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ANOMALOUS STRONG INTERACTION SHIFTS AND WIDTHS
OF THE 3d STATE IN PIONIC Pt AND Au

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The pionic 4f → 3d X-ray transitions in Pt and Au have been observed. The strong interaction monopole shifts $e_0$ and
widths $\Gamma_0$ of the 4f and 3d levels have been deduced. For the pionic 4f levels standard optical potentials predict the experi-
mental values quite well, whereas the deeper bound 3d states have shifts and widths that are smaller by a factor of about
two than the theoretical predictions.

To learn more about the strong pion–nucleus inter-
action and to get a better understanding of the pionic
optical potential, pion absorption from deeply bound
states in pionic atoms has been studied for many
years. The strong interaction effects of several levels
in the same nucleus, but with different principal and
orbital quantum numbers $n$ and $l$ are of particular in-
terest to study the density dependence of the pion–
nucleus interaction. Such studies [1–5] have e.g.
been carried out for pionic Ta, Re and Bi. Measured
were the strong interaction shifts, $e_0$, and widths,
$\Gamma_0$, of the 4f level, a more peripheral state, and also
the shifts and widths of the more deeply bound 3d
orbit. While the standard optical potentials were able
to explain the observed $e_0(4f)$ and $\Gamma_0(4f)$, they failed
to describe the shifts and widths of the 3d level. The
observed $e_0(3d)$ and $\Gamma_0(3d)$ are typically about a
factor two smaller than predicted. A similar observation
has been made for the absorption widths of
other deeply bound pionic–atom states: the 3p orbit
[6] in $^{110}$Pd, the 2p orbit [7] in $^{75}$As and the 1s
orbit [8] in $^{23}$Na. For these cases the absorption
widths have been reported to be narrower by a factor
of about 1.5 as compared to the theoretical predictions.

Several authors [3,9,11–14] have suggested expla-
nations for the anomalous shifts. The strong interac-
tion level shift is due to an interplay between the
attractive P-wave and the repulsive S-wave interaction
terms in the optical potential [3]. Therefore, a small
change in the large absolute value of one of the terms
contributing to the energy shift, can have a large effect
on the values of $e_0$.

For the strong interaction absorption width the S-
and P-wave contributions to the absorption width are
additive. Therefore, the anomalous widths are more
difficult to explain. It seems that one has to go out-
side the framework of the existing optical potential
models to describe the $\pi$–nucleus interaction for these
low-lying levels.

Clearly, these surprising results must be further
studied and we therefore have measured the X-ray
transitions to deep lying orbits in pionic Pt and Au.
These target nuclei are almost spherical, which simpli-
fies the analysis of the spectra. The present measure-
ments are the first experimental results from the new
pion–muon facility of NIKHEF at Amsterdam.

The strong interaction effects grow rapidly from
one level to the next lower one, leading to a fast
decrease in intensity of X rays for subsequent transitions.
Therefore, once the influence of the strong interaction

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\[ (\text{North-Holland Physics Publishing Division}) \]
Fig. 1. The full X-ray spectra (recorded in 8122-channel ADC's) of pionic Pt and Au after a cut has been applied on the prompt part of the time distribution. The spectra are as a consequence of the time window in the time-of-flight spectra essentially free from the neutron-induced gamma-ray background. The energy scale was 0.25 keV/channel. The insert displays part of the prompt X-ray Au spectrum, showing the 4f → 3d pionic hyperfine complex at 1185 keV. The solid lines represent the fits to the data points. The fitted background used in the analysis (dashed curve) was obtained by fitting large energy intervals below and above the X-ray transition. The 9g → 4f, 10g → 4f pionic and the 1158 keV γ-ray were included in the fit.
on an X-ray transition is large enough to be directly observable, as is the case for the pionic \(5g \rightarrow 4f\) transitions in Pt and Au, the subsequent transition will be much broader and weaker. This is one reason why the \(4f \rightarrow 3d\) transition for Pt and Au has not been observed earlier. One also suffers here from a large background induced by neutrons in the Ge detectors. The Ge isotopes have nuclear levels in the energy region of interest. This will cause complications since Ge levels will be excited by inelastic scattering of neutrons emitted after pion absorption in the target. Therefore, in this experiment a new and powerful combination of two techniques has been used. One is Compton suppression to reduce Comptons from high energy \(\gamma\)-ray background and the other a time-of-flight method to discriminate between pionic X-ray transitions and background induced by neutrons from the target.

