HADRONIC ATOMS

L. Tauscher*)

University of Basle, Switzerland

Invited paper at the
Sixth International Conference on High-Energy Physics and Nuclear Structure
Santa Fe, New Mexico, USA
9-14 June 1975

Geneva - 30 June 1975

*) Visitor at CERN, Geneva, Switzerland
HADRONIC ATOMS

L. Tauscher
University of Basle, Switzerland

ABSTRACT

Recent results on the masses of the $\pi^-$, $K^-$, $\bar{p}$, and $\Sigma^-$, as well as on the magnetic moments of the $\bar{p}$ and $\Sigma^-$, are presented. The strong hadron-nucleus interaction is discussed for $\pi^-$, $K^-$, and $\bar{p}$. Especially, the influence of precision measurements of light pionic atoms on the understanding of the $\pi^-$-nucleus s-wave interaction is pointed out. New measurements on deformed nuclei with pions are discussed in terms of the quadrupole deformation of the neutron distribution. The difficulties in understanding the $K^-$-nucleus interaction are demonstrated. Recent measurements on light $\bar{p}$ atoms are reported, in particular the first observed isotope effect in $\bar{p}$ atoms ($^{16}O/^{18}O$) is discussed in terms of differences in the pn and $\bar{pp}$ interaction.

INTRODUCTION

A hadronic atom is a system in which a negatively charged hadron moves in atomic orbits around an atomic nucleus. The system is formed by stopping the hadron in a target. In the very last step of the stopping process the hadron expels a K electron of the target atom by Auger effect and occupies this atomic orbit, which corresponds to a highly excited state of the hadronic atom. As a working hypothesis, we assume that the hadron is captured into a level of distinct main quantum number $n$, with statistically populated $\ell$ sublevels. This certainly does not always correspond to reality, as is demonstrated in a number of measurements and calculations. The deexcitation proceeds via Auger effect high up in the cascade, and later, when the system is more hydrogen-like, mainly via X-ray emission. The cascade is terminated by the strong interaction absorption, in heavy atoms already fairly high up in the cascade (see Fig. 1).

In this paper the capture mechanisms and cascade processes will not be discussed. Instead I refer to the talk of Ponomarev given at this conference.

The experimentalist observes the X-rays of the cascade, measuring energy, fine structure or hyperfine splitting, line broadening, and absolute or relative yield. Also, secondary particles or nuclear $\gamma$-rays related with stopping hadrons are measured. Such experiments will not be discussed in this paper either, and I refer to the recent literature.

The problems to tackle with hadronic atoms are of different aspects.

* Visitor at CERN, Geneva, Switzerland.
Fig. 1 Scheme of the de-excitation cascade of a hadronic atom.

- Elementary: The mass and the magnetic moment of the hadron in orbit may be measured. The elementary hadron-nucleon scattering length is accessible via the hadronic hydrogen system.
- Elementary but in nuclear matter: The behaviour of quasi-bound hadron-nucleon states in nuclear matter influences the hadron-nucleus interaction widely. Its understanding may imply the possibility of extrapolating to the free quasi-bound state.
- Nuclear physics: An early hope was to measure with hadronic atoms the nuclear matter distributions at the nuclear surface and differences in the distributions of neutrons and protons. The momenta of the nucleons in the nucleus (short- and long-range correlations) might be measured, for instance, via the π⁻ absorption or the non-mesonic K decay. In this respect also multibody forces may be of importance. Some data may also be discussed in terms of clustering. The dipole polarizability of the nucleus may be measured in an extremely clean way. Finally, the static quadrupole deformation of the nuclear matter has become a measurable quantity.
- Quantum electrodynamics: Last, but not least, the QED might also be tested with ¯p atoms, provided m_\bar{p} = m_p.

ELEMENTARY PARTICLE PROPERTIES OF HADRONS

Masses

The most accurate mass determinations for most negatively-charged stable hadrons come from hadronic atoms. Use is made of the fact that the X-ray transition energy in a hydrogen-like system is
proportional to first order to the reduced mass of the particle in orbit. The difficulties are of two different kinds:

- The energies of the X-rays have to be measured absolutely with high precision. The standard reached by now is not so much dependent on statistics, but mainly on systematic uncertainties of sometimes unknown origin and magnitude. In this respect, I want to refer to the discussions on muonic atoms during this conference.

