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STRONG INTERACTION EFFECTS IN PIONIC $^{208}$Pb

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The X-ray spectrum of pionic $^{208}$Pb has been measured. The deduced values of the strong interaction monopole shift with respect to the point Coulomb energy are $\epsilon_0(4f) = 1.49 \pm 0.02$ keV and $\epsilon_0(3d) = 19.4 \pm 1.2$ keV. The observed strong interaction absorption widths of this spherical nucleus are found to be $\Gamma_0(4f) = 1.25 \pm 0.02$ keV and $\Gamma_0(3d) = 47.0 \pm 3.6$ keV. Important in the analysis of the pionic 4f level is the intensity balance for this level, giving an additional check on the measured absorption width of the pionic 4f level. For the more peripheral 4f state the measured strong interaction shifts and widths are well explained by standard optical model calculations. The values for the 3d state, however, are not in agreement with these calculations.

In this paper we report on a measurement on pionic $^{208}$Pb, in which the strong interaction shifts $\epsilon_0$ and widths $\Gamma_0$ of deeply bound states of the pionic atom are being investigated. Recent measurements on pionic Pt and Au [1] have shown that the 3d states of these atoms have absorption widths that are smaller than the results from standard optical model calculations by a factor of 1.5. Preliminary data on pionic $^{208}$Pb from a TRIUMF group [2] have been presented at the PANIC conference in Heidelberg. In the interpretation, however, the 3d level width obtained from these data does not necessarily confirm the previously reported anomalously small values. On the other hand, earlier studies [1,3–11] showed similar anomalies in the 3d, 3p, 2p and 1s levels of pionic atoms.

Although the standard optical potentials are able to explain the more peripheral pionic atom states in these nuclei, they fail to describe simultaneously the shifts and widths of the more deeply bound levels. Ericson and Tauscher [12] suggested the possibility of a systematic underestimation of the experimental 3d widths in pionic Ta and Re [3,5,6] as a consequence of these isotopes being strongly deformed nuclei. They assumed that the detailed hyperfine pattern and its
Fig. 1. The X-ray spectrum of pionic $^{208}\text{Pb}$ after selecting the prompt part of the time distribution. The spectrum is essentially free from neutron-induced $\gamma$-ray background, as a consequence of the time window in the time-of-flight spectrum. The main $\pi$X-rays have been indicated in the figure. Most other $\gamma$-rays are nuclear transitions in Tl isotopes occurring after pion capture in the $^{208}\text{Pb}$ nucleus.

distortion could not be correctly dealt with. The present investigation avoids this complication by studying the spherical $^{208}\text{Pb}$ nucleus.

The experiment was performed at the pion beam at SIN, Switzerland. The pion beam was tuned for 100 MeV/c particles. Approximately $10^6 \pi^-$/s were stopped in a $^{208}\text{Pb}$ target [15 g of PbO and 20 g of Pb(NO$_3$)$_2$ enriched to 99% in mass 208]. The experimental set-up and measuring technique, including a BGO Compton suppression spectrometer, were the same as described earlier [1,11], measuring energy and time-of-flight of every event on magnetic tape. This method takes care of any difference in time resolution as a function of $\gamma$-ray energy.

In fig. 1 we show the prompt part of the pionic X-ray spectrum up to 1600 keV. This Compton suppressed spectrum is essentially free from delayed neutron-induced $\gamma$-ray background. Figs. 2a and 2b display details of the same spectrum also on a logarithmic scale, regarding the $5g \rightarrow 4f$ and the $4f \rightarrow 3d$ transitions, respectively. The solid lines represent fits to the data points. Contrary to the analysis of ref. [2], we include in our fits all the transitions in the energy regions of interest. This enables us to reduce considerably systematic errors in the fits, down to 1.4 keV in the $4f \rightarrow 3d$ transition as compared to 4.6 keV in ref. [2]. Our systematic error is mainly caused by the uncertainty in the fitted background (see below).