The experiments were performed at the pion channel with 140 MeV/c pions, which were stopped in platinum and gold targets with thicknesses of 4.29 and 3.86 g/cm\(^2\), respectively. The pionic X rays were detected by two large-volume n-type germanium detectors each surrounded by a Compton suppression shield.

In fig. 1 the full X-ray spectra of Pt and Au are shown, while the insert displays the relevant part of the spectra for the \(4f \rightarrow 3d\) pionic Au X rays, after a cut has been applied on the prompt part of the time distribution. These spectra are essentially free from neutron-induced background.

From the measured spectra we obtained energies and relative X-ray intensities of the pionic transitions (see table 1). The relative X-ray intensities have been corrected for self-absorption in the target. The angular dependence of the target thickness is negligible due to the small solid angle subtended by the Ge detectors.

The strong interaction widths of the \(4f\) and \(3d\) levels (see table 2) were extracted from the spectra by using a lorentzian line shape folded with the response function of the Ge detector, as described in ref. [5]. This instrumental response function is especially important when analyzing the \(5g \rightarrow 4f\) X-ray transition. Since for these transitions the lorentzian line width is of the same order of magnitude. In the case of the broad \(4f \rightarrow 3d\) transitions the lorentzian width is an order of magnitude larger than the instrumental one. The background used when analyzing the \(4f \rightarrow 3d\) tran-

### Table 1
Transitions in pionic Pt and Au populating and depopulating the pionic 4f level.

<table>
<thead>
<tr>
<th>Transition</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4f (\rightarrow 3d)</td>
<td>1159.3 ± 1.7</td>
<td>1130.89</td>
<td>28.4 ± 1.7</td>
<td>17.0 ± 0.8</td>
</tr>
<tr>
<td>5g (\rightarrow 4f)</td>
<td>519.37 ± 0.04</td>
<td>518.26</td>
<td>1.11 ± 0.04</td>
<td>100. ± 7</td>
</tr>
<tr>
<td>6g (\rightarrow 4f)</td>
<td>797.37 ± 0.08</td>
<td>796.32</td>
<td>1.05 ± 0.08</td>
<td>9.3 ± 0.5</td>
</tr>
<tr>
<td>7g (\rightarrow 4f)</td>
<td>964.48 ± 0.8</td>
<td>964.15</td>
<td>0.3 ± 0.8</td>
<td>4.1 ± 0.3</td>
</tr>
<tr>
<td>8g (\rightarrow 4f)</td>
<td>1072.2 ± 1.5</td>
<td>1073.10</td>
<td>0.8 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>9g (\rightarrow 4f)</td>
<td>1148.1 ± 1.5</td>
<td>1147.79</td>
<td>0.6 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>10g (\rightarrow 4f)</td>
<td>1201.20</td>
<td>1200.70</td>
<td>0.4 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>11g (\rightarrow 4f)</td>
<td>1240.70</td>
<td>1240.70</td>
<td>0.08 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>12g (\rightarrow 4f)</td>
<td>1270.73</td>
<td>1270.73</td>
<td>0.06 ± 0.2</td>
<td></td>
</tr>
</tbody>
</table>