- The electromagnetic transition energies have to be calculated very accurately. These calculations were to some extent uncertain due to discrepancies between theory and experiment in muonic atoms. According to a recent experiment at CERN, such discrepancies do not exist. The group which reported the discrepancies could not reproduce the earlier results, without however being able to state which of their experiments is more reliable (cf. contribution of Hargrove to this conference). Controversial opinions exist on the magnitude of the QED correction of order $a^2(aZ)^2$, which was calculated by four authors. Three authors obtain almost negligible contributions. Chen's calculations are not confirmed by the recent CERN experiment. The calculations as performed to obtain the mass values, therefore, do not contain the $a^2(aZ)^2$ contribution at all.

The pion mass has not changed since 1973. However, the error of the CERN measurement can now be reduced due to the uncertainty removed in the calculation. The values therefore are

\[ m_\pi^- = 139.569 \pm 0.006 \text{ MeV (CERN)} \]
\[ m_\pi^- = 139.566 \pm 0.010 \text{ MeV (Shafer)} \]

Average: \[ m_\pi^- = 139.568 \pm 0.005 \text{ MeV} \]

The $K^-$ mass was measured at CERN in 1972. In this measurement the lines of highest energy were omitted in the $K^-$ mass determination. Instead they were used to obtain the $K^-$ polarizability. An upper limit of the $K^-$ polarizability was derived there, which was, however, two orders of magnitude too insensitive to what recent experimental and theoretical results estimate. We therefore include the two additional lines ($K^-\text{Ba} 7-6$ and $K^-\text{Au} 8-7$) in the $K^-$-mass evaluation and arrive at

\[ m_{K^-} = 493.688 \pm 0.030 \text{ MeV (CERN)} \]

A recent measurement of the $K^-$ mass was performed at Brookhaven by the Columbia group. They derive from a series of transitions in $K^-\text{Pb}$, ranging from 13-12 down to 8-7 a mass of

\[ m_{K^-} = 493.657 \pm 0.020 \text{ MeV (Columbia)} \]

Both measurements agree within the errors, and the average of both is

\[ \bar{m}_{K^-} = 493.667 \pm 0.017 \text{ MeV} \]
with a remarkable error of less than $3.5 \times 10^{-5}$. In the same measurement the Columbia group has observed $\Sigma^-$-atomic X-rays from Pb, ranging from 15-14 down to 11-10. They deduce a mass of the $\Sigma^-$ of

$$m_{\Sigma^-} = 1197.24 \pm 0.14 \text{ MeV}.$$ 

This is an agreement with a measurement done in emulsions, where $m_{\Sigma^-} = 1197.36 \pm 0.10 \text{ MeV}$ was derived$^{18}$. It agrees also with a bubble-chamber measurement, which gave $m_{\Sigma^-} = 1197.43 \pm 0.11 \text{ MeV}^{19}$. The mass of the antiproton was obtained again by the Columbia group$^{17}$, who extracted it from the transitions 16-15 down to 11-10 in pPb. They obtain

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

This value does not compare very well with the proton mass, as

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

However, the difference is not really significant. The result may also be interpreted as a test of QED. I should perhaps not forget to point out that, as the experiment has no direct check on the absolute calibration, such as a known nuclear $\gamma$ line (cf. Ref. 11), a slight unrecognized systematic shift of the order of 10 eV might be responsible for the effect.

**Magnetic moments**

The magnetic moments of the $\bar{p}$ and $\Sigma^-$ may be measured by observing the fine structure splitting of an X-ray transition. This splitting is to first-order perturbation proportional to the magnetic moment of the particle in orbit. The experimental difficulty is to have sufficient resolution in order to resolve the fine structure components. The magnetic moment of the $\bar{p}$ as measured in $\bar{p}$ atoms was first reported by Fox et al.$^{20}$. A detailed analysis of this experiment, later reported by Roberts et al.$^{21}$, resulted in a value of

$$\mu_{\bar{p}} = -2.819 \pm 0.056 \text{ n.m.}.$$ 

The splitting of the 11-10 transition in $\bar{p}$Pb and $\bar{p}$U was analysed.

A recent measurement of the Columbia group$^{17}$, in which the same elements and the same transition were investigated, resulted in

$$\mu_{\bar{p}} = -2.790 \pm 0.021 \text{ n.m.}.$$ 

Both measurements are in agreement with each other and also with the magnetic moment of the proton, $\mu_p = 2.7928456 \text{ n.m.}$. Figure 2 shows the 11-10 transition in $\bar{p}$U as obtained by the Columbia group. The splitting is well resolved, and the peak-to-background ratio is very good.