In table 1 the results of the pionic X-ray intensities and transition energies are presented. The experimental energies and intensities are in rather good agreement with the calculated values, obtained by using the pionic X-ray cascade code STARKEF, which uses the observed transition energies and level widths as input.

In table 2 we present the strong interaction shifts and widths of the $4f$ and $3d$ levels, determined as in earlier work [6,11], from the X-ray spectrum using a lorentzian shape folded with the response function of the Ge-detector. This instrumental response function is of vital importance [1,11] in extracting the lorentz-
Fig. 2. (a), (b) These figures display part of the prompt X-ray $^{208}_{\text{Pb}}$ spectrum, showing the energy regions of the $5g \rightarrow 4f$ and $4f \rightarrow 3d$ X-ray transitions, respectively. The solid lines represent the fits to the data points. The fitted backgrounds also shown in the figures were obtained by fitting large energy intervals below and above the regions of interest. The various $\gamma$-rays also included in the fitting procedure have all been identified as transitions from Tl isotopes in the mass region $A = 200-205$. 

\[ \chi^2 = 1.02 \]
Table 1

Transition energies and relative intensities of pionic X-rays in $^{208}\text{Pb}$ populating and depopulating the pionic 4f level. The calculated energies are the point Coulomb energies with corrections for Lamb shift and vacuum polarization, see text for the shift due to the nuclear finite size.

<table>
<thead>
<tr>
<th>$\pi$X-ray transition</th>
<th>Energies (keV)</th>
<th>$\epsilon_0$ (4f) (keV)</th>
<th>$\Gamma_0$ (4f) (keV)</th>
<th>Relative intensities (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>experiment</td>
<td>calculated</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5g $\rightarrow$ 4f</td>
<td>575.26 ± 0.02</td>
<td>573.77</td>
<td>1.49 ± 0.02</td>
<td>1.25 ± 0.02</td>
</tr>
<tr>
<td>6g $\rightarrow$ 4f</td>
<td>882.51 ± 0.08</td>
<td>881.12</td>
<td>1.39 ± 0.08</td>
<td>1.31 ± 0.08</td>
</tr>
<tr>
<td>7g $\rightarrow$ 4f</td>
<td>1067.98 ± 0.15</td>
<td>1066.57</td>
<td>1.41 ± 0.15</td>
<td>1.2 ± 0.4</td>
</tr>
<tr>
<td>8g $\rightarrow$ 4f</td>
<td>1188.17 ± 0.16</td>
<td>1186.87</td>
<td>1.30 ± 0.16</td>
<td>1.2 ± 0.5</td>
</tr>
<tr>
<td>9g $\rightarrow$ 4f</td>
<td>1270.73 ± 0.13</td>
<td>1269.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10g $\rightarrow$ 4f</td>
<td>1329.53 ± 0.17</td>
<td>1328.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11g $\rightarrow$ 4f</td>
<td>1371.44</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12g $\rightarrow$ 4f</td>
<td>1404.36</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13g $\rightarrow$ 4f</td>
<td>1429.89</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4f $\rightarrow$ 3d</td>
<td>1279.4 ± 1.2</td>
<td>1261.46</td>
<td>9.5 ± 0.5</td>
<td>6.22</td>
</tr>
</tbody>
</table>

The relative intensities (table 1) of the pionic X-rays were obtained in the same way as described in ref. [11] and from the intensity balance of the 4f level an independent strong interaction absorption width for the 4f level was calculated using an electromagnetic radiative width $\Gamma_{\text{rad}}(4f) = 146.1$ eV.

