\( \bar{p}p \) INTERACTIONS IN \( \bar{p} \) ATOMS

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1. INTRODUCTION

Whenever an orbiting electron in an ordinary atom or ion is replaced by a negative muon or hadron an exotic atom is formed. If the particular substitute is an antiproton the result is an antiprotonic atom. Such systems can be regarded as being pure hydrogen-like as a consequence of the fact that the antiproton is considerably closer to the nucleus than the electrons owing to its much higher mass. The solution of the Dirac equation for a point-like nucleus already leads to a good description for the energies of the system:

\[ E = \mu \left\{ 1 + \left[ Z\alpha \left( n - \left( j + \frac{1}{2}\right) + \sqrt{(j + \frac{1}{2})^2 - Z^2\alpha^2}\right) \right] \right\}^{-\frac{1}{2}} \]

\[ \mu : \text{reduced mass} \]
\[ n : \text{main quantum number} \]
\[ j : \text{angular momentum quantum number} \]

When an antiproton, having a certain momentum, is slowed down and brought to rest, it is captured into an atomic orbit and cascades down. For calculations it is assumed that the capture into the different sublevels is according to their statistical weight. If required by experimental results, the statistical distribution is corrected by an exponential in \( \lambda \).

Once captured into atomic orbits, the \( \bar{p} \) cascades through the electron cloud via Auger effect. For low \( n \)-values, far inside the electronic 1s orbit however, X-ray transitions dominate. Close to the nucleus, that is when its wave function overlaps sufficiently with the nucleus, the antiproton interacts with the nucleons, is scattered, and absorbed. Hence the cascade terminates for different \( Z \) at different \( n \). Scattering and absorption contribute a strong interaction shift and width to the electromagnetic energy and the radiation width of the low-lying levels (Fig. 1). These effects can be traced out by recording the X-rays of \( \bar{p} \) atoms, which deliver the three quantities detectable in \( \bar{p}N \) interactions:

\[ \Delta E = E^{\text{exp}} - E^{\text{em}} \]  
strong interaction shift of the last level (difference between measured and calculated pure electromagnetic energy);

\[ \Gamma_{\text{low}} = \]  
strong interaction width of the last level;

\[ \Gamma_{\text{up}} = \]  
strong interaction width of the last but one level.

The last quantity is received by balancing the transitions feeding the last but one level with those depopulating it.
2. **EXPERIMENT**

Since the first discovery of antiprotonic X-rays\(^1\) more data of \(\bar{p}\) atoms have become available. Figure 2 shows the experimental arrangement, consisting of a telescope to identify the incoming \(\bar{p}\), a moderator to slow it down so that it is stopped in the x-shaped target (to reduce absorption of the X-rays in the target itself), and finally of solid-state detectors to record the X-rays. A \(\bar{p}\) trigger is given by the coincidence of all scintillation counters vetoed by two Čerenkovs to suppress the pion background. The coincidence of an X-ray signal of the solid-state detectors with a \(\bar{p}\) trigger defines a true event. Calibration of the X-ray spectra is provided by recording X-rays from a radioactive source in accidental coincidence. Furthermore, undistorted higher transitions and X-rays from suitably selected target container material are used for calibration. Both can be calculated with high accuracy.

3. **RESULTS**

The outcome of measurements on antiprotonic X-rays concerning the strong interaction effects are listed in Table 1. In the early measurements on \(\bar{p}\) atoms only the upper width could be received. With the high resolution solid-state spectrometers nowadays available, shifts and widths of the lower levels can be deduced with high accuracy. Figure 3 shows the X-ray spectrum of \(\bar{p}^-\)He recently measured at CERN (data still in evaluation). The Balmer series appears with excellent statistics up to its limit. The impressing fact is, however, that the M series could be obtained even down to the 4-3 transitions at 3.9 keV with an excellent efficiency, which is extremely important to determine the width of the 3d level.

4. **INTERPRETATION OF DATA**

The energy of the levels and consequently the energy of the transitions is calculated by solving numerically the Dirac equation with an electromagnetic potential, taking into account the finite size of the nucleus and the vacuum polarization. Where necessary, minor effects such as nuclear polarization and electron screening are treated with perturbative methods. The strong interaction is described by adding a complex potential of the form

\[
V_{SI} = -2\pi \frac{m_p}{\mu^2} A \rho(r)
\]  

(1)

where

- \(\rho(r)\) is the nuclear matter distribution
- \(m_p\) is the mass of the antiproton
- \(\mu\) is the reduced mass.
\( V_{SI} = -2\pi \frac{m_\pi}{\mu^2} \left[ A_{pp} \rho_p(r) + A_{pn} \rho_n(r) \right] \)

where

- \( \rho_n \) is the distribution of the neutron
- \( \rho_p \) is the distribution of the protons.