The magnetic moment of the $\Sigma^-$ is difficult to measure, due to the fact that only a few $\Sigma^-$ are created by $K^-$ absorption on a nucleus and escape from it, forming a $\Sigma^-$ atom in the target$^{22}$. In
Fig. 2 The 11→10 transition in $\bar{\rho}U$ as obtained by the Columbia group (Ref. 17).

addition, the processes of $K^-$ absorption and $\Sigma^-$-atom formation are simultaneous in the experimental time scale. $\Sigma^-$ and $K^-$ X-rays, therefore, cannot be separated and appear in the same spectrum, resulting in low-intensity $\Sigma^-$-atomic lines on a high background from the $K^-$-atomic spectrum. Another difficulty is caused by the weak splitting of the $\Sigma^-$ X-ray lines, which is about 300 eV at most and has to be compared with the experimental resolution, which is of 1.2 keV. A delicate $\chi^2$ analysis is therefore necessary, keeping the experimental resolution fixed and varying $\mu_{\Sigma^-}$, when fitting the line shape of the $\Sigma^-$-atomic X-ray.

Figure 3 shows the 12→11 transition in $\Sigma^-$Pb as recorded by the Columbia group. The peak-to-background ratio is unfortunate, as expected, and no broadening of the $\Sigma^-$ line is visible if compared with the adjacent kaonic line. Figure 4 demonstrates the $\chi^2$ analysis. The figure is taken from Roberts et al. Two minima are obtained for $\chi^2$, corresponding to a positive and a negative value for $\mu_{\Sigma^-}$. A significantly better $\chi^2$ is obtained for negative values of $\mu_{\Sigma^-}$. The result of Ref. 23 is obtained from a measurement of the 12→11 transition in $\Sigma^-$Pb, $\Sigma^-{}^{208}$Pb, and $\Sigma^-{}^{197}$Pt. It is

$$\mu_{\Sigma^-} = -1.48 \pm 0.37 \text{ n.m.}$$
Fig. 3 The 12-11 transition in Σ⁻Pb as obtained by Ref. 17.

Fig. 4
χ² analysis of the 12-11 transition in several elements as obtained by Ref. 23.
The Columbia measurement of the 12-11 transition in Pb cannot distinguish between a positive and negative value, as both give the same \( \chi^2 \) minimum. Their result is\(^{17}\)

\[
\begin{align*}
\mu_{\pi^-} &= -1.40 \pm 0.41 \pm 0.28 \\
&\quad \text{n.m.} \\
&\quad +0.65 \pm 0.28 -0.41
\end{align*}
\]

Both experiments have about the same accuracy and agree very well. This may be considered as proof of the consistency and value of the method. The measured value does not agree with the SU(3) prediction of \( \mu_{\pi^-} = -0.88 \) n.m. It agrees, however, with the magnetic moment of the \( \Xi^- \) (\( \mu_{\Xi^-} = -2.2 \pm 0.8 \) n.m.)\(^{24}\), which, according to SU(3), should be equal to \( \mu_{\Sigma^-} \).

**STRONG INTERACTION EFFECTS**

Strong interaction effects in hadronic atoms may be observed in three ways. The elastic hadron-nucleus interaction and dispersive effects due to absorption may shift the binding energy of the last observable level (Fig. 1) with respect to pure electromagnetic interaction, resulting in an energy shift of the X-ray transition. Due to absorption this level is also broadened, resulting in an abnormal width of the X-ray line. Moreover, the absorption out of the upper level of the transition leads to an intensity reduction of the X-ray transition compared to the population of the upper level. This population may be measured by summing up the yields of those transitions populating the upper level. Absolute yield measurements of the attenuated line must rely on cascade calculations in order to obtain the population of the upper level.

Strong interaction effects were observed in \( \pi^- \), \( K^- \), \( \bar{p} \), and \( \Sigma^- \) atoms (cf. H. Koch\(^{25}\) and references quoted there).

**Pionic atoms**

Since the review article of Backenstoss\(^{26}\) on pionic atoms, new data on shifts and widths have been obtained\(^{27}\) (Table I). The progress in precision, especially on the \( 1s \) data of light elements, is considerable. In particular, the measurement on \( \pi^- {^3}\text{He} \) turned out to be of fundamental interest. For the theory of pionic atoms I want to refer to a recent review article of Hufner\(^{28}\) and the references quoted there.

