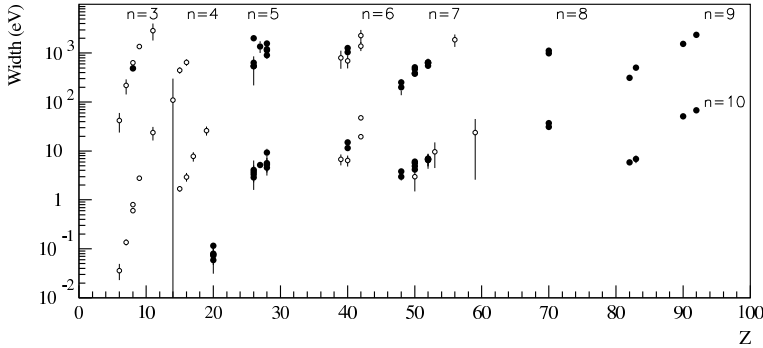


Fig. 1. Antiprotonic strong interaction level widths as a function of atomic number Z . Full circles — values determined in the PS209 experiment; open circles — earlier data [9].

Figure 2 shows the neutron to proton density ratio for six example isotopes determined from the strong interaction level widths and shifts. The halo factor (f_{halo}) and predictions of Hartree–Fock–Bogoliubov (HFB) calculations (with SkP Skyrme force) are also presented. There is a good

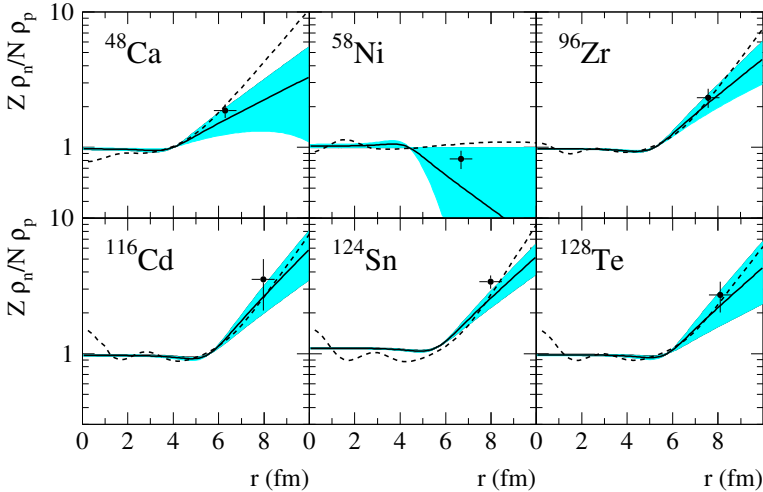


Fig. 2. Normalized neutron to proton density ratio ($Z \rho_n / N \rho_p$) deduced from the strong-interaction level widths and shifts (solid lines with errors indicated by a grey band) and charge distributions given in Ref. [19] (Sn nuclei — see more explanation in Ref. [14]) and Ref. [18] (other nuclei). They are compared with f_{halo} measured in the radiochemical experiments (marked with crosses at a radial distance corresponding to the most probable annihilation site) and with the HFB model calculations (with SkP Skyrme force) [21] (dashed lines).

agreement of both experimental methods and theoretical predictions for most of the isotopes studied. The obtained neutron density distributions were used to determine Δr_{np} for several isotopes.

Figure 3 presents Δr_{np} as a function of the asymmetry parameter $\delta = (N - Z)/A$. The linear relationship $\Delta r_{np} = (a + b\delta)$ fm was fitted with $a = (-0.03 \pm 0.02)$ and $b = (0.90 \pm 0.15)$ and χ^2_ν of 0.5. (This relationship is slightly different from the one given in Ref. [11] due to the larger amount of data evaluated and included in the fit.) This is in fair agreement with Relative Mean Field (RMF) calculations and with the global fit to the antiprotonic data performed by Friedman [2, 25].

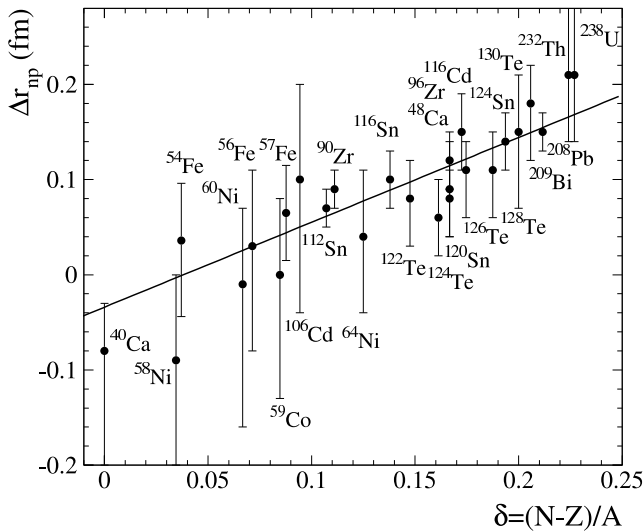


Fig. 3. Difference Δr_{np} between the r.m.s. radii of the neutron and proton distributions, as deduced from the antiprotonic atom X-ray data, as a function of $\delta = (N - Z)/A$. The proton distributions were obtained from electron scattering data [19] (Sn nuclei) or from muonic atom data [18, 22, 23] (other nuclei). The full line represents the linear relationship between δ and Δr_{np} as obtained from a fit to the experimental data.

3. Outlook

A continuation of the PS209 research programme was not possible after closing down of the Low Energy Antiproton Ring (LEAR) at CERN in 1996. The project of a new facility, FAIR and FLAIR, provides a perspective for the continuation of the studies of medium and heavy antiprotonic atoms. The future accelerator facility for beams of ions and antiprotons at Darmstadt will produce the highest flux of antiprotons in the world. The proposed

Facility for Low-energy Antiproton and Heavy-Ion Research (FLAIR) opens up the possibility to create low-energy antiprotons. The planned complex of storage rings will deliver high-brightness and high-intensity ($10^6/\text{s}$) beam of antiprotons in a wide range of energies: from 30 MeV to 20 keV. Both slow and fast extraction will be possible. The slow extracted \bar{p} beam, more intense (by 1–2 orders of magnitude) than at LEAR will allow very efficient measurements of antiprotonic X-rays especially if the new, digital electronics is used. Below the most interesting cases for future study are listed:

- Ca: doubly-magic ^{40}Ca and ^{48}Ca isotopes (possible measurement of 3 levels for each isotope and study of the neutron halo evolution between $N = 20$ and $N = 28$);
- odd- A isotopes (*eg.* Sn) — study of unpaired nucleon effect, looking for LS effect;
- deformed even- A nuclei:
 - study of deeply-bound states via E2 resonance;
 - study of the influence of deformation on neutron–proton rms differences.
- search for quasi-bound $\bar{p}p$ states.

The expected better energy resolution of detectors together with order of magnitude better statistics than one achieved with the LEAR facility will open new perspective for the antiprotonic X-ray studies.

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