There are few attempts to interpret the quantities \( A_{pp} \) and \( A_{pn} \) in a more extensive way\(^2\) as is done for pionic and kaonic atoms\(^3\). In first order approximation they can be regarded as the effective s-wave scattering lengths of the \( pp \) and \( pn \) system, respectively. In order to get a best fit to the widths and shifts of \( N \) and \( O \) which have been the most precise measurements up to recently, the parameter of Eq. (1) was chosen to\(^4\)

\[ \tilde{\Lambda} = (2.9 + i 1.5) \text{ fm} \]

But the free scattering length predicted by theory based on OBEF leads to\(^5\)

\[ \tilde{\Lambda} = (-0.9 + i 0.7) \text{ fm} \]

A somewhat similar situation exists for \( K^- \) atoms\(^6,7\). There the free scattering length according to Ref. 8 gives

\[ A_{K^-p} = (-0.9 + i 0.66) \]
\[ A_{K^-n} = (-0.7 + i 0.62) \].

A best fit to kaonic atom data results in\(^7,9\)

\[ A_{eff}^{K^-p} = (1.03 + i 1.54) \text{ fm} \]
\[ A_{eff}^{K^-n} = (0.13 + i 0.4) \text{ fm} \]

The striking fact is the opposite sign of the real part of the potential. For \( K^- \) atoms it may, however, be explained by taking care of the \( V_0(1405) \) resonance just below threshold\(^10\).

Whether antiprotonic atoms can be treated in a similar way will be shown by the outcome of future experiments.

Protonium or antiprotonic hydrogen is a suitable system for picking out such information. Besides its great cosmological importance\(^11\) this fundamental system, predestined to deduce sign and magnitude of the \( pp \) scattering length, may also clear up the question whether there are strongly bound states and resonances close to threshold\(^12\).
The pure electromagnetic energies of the interesting X-ray transitions are

\begin{align*}
2p-1s & : \quad 9.4 \text{ keV} \\
3p-1s & : \quad 11.1 \text{ keV} \\
3d-2p & : \quad 1.7 \text{ keV}
\end{align*}

Taking the scattering length from Ref. 5, the shift and width range between 0.2 keV to 0.85 keV and from 0.17 keV to 0.43 keV, respectively. There are two experiments in preparation at CERN to measure X-rays of protonium. In one, a liquid or gaseous target and high-resolution solid-state detectors are used while in the other, proportional counters with a gaseous target are applied.

Both experiments have to tackle enormous problems arising from low stop rates, the absorption of X-rays in the target and its walls, and the prompt background from charged particles created in the annihilation. The most restricting effect is, however, the Stark mixing appearing when the small \( \bar{p}p \) system is drifting into an electronic hydrogen atom and the atomic states are mixed. Absorption then takes place in higher orbits and may reduce the intensity of the last transition to an undetectable amount.

5. ISOTOPE EFFECT MEASUREMENTS

Whenever the distributions of protons and of neutrons are well known, \( \bar{p}p \) and \( \bar{p}n \) interaction may be separated by analysing isotopic effects. The following simple treatment shows how this can be tried. The difference between the Hamiltonians for both isotopes is small and essentially proportional to the difference of the neutron densities \( \Delta \rho_n \) in both isotopes:

\[ H^1 - H^2 = H' \propto \Delta \rho_n (r) \]

Hence in first approximation the difference of shifts and widths between both isotopes is described by the product of \( A_{\bar{p}n} \) and the overlap of the antiproton with the difference of the neutron densities, essentially effective at the surface of the nucleus:

\[ \Delta \epsilon = 1 \frac{\Delta \Gamma_{\text{low}}}{\Gamma_{\text{low}}} \propto A_{\bar{p}n} \langle \psi | \Delta \rho_n | \psi \rangle, \]

where \( \psi \) is the complete wave function of \( \bar{p} \) in the isotope 1.

It is assumed that the proton distributions do not change much from one isotope to the other and that ansatz (2) holds. Although there is a slight dependence upon the choice of the wave function of the antiproton, the ratio of relative shift to relative width is equal to the ratio of real to imaginary part of \( A_{\bar{p}n} \):

\[ \frac{\Delta \epsilon}{\Delta \Gamma/2} = \frac{\text{Re} A_{\bar{p}n}}{\text{Im} A_{\bar{p}n}} \quad \text{(3)} \]
Figure 4 shows antiprotonic spectra of $^{16}\text{O}/^{18}\text{O}^{16}$). This first measured isotope effect in $\bar{p}$ atoms is clearly seen in the intensity reduction of the last observable transition (4-3) due to the strong absorption. These spectra are taken up simultaneously under identical conditions, so channels can be compared directly. All lines of $^{18}\text{O}$ are shifted noticeably to higher energies owing to the higher reduced mass. The presence of the complete N series provides a high precision measurement of the upper width. When the analyses of the data are finished, the ratio of the real and imaginary part of the $\bar{p}n$ scattering amplitude at low energies can be deduced from Eq. (3).