The interpretation of pionic atom data is usually done via an optical \( \pi^- \) nucleus potential\(^{24}\).


\[-2\mu V(r) = 4\pi \left\{ p_1 (a_p \rho_p + a_n \rho_n) + p_2 B_0 (\rho_n + \rho_p)^2 \right\} + \text{Pauli correlation corrections} + \text{terms of order } 1/A + \nabla \frac{\alpha(r)}{1 + (4\pi/3) \xi \alpha(r)} \nabla \right\}

with \( \alpha(r) = q_1 (c_p \rho_p + c_n \rho_n) + q_2 C_\alpha (\rho_n + \rho_p)^2 \), and \( \rho_n, \rho_p \) the neutron and proton densities, respectively. \( n_1, q_1, p_2, q_2 \) are kinematical factors. The constants \( a_n, a_p, c_n \), and \( c_p \) are the elementary \( \pi^- \) nucleon scattering lengths for the \( s^- \) and the \( p^- \)-wave, respectively. They are\(^{10}\)

\[
\begin{align*}
    a_n &= -0.092 \text{ m}^{-1} \\
    a_p &= +0.083 \text{ m}^{-1} \\
    c_n &= 0.385 \text{ m}^{-3} \\
    c_p &= 0.037 \text{ m}^{-3}.
\end{align*}
\]

The constants \( B_0, C_\alpha \) represent the \( \pi^- 2N \) interaction, especially the absorption.

**Table I: Strong interaction data for pionic atoms after 1970**

<table>
<thead>
<tr>
<th>Level</th>
<th>Element</th>
<th>Ref.</th>
<th>( E ) (eV)</th>
<th>( \Gamma ) (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1s</td>
<td>d</td>
<td>27a</td>
<td>(-4.6 \pm 1.6)</td>
<td>-</td>
</tr>
<tr>
<td>1s</td>
<td>(^3)He</td>
<td>27b</td>
<td>(-54 \pm 20)</td>
<td>110 (\pm 120)</td>
</tr>
<tr>
<td>1s</td>
<td>(^4)He</td>
<td>27c</td>
<td>(-76 \pm 2)</td>
<td>45 (\pm 3)</td>
</tr>
<tr>
<td>1s</td>
<td>(^6)Li</td>
<td>27d</td>
<td>(-324 \pm 3)</td>
<td>195 (\pm 12)</td>
</tr>
<tr>
<td>1s</td>
<td>(^7)Li</td>
<td>27d</td>
<td>(-570 \pm 4)</td>
<td>195 (\pm 13)</td>
</tr>
<tr>
<td>1s</td>
<td>(^9)Be</td>
<td>27d</td>
<td>(-1395 \pm 9)</td>
<td>591 (\pm 14)</td>
</tr>
<tr>
<td>1s</td>
<td>(^{20})Ne</td>
<td>27e</td>
<td>(-33340 \pm 500)</td>
<td>14500 (\pm 3000)</td>
</tr>
<tr>
<td>2p</td>
<td>(^4)He</td>
<td>27c</td>
<td>-</td>
<td>((7.2 \pm 3.3) \times 10^{-4})</td>
</tr>
<tr>
<td>2p</td>
<td>(^{16})O</td>
<td>27f</td>
<td>(4.1 \pm 2.3)</td>
<td>11 (\pm 6)</td>
</tr>
<tr>
<td>2p</td>
<td>Al</td>
<td>27g</td>
<td>(212 \pm 23)</td>
<td>-</td>
</tr>
<tr>
<td>2p</td>
<td>P</td>
<td>27h</td>
<td>(366 \pm 31)</td>
<td>-</td>
</tr>
<tr>
<td>2p</td>
<td>A</td>
<td>27i</td>
<td>(825 \pm 100)</td>
<td>1170 (\pm 170)</td>
</tr>
<tr>
<td>3d</td>
<td>Ba</td>
<td>27j</td>
<td>(5440 \pm 270)</td>
<td>4300 (\pm 900)</td>
</tr>
<tr>
<td>3d</td>
<td>(^{14})Ce</td>
<td>27i</td>
<td>(7030 \pm 290)</td>
<td>5600 (\pm 1000)</td>
</tr>
<tr>
<td>3d</td>
<td>(^{18})Ce</td>
<td>27i</td>
<td>(7210 \pm 330)</td>
<td>6500 (\pm 900)</td>
</tr>
<tr>
<td>4f</td>
<td>Ho</td>
<td>36</td>
<td>(350 \pm 80)</td>
<td>210 (\pm 40)</td>
</tr>
<tr>
<td>4f</td>
<td>Lu</td>
<td>36</td>
<td>(670 \pm 70)</td>
<td>230 (\pm 70)</td>
</tr>
</tbody>
</table>
Due to the cancellation of $\pi^-n$ and $\pi^-p$ contributions in the elastic $s$-wave interaction, the dominating contribution comes from the Pauli correlation corrections. This is, in fact, confirmed by the experiment, and it is interpreted as proof for the granular structure of nuclear matter. The elastic $p$-wave interaction is dominated by the $\pi^-n$ interaction as $c_p = 10^2 c_n$. This would allow, in principle, for testing neutron distributions. The potential suffers, however, from the fact that the $\pi^-2n$ interaction is not known, i.e., $B_0$ and $C_0$ are free parameters. In addition, it is still being discussed whether the Lorentz-Lorenz effect in the $p$-wave is present, and if it is, of which weight it should be, i.e., $\xi$ is also a free parameter. The five parameters could be fitted to reproduce the experimental data sufficiently. For very light nuclei and for isotope effects, however, the potential fails.