Table 1

<table>
<thead>
<tr>
<th>Transition</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4f (\rightarrow 3d)</td>
<td>1185.8 ± 1.4</td>
<td>1160.54</td>
<td>25.3 ± 1.4</td>
<td>14.4 ± 1.0</td>
</tr>
<tr>
<td>5g (\rightarrow 4f)</td>
<td>533.18±0.07</td>
<td>532.9</td>
<td>33.18 ± 0.07</td>
<td>100. ± 7</td>
</tr>
<tr>
<td>6g (\rightarrow 4f)</td>
<td>818.40±0.09</td>
<td>818.1</td>
<td>43.40 ± 0.09</td>
<td>10.9 ± 1.1</td>
</tr>
<tr>
<td>7g (\rightarrow 4f)</td>
<td>990.39±0.15</td>
<td>989.04</td>
<td>33.39 ± 0.15</td>
<td>3.5 ± 0.4</td>
</tr>
<tr>
<td>8g (\rightarrow 4f)</td>
<td>1102.1 ± 0.5</td>
<td>1100.63</td>
<td>1.5 ± 0.5</td>
<td>1.3 ± 0.2</td>
</tr>
<tr>
<td>9g (\rightarrow 4f)</td>
<td>1178.6 ± 0.8</td>
<td>1177.06</td>
<td>1.5 ± 0.8</td>
<td>0.4 ± 0.2</td>
</tr>
<tr>
<td>10g (\rightarrow 4f)</td>
<td>1233.1 ± 2.6</td>
<td>1232.52</td>
<td>0.08 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>11g (\rightarrow 4f)</td>
<td>1273.05</td>
<td>1273.05</td>
<td>0.08 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>12g (\rightarrow 4f)</td>
<td>1303.86</td>
<td>1303.86</td>
<td>0.06 ± 0.02</td>
<td></td>
</tr>
</tbody>
</table>

a) Present work.
b) Reference [10].
c) These electromagnetic transition energies include finite size effects, vacuum polarization, Lamb shift and electron screening. A Fermi distribution for the nuclear density was assumed with \(c=6.35\) fm, \(\rho=2.3\) fm.
d) Calculated with a cascade program.
results in Pt and Au was obtained by fitting an exponential function over larger energy intervals below and above (up to 2 MeV) the transition energy. This background was then used in the fits of the X-ray transition. As it also determines the intensity of the 4f → 3d X-ray, the background is a crucial check of the intensity balance for the 4f level. As is indicated in the insert of fig. 1 we simultaneously fitted the 9g → 4f, 10g → 4f pionic X rays, and the 1158 keV γ-ray, which coincide with the chosen energy interval for the fit.

From the relative intensities of the pionic X rays, the feeding of the 4f level can be determined. The yield of the 4f → 3d transition depopulating the 4f level can be used to determine its strong interaction width Γ0(4f). From the experimental X-ray intensities and the electromagnetic radiative widths Γrad(4f) = 119.8 eV (Pt) and 126.5 eV (Au) the strong interaction widths Γ0(4f) = 0.69 ± 0.10 keV and 0.89 ± 0.13 keV were obtained for pionic Pt and Au, respectively. The values compare well with the theoretical values and the directly measured values given in table 2. This result indicates that the background subtraction is correct. The systematic error, contributing to the uncertainty in the analyzed experimental Lorentz widths of the 3d levels in Pt and Au, is estimated to be 2 keV, about half the statistical error given in table 2.

For the Au data the 5g → 4f and the 4f → 3d transitions were fitted with and without hyperfine components to determine its influence on the analysis. Due to the small quadrupole moment of $^{197}$Au ($Q = 0.59$) and the low spin value of the nuclear ground state, the hyperfine splitting in the 4f → 3d transition is of the order of 2.8 keV, about half the experimental uncertainty in the fitted value for the strong interaction width Γ0.