Finally, a very recent measurement shows the variety of possibilities opened up by using X-rays of $\bar{p}$ atoms. From a high-precision measurement it was found$^{17}$) that the magnetic moment of the antiproton is

$$\mu_\bar{p} = (-2.791 \pm 0.021) \mu_\text{N}$$
$$\mu_\text{p} = (2.793 \pm 1.1 \times 10^{-8}) \mu_\text{N}$$

for comparison.

This was deduced from the fine structure splitting of the transition 11-10 in $\bar{p}\text{Pb}$ and $\bar{p}\text{U}$. From the precise measurement of the energy of X-ray transitions in $\bar{p}\text{Pb}$ for the $\bar{p}$-mass the value:

$$m_\bar{p} = 938.179 \pm 0.058 \text{ MeV}$$

was found, so that

$$m_\text{p} - m_\bar{p} = (100 \pm 58) \text{ keV}.$$ 

6. CONCLUSION

Due to the lack of sufficient data, the antiproton-nucleon interaction is not well understood at low energies. There are new $\bar{p}$ atom data in evaluation$^{18}$) which may help to clear up the situation. For the pure $\bar{p}p$ interaction, however, the outcome of the protonium experiments is extremely important. In order to separate antiproton-proton from antiproton-neutron interactions, the studies of isotope effects should be continued.
REFERENCES


   G.B. Dover, invited talk to the 4th Internat. Symposium on Antinucleon-Nucleon Interactions, Syracuse University, 2-4 May 1975, proceedings in preparation.


14) Experiment P7, Basel-Karlsruhe-Stockholm-CERN Collaboration.

15) Experiment S147, CERN-Daresbury-Mainz-TRIUMF Collaboration.


20) H. Koch, private communication.
Table 1
Measurements on $p$ atoms with respect to $p$-N interactions

<table>
<thead>
<tr>
<th>Target</th>
<th>Transition</th>
<th>$E_{\text{em}}$ (£eV)</th>
<th>$\varepsilon$ (£eV)</th>
<th>$\Gamma_{\text{low}}$ (£eV)</th>
<th>$\Gamma_{\text{up}}$ (£eV)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^4$He</td>
<td>3-2</td>
<td>11.129</td>
<td>15 ± 82</td>
<td>191 ± 170</td>
<td></td>
<td>19</td>
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<tr>
<td>$^14$N</td>
<td>4-3</td>
<td>55.824</td>
<td>-39 ± 51</td>
<td>173 ± 34</td>
<td>0.13 ± 0.03</td>
<td>4, 20</td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>4-3</td>
<td>73.562</td>
<td>-60 ± 72</td>
<td>648 ± 150</td>
<td>0.49 ± 0.12</td>
<td>4, 20</td>
</tr>
<tr>
<td>P</td>
<td>5-4</td>
<td>123.23</td>
<td></td>
<td></td>
<td>1.14 ± 0.25</td>
<td>9</td>
</tr>
<tr>
<td>$^{32}$S</td>
<td>5-4</td>
<td>140.50</td>
<td>-41 ± 44</td>
<td>760 ± 110</td>
<td>760 ± 110</td>
<td>7*</td>
</tr>
<tr>
<td>Cl</td>
<td>5-4</td>
<td>158.8</td>
<td></td>
<td></td>
<td>8.00 ± 2.22</td>
<td>9</td>
</tr>
<tr>
<td>K</td>
<td>5-4</td>
<td>199.37</td>
<td></td>
<td></td>
<td>26.8 ± 7.0</td>
<td>9</td>
</tr>
<tr>
<td>Sn</td>
<td>8-7</td>
<td>298.68</td>
<td></td>
<td>3.07 ± 1.79</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>I</td>
<td>8-7</td>
<td>335.91</td>
<td></td>
<td>9.93 ± 7.68</td>
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<td>9</td>
</tr>
<tr>
<td>Pr</td>
<td>8-7</td>
<td>416.92</td>
<td></td>
<td>24.7 ± 56.8</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>$^{18}$O-$^{16}$O</td>
<td>4-3</td>
<td>60 ± 50</td>
<td>0.27 ± 0.15</td>
<td>0.27 ± 0.15</td>
<td>16**</td>
<td></td>
</tr>
</tbody>
</table>

*) Improved new measurement, $\Gamma_{\text{low}}$ different from that measured in Ref. 9.

**) Preliminary results.
Figure captions

Fig. 1 : Level scheme of an $\bar{p}$ atom demonstrating cascading, Ref. 7.

Fig. 2 : Experimental set-up:
- S Scintillations counters
- C Čerenkov counters
- Cu-Mod Copper moderator
- C-Mod Carbon moderator
- Cu Copper shielding
- T Target
- Ge(Li) Solid-state detectors.
(Ref. 6).

Fig. 3 : $\bar{p}$-$^4$He spectrum, Ref. 16.

Fig. 4 : $\bar{p}$-$^{16}$O/$^{18}$O spectra, Ref. 16.
Fig. 3