Some progress was made in the interpretation of the $1s$-level data by including $1/A$ terms. Taking $a_n$ and $a_p$ as given and accepting the Fermi gas model to calculate the Pauli corrections, the Re $B_0$ could be determined. It turned out that it is repulsive and of the same magnitude as Im $B_0$:

$$\text{Re } B_0 = -\text{Im } B_0.$$  

The $s$-level data have also revealed the interesting feature that the $\pi^-$-nucleus scattering lengths, as obtained from pionic atoms, are proportional to $A$. This is shown in Fig. 5. Further, the $\pi^-^{12}$C, $\pi^-^{16}$O, and $\pi^-^{20}$Ne scattering lengths are just 3, 4, and 5 times the measured $\pi^-\alpha$ scattering length:

$$\frac{d\sigma_{\pi A}}{d\Omega} \propto n_{\pi A}^{\alpha}.$$  

![Fig. 5](image)

The experimental $\pi^-$-nucleus scattering length $a_{\pi A}$ as obtained from pionic atom data (Ref. 35) as a function of $A$ (figure taken from Ref. 28).
Apparently the π⁻α interaction, elastic and absorptive, contains already most of the complications of the π⁻ nucleus interaction in general, at least as far as s-wave interaction is concerned.

Recently, measurements were reported from SIN\textsuperscript{36} and Rutherford\textsuperscript{37}, where the pionic 5-4 transition in Ho, Lu, and Ta was measured, and whose outcome was the spectroscopic quadrupole moment of these nuclei.

According to Scheck\textsuperscript{38}, the strong interaction shifts and widths of the members of a hyperfine multiplet are composed of a monopole and a quadrupole contribution:

\[
\begin{align*}
\varepsilon &= \varepsilon_0 + \varepsilon_2 \cdot C(j, \lambda, m) \\
\Gamma &= \Gamma_0 + \Gamma_2 \cdot C(j, \lambda, m)
\end{align*}
\]

with \( C(j, \lambda, m) \) an angular momentum factor. \( \varepsilon_2 \) and \( \Gamma_2 \) are related to the quadrupole distribution \( \rho_2 \) by

\[
\frac{\varepsilon_2}{\varepsilon_0} \sim \frac{\Gamma_2}{\Gamma_0} \sim \frac{\int \rho_2 r^2 \phi^2 dr}{\int \rho_0 r^2 \phi^2 dr}.
\]

This is claimed to be almost model independent, as far as strong interaction is concerned. As the above experiments had to include \( \varepsilon_2 \) and \( \Gamma_2 \) in their analysis in order to get agreement with the \( Q \) values from \( \mu \) atoms\textsuperscript{39}, they have, although not explicitly, determined \( \varepsilon_2 \) and \( \Gamma_2 \). This means they may be evaluated in terms of nuclear matter deformations. Moreover, since \( c_n = 10 \cdot c_p \), a determination of \( \varepsilon_2 \) directly determines a certain higher moment of the neutron's quadrupole distribution.

Kaonic atoms

Recently an impressive survey of kaonic X-ray lines in elements from \( Z = 2 \) up to \( Z = 92 \) was published by Wiegand and Godfrey\textsuperscript{40}. They measured essentially absolute yields. Pronounced variations of the yield of a given transition between circular orbits with \( Z \) are observed (Fig. 6). Intensity valleys are at \( Z \sim 28, \sim 38, \sim 60, \) and \( \sim 75 \). Condo pointed out that the lattice distances show a similar periodicity\textsuperscript{41}. Apparently, absolute yields depend very much on the capture process and the related initial populations of \((n,\lambda)\)-states.

Reliable information on details of the cascade are best obtained from measurements of relative yields of transitions with \( \Delta n \geq 1 \). A variety of such data has been published\textsuperscript{22,27g,26a,b}. A list of the most recent strong interaction effects in kaonic atoms is given in Table II.

