Antiprotonic atoms X rays

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Antiprotonic X rays were used to investigate the nuclear matter densities. Neutron densities in 26 isotopes were determined using this method. The information on the nuclear matter density at relatively large radii was then converted to rms radii by the use of a two-parameter Fermi-function profile. The obtained systematics of differences of the neutron and proton rms radii is in a fair agreement with theoretical calculations and results of other experimental methods.

1 Introduction

The antiprotonic atoms are the good probe to study the nuclear periphery. Antiprotons captured into atomic orbits cascade down emitting X rays. In the vicinity of a nucleus the strong interaction reveals its presence: antiprotonic levels are shifted if compared to the pure electromagnetic energy and become broadened. The width and shift of the levels give an information on the nuclear matter density at the nuclear periphery.

The antiprotonic cascade ends with the annihilation on a peripheral nucleon: a neutron or a proton. If all produced pions miss the target nucleus two kinds of residues can be created with one neutron or one proton removed from the target nucleus. The yields of these products are proportional to the neutron and the proton densities at the nuclear surface.
2 The experiment

The experiment was performed at CERN (LEAR facility) within the PS209 collaboration in two runs: 4 weeks in 1995 and 3 weeks in 1996.

Two experimental methods based on the phenomena described above were used to study distribution of nuclear matter at relatively large radii in nuclei.

The first method is based on the measurements of antiprotonic X-rays. The line shapes, intensities and energies allow to determine the level widths and shifts induced by the strong interaction. At present, 44 level shifts and 62 level widths for 34 isotopes (see Fig. 1) have been evaluated [1, 2, 3].

In the second method the yield of the radioactive antiproton annihilation residues one mass unit lighter that the target was measured. The yield of products with one neutron less than the target neutron number $N_t$ (annihilation on a neutron) and those with one proton less than the target proton number $Z_t$ (annihilation on a proton) were determined [5, 6, 7]. The halo factor was calculated using these yields [5]. This factor gives the normalized neutron to proton density ratio at a distance about 2.5 fm larger than half density charge radius [8].

3 Results and data interpretation

The obtained in this experiment halo factors were compared with the results of other experiments examining a difference in neutron and proton density distributions, i.e. the
difference of the neutron and proton rms radii $\Delta r_{np}$. This comparison shows that $\Delta r_{np}$ result mainly from differences of the surface thickness in neutron and proton densities and not from differences of the half density radii $r_{np}$. In the data analysis density distributions were assumed in the form of two-parameter-Fermi distribution for both, the protons and neutrons. The proton densities were adapted from the compilations [9, 10].

The simple optical potential of the antiproton-nucleus interaction of the form: $V_{opt} \sim \alpha \cdot (\rho_p + \rho_n)$ ($\alpha$ - antiproton effective scattering length, $\rho_p$ and $\rho_n$ proton and neutron densities) was used in the X-ray data analysis. The potential was taken from [11]: $\alpha = 2.5 + i \cdot 3.4$. The details of this analysis and the way of neutron density extraction from the level widths and shifts was described in several articles [3, 12, 13, 14].

Fig. 2 shows 3 examples of the neutron to proton density ratios. Neutron densities were deduced from the X-ray data analysis. In the same figure the theoretical calculations with the Hartree-Fock-Bogoliubov (HFB) method using SkP Skyrme force are presented jointly with the halo factors. The good agreement of both experimental results and theoretical predictions can be observed. This is the case in the most of examined isotopes except of $^{106}$Cd, $^{112}$Sn and $^{144}$Sm [13]: the isotopes with weakly bound proton. The effect of quasi-bound pp states was proposed [16] as an explanation of this discrepancy.