By subtracting from the fitted values the radiative widths of the initial and final levels, we arrive at the values presented in table 2. In the case of Γ0(3d) one has to correct for Γ0(4f) in the experimental line width as well. The experimental shifts of the levels due to the strong interaction are also shown in table 2. They are obtained from the strong interaction shift of the transition energies in table 1 by correcting for the strong interaction shift of the upper level. Since several nl

\[ \rightarrow 4f \) transitions have been observed, a weighted average of the experimental strong interaction shifts e0(4f) is given. Also shown in table 2 are the predictions of three commonly used optical potentials for the strong interaction effects e0 and Γ0. The shift due to the Coulomb finite size effect is shown separately. While there is some variation, all three models essentially agree on the observed e0 and Γ0 for the 4f state. How-

### Table 2

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>e0 (keV)</th>
<th>shift due to finite size of the nucleus</th>
<th>Γ0 (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>experiment</td>
<td>theory a) parameter set</td>
<td>from intensity balance</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>II</td>
<td>III</td>
</tr>
<tr>
<td>pionic 4f level</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pt</td>
<td>1.10 ± 0.04</td>
<td>1.04</td>
<td>1.12</td>
</tr>
<tr>
<td>Au</td>
<td>1.39 ± 0.07</td>
<td>1.16</td>
<td>1.43</td>
</tr>
<tr>
<td>pionic 3d level</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pt</td>
<td>29.5 ± 1.7</td>
<td>35.8</td>
<td>44.2</td>
</tr>
<tr>
<td>Au</td>
<td>26.7 ± 1.4</td>
<td>37.3</td>
<td>46.3</td>
</tr>
</tbody>
</table>

a) Parameter used in reference [3].
ever, the observed strong interaction width, $\Gamma_0(3d)$, is again much smaller than predicted by any of the models. Therefore, the same anomaly which was observed in Ta, Re and Bi is also found for the deeply bound pionic 3d state in Pt and Au. The shift is also not well predicted by the optical potential models, but the disagreement is not quite as large as for the width.

As mentioned above, there are explanations for the shift $e_0(3d)$. The modified optical potential by Ericson and Tauscher [9] for example yields a shift $e_0(3d)$ for Au that is about 10% larger than the experimental value. The addition of an energy-dependent term to the S-wave parameter $b_0$ of the optical potential as discussed by these authors effectively shifts some strengths of the attractive P-wave part to the repulsive S-wave part in the conventional potential. Another way to explain the small observed shifts has been suggested by Seki [13] and Kunselman et al. [14]. These authors point out that by using a neutron density distribution that is more extended than the proton distribution one can explain the shifts $e_0(3d)$ and $e_0(4f)$. We find that an increase of the neutron half-density radius, $c_n$, by 0.6 fm yields an agreement with our measurements. No theory, however, can explain the observed anomalous widths $\Gamma_0(3d)$. An increase of the neutron half-density radius as suggested in refs. [13,14] has very little effect on $\Gamma_0(3d)$; one would need an unrealistically large $c_n - c_p$ of 2 fm to obtain agreement with the measured $\Gamma_0(3d)$.

We find that the strong interaction width, and to some extent also the shift, of the deeply bound 3d level is anomalously small. This confirms similar effects observed in other deeply bound states of pionic Na, As, Pd, Ta, Re and Bi. While there are some theoretical explanations for the small observed shifts, no attempt to describe the anomalously narrow widths has yet been successful. The absorption widths of the low lying states therefore remain a puzzle.

The authors are grateful to the CERN staff, especially to Dr. B.W. Allardyce and his crew, for putting at our disposal the SC muon channel for trial experiments during the summer of 1982. We also want to acknowledge the valuable contribution of Ir. J.G. Kromme, Interuniversitary Reactor Institute, Delft, in the development of the CAMAC-driver and parts of the real time program. This work is part of the research programme of NIKHEF-K at Amsterdam, made possible by financial support from the Foundation for Fundamental Research on Matter (FOM) and the Netherlands' Organization for the Advancement of Pure Research (ZWO).

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