The interpretation of these data in terms of an optical potential

\[
-2\mu V(r) = 4\pi p[a_p \rho_p + a_n \rho_n]
\]

is complicated, due to the strong K⁻ absorption, and due to the fact that the free scattering length approach \((a_n, a_p \text{ free K⁻N scattering})\)
Fig. 6 Absolute intensities of several X-ray transitions (10-9, 9-8, 8-7, etc.) as a function of $Z$ as measured in Ref. 40.
Table II: Summary of recent strong interaction data in kaonic atoms
(shift calculated with $m_K^- = 493.691$ MeV)

<table>
<thead>
<tr>
<th>Element</th>
<th>Transition</th>
<th>$\Gamma_{\text{low}}$ (eV)</th>
<th>$\Gamma_{\text{up}}$ (eV)</th>
<th>$C$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{18}\text{B}$ a)</td>
<td>3-2</td>
<td>$810 \pm 100$</td>
<td>-</td>
<td>$-200 \pm 35$</td>
</tr>
<tr>
<td>$^{11}\text{B}$ a)</td>
<td>3-2</td>
<td>$700 \pm 80$</td>
<td>-</td>
<td>$-160 \pm 35$</td>
</tr>
<tr>
<td>$^{17}\text{C}$ a)</td>
<td>3-2</td>
<td>$1730 \pm 150$</td>
<td>$0.98 \pm 0.19$</td>
<td>$-575 \pm 80$</td>
</tr>
<tr>
<td>Al b)</td>
<td>4-3</td>
<td>$490 \pm 160$</td>
<td>-</td>
<td>$-123 \pm 50$</td>
</tr>
<tr>
<td>Si b)</td>
<td>4-3</td>
<td>$810 \pm 120$</td>
<td>-</td>
<td>$-223 \pm 50$</td>
</tr>
<tr>
<td>P a)</td>
<td>4-3</td>
<td>$1440 \pm 120$</td>
<td>$1.94 \pm 0.33$</td>
<td>$-315 \pm 80$</td>
</tr>
<tr>
<td>S a-d)</td>
<td>4-3</td>
<td>$2370 \pm 120$ a)</td>
<td>$3.25 \pm 0.41$ a)</td>
<td>$-460 \pm 50$ e)</td>
</tr>
<tr>
<td>Cl a-d)</td>
<td>4-3</td>
<td>$2850 \pm 240$ a)</td>
<td>$5.7 \pm 1.5$ a)</td>
<td>$-990 \pm 190$ a)</td>
</tr>
<tr>
<td>Co c)</td>
<td>5-4</td>
<td>$680 \pm 290$</td>
<td>-</td>
<td>$-460 \pm 100$</td>
</tr>
<tr>
<td>Ni b,c)</td>
<td>5-4</td>
<td>$1020 \pm 120$ e)</td>
<td>$6.0 \pm 2.3$ b)</td>
<td>$-190 \pm 60$ e)</td>
</tr>
<tr>
<td>Cu b)</td>
<td>5-4</td>
<td>$1650 \pm 750$</td>
<td>$7.1 \pm 3.8$</td>
<td>$-215 \pm 220$</td>
</tr>
<tr>
<td>Ag c)</td>
<td>6-5</td>
<td>$2850 \pm 1500$</td>
<td>-</td>
<td>$-595 \pm 300$</td>
</tr>
<tr>
<td>Cd c)</td>
<td>6-5</td>
<td>$2100 \pm 1300$</td>
<td>-</td>
<td>$-210 \pm 100$</td>
</tr>
<tr>
<td>In c)</td>
<td>6-5</td>
<td>$2340 \pm 1200$</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

a) CERN, Ref. 42a.
b) BNL, Ref. 42b.
c) Rutherford, preliminary data, Ref. 42c.
d) Berkeley, Ref. 40.
e) Averaged.

length) does not apply, partly because of the $Y_0^*$ quasi-bound state just below threshold. Several approaches were made to describe the kaonic atom data:

- The parameters $a_n, a_p$ were treated as phenomenological free parameters to fit to the data$^{42a,b,43}$. The fits are reasonable. However, the relation of $a_n$ and $a_p$ with the elementary $K^N$ interaction is lost, and the form of the potential is not justified.

- The effective free on-shell $T$-matrix below threshold was calculated by averaging the $K^N$ amplitudes over the available $K^N$ relative energies$^{44}$. This approach fits the data reasonably.

- Refinements consider off-shell effects, resonance propagation, 2N correlations, etc.$^{45}$. The derived potentials do not fit the data much better than the previous methods. However, the potential becomes non-local, and local approximations do not follow the matter distributions.