Using neutron densities deduced from the X-ray data and proton densities from the compilation [9, 10], the difference of neutron and proton root mean square radii $\Delta r_{np}$ was deduced for the studied isotopes under the assumption of 2pF proton and neutron density distributions. The calculated $\Delta r_{np}$ values are presented in the Table 1 and in Fig. 3 (as a function of the asymmetry parameter $\delta = (N - Z)/A$). The linear relationship $\Delta r_{np}$ as a function of $\delta$ was fitted. The function $\Delta r_{np}(\delta)$ was finally parametrized using following coefficients: $\Delta r_{np} = (-0.03 \pm 0.02) + (0.90 \pm 0.15) \cdot \delta$ fm.
Table 1: Neutron and proton root mean square radii differences $\Delta r_{np}$, obtained from antiprotonic X-ray data.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$\Delta r_{np}$ [fm]</th>
<th>Isotope</th>
<th>$\Delta r_{np}$ [fm]</th>
<th>Isotope</th>
<th>$\Delta r_{np}$ [fm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}$Ca</td>
<td>-0.08$^{+0.05}_{-1.0}$</td>
<td>$^{48}$Ca</td>
<td>0.09$^{+0.05}_{-0.05}$</td>
<td>$^{50}$Co</td>
<td>0.00$^{+0.08}_{-0.13}$</td>
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<tr>
<td>$^{48}$Ca</td>
<td>0.00$^{+0.05}_{-0.05}$</td>
<td>$^{54}$Fe</td>
<td>0.04$^{+0.06}_{-0.08}$</td>
<td>$^{54}$Zr</td>
<td>0.12$^{+0.03}_{-0.03}$</td>
</tr>
<tr>
<td>$^{54}$Fe</td>
<td>0.04$^{+0.06}_{-0.08}$</td>
<td>$^{56}$Fe</td>
<td>0.03$^{+0.08}_{-0.11}$</td>
<td>$^{96}$Zr</td>
<td>0.12$^{+0.03}_{-0.03}$</td>
</tr>
<tr>
<td>$^{56}$Fe</td>
<td>0.03$^{+0.08}_{-0.11}$</td>
<td>$^{57}$Fe</td>
<td>0.07$^{+0.05}_{-0.05}$</td>
<td>$^{106}$Cd</td>
<td>0.10$^{+0.10}_{-0.14}$</td>
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<td>$^{57}$Fe</td>
<td>0.07$^{+0.05}_{-0.05}$</td>
<td>$^{58}$Ni</td>
<td>-0.09$^{+0.09}_{-0.16}$</td>
<td>$^{112}$Sn</td>
<td>0.07$^{+0.02}_{-0.02}$</td>
</tr>
<tr>
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<td>$^{60}$Ni</td>
<td>-0.01$^{+0.08}_{-0.15}$</td>
<td>$^{116}$Sn</td>
<td>0.10$^{+0.03}_{-0.03}$</td>
</tr>
<tr>
<td>$^{64}$Ni</td>
<td>0.04$^{+0.07}_{-0.08}$</td>
<td>$^{60}$Ni</td>
<td>-0.01$^{+0.08}_{-0.15}$</td>
<td>$^{120}$Sn</td>
<td>0.08$^{+0.03}_{-0.04}$</td>
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<tr>
<td>$^{64}$Ni</td>
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<td>$^{130}$Te</td>
<td>0.15$^{+0.08}_{-0.08}$</td>
</tr>
<tr>
<td>$^{122}$Te</td>
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<td>$^{124}$Te</td>
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<td>$^{126}$Te</td>
<td>0.11$^{+0.03}_{-0.05}$</td>
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<tr>
<td>$^{126}$Te</td>
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<td>$^{128}$Te</td>
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<td>$^{130}$Te</td>
<td>0.15$^{+0.08}_{-0.08}$</td>
</tr>
<tr>
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<td>$^{208}$Pb</td>
<td>0.15$^{+0.02}_{-0.02}$</td>
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<td>$^{120}$Sn</td>
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<td>$^{209}$Bi</td>
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<td>$^{124}$Sn</td>
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<td>0.21$^{+0.07}_{-0.07}$</td>
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<tr>
<td>$^{126}$Te</td>
<td>0.11$^{+0.03}_{-0.05}$</td>
<td>$^{232}$Te</td>
<td>0.21$^{+0.07}_{-0.07}$</td>
<td>$^{238}$U</td>
<td>0.21$^{+0.07}_{-0.07}$</td>
</tr>
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Figure 3: Difference $\Delta r_{np}$ between the rms radii of the neutron and proton distributions 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 [10] (Sn nuclei) or from muonic atom data [9, 17, 18] (other nuclei). The full line represents the linear relationship between $\delta$ and $\Delta r_{np}$ as obtained from a fit to the experimental data.
4 Comparison with other experiments and theoretical calculations