- The data may also be reproduced by assuming separable $K^N$ potentials, folded with the nuclear matter distribution$^{46}$. The range of the $K^N$ force is obtained from $K^-\text{He}$ scattering, and the potential depth from the elementary $K^N$ scattering lengths. The result is surprisingly good, since apart from the nuclear matter distribution, no nuclear physics is necessary as input.
Several sets of the parameters $a_n$ and $a_p$ are given in Table III.

I should point out that none of the potentials derived so far fits the lower level shift and width and the upper level width without manipulating the individual surface parameters of the matter distribution.$^7$

Table III: Free and effective $K^-$-nucleon coupling constants (fm)

<table>
<thead>
<tr>
<th>Reference</th>
<th>$\text{Re } a_n$</th>
<th>$\text{Im } a_n$</th>
<th>$\text{Re } a_p$</th>
<th>$\text{Im } a_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free a)</td>
<td>-0.07</td>
<td>0.62</td>
<td>-0.90</td>
<td>0.66</td>
</tr>
<tr>
<td>Bardeen b)</td>
<td>+0.13</td>
<td>0.40</td>
<td>1.00</td>
<td>1.60</td>
</tr>
<tr>
<td>Egger c)</td>
<td>+0.13</td>
<td>0.40</td>
<td>0.99</td>
<td>0.98</td>
</tr>
</tbody>
</table>

a) Ref. 48
b) Ref. 44
c) Ref. 27g.

We are left with a bunch of experimental and theoretical problems:
- The $K^-N$ scattering matrix has nine parameters, not known well enough to make unambiguous extrapolations.$^8$
- The $K^-N$ scattering lengths are not measured yet. Experiments to study the kaonic hydrogen are going on at CERN and Rutherford.
- The $Y_0^*$ in nuclear matter should be treated more carefully, and correct kinematics and off-shell propagation must be included.
- Correlation effects (terms $\propto \rho^2$) must be accounted for.
- The $p$-wave interaction and a possible Lorentz-Lorenz effect in the kaon-nucleus interaction has to be considered.$^9$
- The question of how far $Y_1^*$ contributes to the $p$-wave interaction must be solved$^{10}$.

$p$ atoms

The amount of $\bar{p}$ atomic data has not increased very much since 1973$^{25}$. Measurements on several elements are on the way to being published$^{54}$. I want to discuss here those measurements done at CERN recently, namely, $\bar{p}^3\text{He}$, $^{16}O$, $^{18}O$, and $^{32}S$. The nuclear shapes of all four elements are known, also for neutrons. Figure 7 shows the $\bar{p}^3\text{He}$ spectrum. The series 3-2, 4-2 up to the series limit is measured with high resolution. The outstanding feature, however, is the observation of the 4-3, 5-3, and 6-3 transitions, without any efficiency loss. The energy of the 4-3 transition is as low as 3.8 keV. The analysis of this measurement is not yet completed, but the width of the 3d level is expected.

For the first time a clear isotope effect was observed for $\bar{p}$ atoms in the case of $^{16}O/^{18}O$. Figure 8 shows the two spectra. The effect of the two additional neutrons in $^{18}O$ is clearly seen: the 4-3 transition in $^{16}O$ is weaker and broader than in $^{18}O$. The cascade shows particular enhancement of cross-over transitions, as
the series 5-4, 6-5 up to 10-4 is observed. Since the measurement was done in water, transfer from hydrogen to oxygen may be the reason. The data are still preliminary and incomplete:

<table>
<thead>
<tr>
<th></th>
<th>$^{16}O$</th>
<th>$^{18}O$</th>
<th>$^{18}O - ^{16}O$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_{4f}$</td>
<td>$0.67 \pm 0.15$</td>
<td>$0.90 \pm 0.18$</td>
<td>$0.23 \pm 0.15$</td>
</tr>
<tr>
<td>$\epsilon_{3d}$</td>
<td>$-120 \pm 40$</td>
<td>$-180 \pm 50$</td>
<td>$60 \pm 50$</td>
</tr>
</tbody>
</table>
Fig. 8 The $\bar{p}^{16}O/^{18}O$ spectra from the CERN measurement (Ref. 52).
I want to discuss these data in a demonstrative but not precise way. The complex energy shift is given by

\[ E = a_\Omega p p + a_\Omega n n, \]

where \( \Omega_p, \Omega_n \) are the overlaps of the unperturbed \( \bar{p} \) wave function with the protons and neutrons, respectively. The matter distributions are supposed to be known\(^{53}\), and we obtain

\[ \Omega_p^{(16}O) = \Omega_p^{(18}O) \]
\[ \Omega_p^{(16}O) = \Omega_n^{(16}O) \]
\[ \Omega_n^{(16}O) = \frac{1}{2} \Omega_n^{(18}O). \]