The $^{208}\text{Pb}$ nucleus is one of the most intensely studied isotopes by many experiments as well as by a theory and because of this is a good case for comparisons. Figure 4 shows compilation of $\Delta r_{np}$ in $^{208}\text{Pb}$ determined in hadron scattering experiments and the average value is $\Delta r_{np} = 0.17 \pm 0.02$ fm. The results are compared with the value $\Delta r_{np} = 0.15 \pm 0.02$ fm obtained from antiprotonic X-rays. The theoretical predictions for $\Delta r_{np}$ are also shown. All presented results agree very well.

The results of these comparisons can be used as an additional confirmation of the assumption presented in section 3 that the neutron and proton distributions in a given isotope differ mainly by the surface thickness and not by the half density radius. Figure 5 shows the results of $\Delta r_{np}$ obtained from the analysis of X-ray data in $^{208}\text{Pb}$ with the assumption that $c_n \neq 0$. One can see that the average $\Delta r_{np}$ from various experiments allows $c_n \leq 0.1$ fm only.

In Fig. 4 a good agreement of $\Delta r_{np}$ for $^{208}\text{Pb}$ obtained in the hadron scattering and in the $\overline{p}$ experiments is evident. However, the situation is not so good if one compares $\Delta r_{np}$ obtained for other isotopes [27] – the old data from different experiments are much more scattered. The scatter of the theoretical values is significantly smaller. Examples of HF and HFB calculations are shown in Fig. 6, while the predictions of a Droplet Model were presented in Ref. [28].
Figure 5: The difference of neutron and proton rms radii in $^{208}$Pb obtained in the X-ray data analysis as a function of $\Delta c_{np}$. The dashed line with a grey band describes an average $\Delta r_{np}$ value for $^{208}$Pb obtained from hadron scattering experiments – see Fig. 4.

Figure 6: The difference $\Delta r_{np}$ between the rms radii of the neutron and proton distributions as a function of $\delta = (N - Z)/A$ calculated by mean field models. Open points Ref. [15] (HFB model with SkP force); full triangles - Ref. [29] (HF model, SLy4 force); asterisks - Ref. [24] (HF model, SkX force). The full line is the linear relationship between $\delta$ and $\Delta r_{np}$ as obtained from the fit to the HFB model calculations (open points). The dashed line is the fit to the antiprotonic atom data as presented in Fig. 3.
5 Summary

A rich set of data concerning antiprotonic atoms was gathered in the PS209 experiment. The data were analyzed using a simple optical potential and density distributions in a form of 2pF function. The neutron density distributions and neutron-proton rms radii differences were determined. Despite the model dependence of data treatment a good agreement with various theories (HF and HFB calculations, Droplet Model predictions) was obtained for density distributions and rms radii differences. Also a fair agreement with other experimental results of $\Delta r_{np}$ was obtained.

The presented experimental data make an interesting material for theory—the search of a new, more sophisticated optical potential [30, 31, 32].

The PS209 experiment of course didn’t exhaust all the interesting topics in the medium and heavy antiprotonic atoms. For example: measurements of X rays for deformed even-A nuclei and for odd-A nuclei or the investigation of the properties of deeply bound $\bar{p}$ states via E2 resonance would be of great interest. The FLAIR (Facility for Low-Energy Antiproton and Ion Research) planned at Darmstadt will allow a continuation of the presented studies.

References