The isotope effect therefore is entirely due to the neutrons:

\[ \Delta E^{(18}O - 16}O = E^{(18}O) - E^{(16}O) = a_\Omega n n^{(16}O). \]

With the numbers above, we obtain

\[ \text{Re } a_n / \text{Re } a_p = 1.0 \pm 0.7 \]
\[ \text{Im } a_n / \text{Im } a_p = 0.6 \pm 0.4. \]

These numbers should not be taken literally, as I wanted to show only along which lines such data may be analysed.

The third measurement of the CERN group was done with \( \bar{p}^{32}S \). The results are

\[ \varepsilon_{4f} = -41 \pm 44 \text{ eV} \]
\[ \Gamma_{4f} = 760 \pm 110 \text{ eV} \]
\[ \gamma_{5-4}^{\text{rel}} = (20 \pm 3) \% \].

Sulphur is a particularly interesting nucleus, since its charge distribution is extremely well known\(^{53}\). As the number of protons is equal to the number of neutrons, the neutron distribution may be obtained with high reliability\(^{53}\). Finally, sulphur is the only nucleus where rather precise data exist now for \( \pi^- \), \( K^- \), and \( \bar{p} \), and therefore strong constraints are set on the interpretation of the data.

The discussion of \( \bar{p}N \) resonances below threshold have shed new light on the \( \bar{p} \) atoms\(^{54}\). The simple free scattering length approach does not work with \( \bar{p} \) atoms either\(^{55}\), which is not too surprising as the interaction is so strong. However, a quantitative understanding of the \( \bar{p} \) atomic data, at present not even yet tried, must include such resonances, if they exist.
CONCLUSIONS

The hadron-nucleus interaction is not yet understood quantitatively, in particular the $K^-$ and $\bar{p}$ atom data are difficult to interpret. The strategy I propose (and which is supported by the experimental program of the CERN group) is to study the hadron-nucleus interaction on light nuclei. The nuclear wave functions are known; no, or only minor, uncertainties arise from the nuclear matter distributions, and the overlaps of the hadron with the nuclear matter have low moments (low $\ell$ values) resulting in only little sensitivity on the extreme nuclear surface. Once the light nuclei are understood, the heavier ones might then yield some of the information I mentioned at the beginning of my paper. From the experimentalist this would require more accurate data on light elements, for pions especially on the 2$p$ level. Accurate isotope effects are necessary to study the differences in the hadron proton-hadron neutron interaction and the Lorentz-Lorenz effect. The hadronic hydrogen system has to be studied carefully to obtain the elementary hadron-nucleon interaction strength. The more intense beams available now may allow for measuring more than only three quantities ($T_{up}^1, T_{low}^1, \epsilon_{low}^1$) per nucleus, by looking at parallel transitions or by making use of the E2 mixing technique as discussed by Leon. Finally, it might become possible to measure the X-rays in coincidence with outgoing particles.

REFERENCES

7. L. Ponomarev, Mesosatomic processes in light atoms, invited paper to this conference.
9. P. Ebersold, B. Aas, W. Dey, R. Eichler, H.J. Leisi, W.W. Sapp and H.K. Walter, Observation of nuclear rotational spectra in pion capture on $^{172}$Lu and $^{165}$Ho, contributed paper to this conference.
    E. Borie, Corrections of order α²(αZ)² to energy levels of muonic atoms, SIN preprint, 1975.
    M.K. Sundaresan and P.J.S. Watson, contributed paper to this conference.
17. G. Dugan, Y. Asano, M.Y. Chen, S. Cheng, E. Hu, L. Lidofsky, W. Patton, C.S. Wu, V. Hughes and D. Lu, Fundamental properties of \( K^- \), \( \bar{\nu} \), and \( \bar{\mu} \) from exotic atoms, contributed paper to this conference.
33. G. Baym and G.E. Brown, The Lorentz-Lorenz correction in pionic atoms and pion condensates, contributed paper to this conference.
53. I. Sick, private communication.
54. T. Kalogeropoulos, Nucleon-antinucleon system, invited paper at this conference.
    L.N. Bogdanova, O.D. Dalkarov, B.O. Kerbikov and I.S. Shapiro, Narrow resonances, preprint ITEP-27, Moscow, 1975