In table 2 the experimental results are compared with standard optical potential calculations [14–16] along with those of Pt, Au from ref. [1] and Pb from ref. [2] the same sets of parameters were used as in ref. [13]. All four models agree reasonably well with the observed $\epsilon_0$ and $\Gamma_0$ values for the 4f level. An anomaly is only observed for the 3d states. The agreement between the present experimental values and those reported in ref. [2] is reasonably good. The comparatively large systematic error reported by this group [2] of 0.05 keV and 1.0 keV for the shifts and 0.08 keV and 4.6 keV for the widths of the 4f and 3d pionic $^{208}\text{Pb}$ levels, respectively, is due to their way of analyzing the data. Moreover, the addition of statistical and systematical errors to obtain a standard deviation as is done in ref. [2] followed by the statement that the experimental values for the 3d levels are only three standard deviations off the theoretical value is incorrect. In our opinion, multiplication of a systematic error by a factor of 3, in this case 4.6 keV for the error in $\Gamma_0(3d)$, is not allowed. We claim, therefore, that also the data of ref. [2] disagree with theory. In the case of the 4f states in Pt, $^{197}\text{Au}$ and $^{208}\text{Pb}$ the ex-
Table 2
Strong interaction monopole shifts $\epsilon_0$ with respect to the calculated point Coulomb energy (see text) and absorption widths $\Gamma_0$ for pionic 4f and 3d levels in Pt, $^{197}$Au (depicted from ref. [1]), and $^{208}$Pb. The listed widths are corrected for radiative widths as well as the absorption widths of the higher level. The same sets of parameters were used as in ref. [13].

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Level</th>
<th>$\Gamma_0$ (keV)</th>
<th>Optical Potential Calculation</th>
<th>$\epsilon_0$ (keV)</th>
<th>Optical Potential Calculation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Experiment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Intensity Balance</td>
<td>Direct</td>
<td>I $^{a)}$ $(\xi = 1)$</td>
<td>II $^{b)}$ $(\xi = 1)$</td>
</tr>
<tr>
<td>Pt</td>
<td>4f</td>
<td>0.69 ± 0.10</td>
<td>0.59 ± 0.05</td>
<td>0.63</td>
<td>0.64</td>
<td>0.74</td>
</tr>
<tr>
<td>$^{197}$Au</td>
<td>4f</td>
<td>0.81 ± 0.13</td>
<td>0.77 ± 0.04</td>
<td>0.72</td>
<td>0.74</td>
<td>0.85</td>
</tr>
<tr>
<td>$^{208}$Pb</td>
<td>4f</td>
<td>1.30 ± 0.03 $^{d)}$</td>
<td>1.09</td>
<td>1.09</td>
<td>1.37</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>3d</td>
<td>1.1 ± 0.2</td>
<td>1.25 ± 0.02</td>
<td>1.09</td>
<td>1.09</td>
<td>1.37</td>
</tr>
<tr>
<td>Pt</td>
<td>3d</td>
<td>37 ± 5</td>
<td>61.5</td>
<td>55.3</td>
<td>73.0</td>
<td>45.1</td>
</tr>
<tr>
<td>$^{197}$Au</td>
<td>3d</td>
<td>34 ± 4</td>
<td>65.6</td>
<td>60.4</td>
<td>80.2</td>
<td>47.7</td>
</tr>
<tr>
<td>$^{208}$Pb</td>
<td>3d</td>
<td>47.4 ± 2.6 $^{d)}$</td>
<td>84.2</td>
<td>73.9</td>
<td>104.4</td>
<td>60.3</td>
</tr>
<tr>
<td>$^{208}$Pb</td>
<td>3d</td>
<td>47.0 ± 3.6</td>
<td>84.2</td>
<td>73.9</td>
<td>104.4</td>
<td>60.3</td>
</tr>
</tbody>
</table>

$^{a)}$ Tauscher [14].
$^{b)}$ Batty et al. [15].
$^{c)}$ Seki and Masutani [16] (the "b-2R" set of parameters).
$^{d)}$ Not including the systematic errors claimed by ref. [2]; these are reported to be 0.05 and 1.0 keV for the shifts and 0.08 and 4.6 keV for the widths of the pionic 4f and 3d levels, respectively.
Experimental values for $e_0(4f)$ and $\Gamma_0(4f)$ as demonstrated in table 2, increase to first order with $Z^{2(2l+3)/3}$ as is expected from theory. These 4f states are still dominated by the velocity-dependent non-local term of the optical potential. On the other hand, the picture is completely different for the 3d states: The shift $e_0(3d)$ steadily decreases with increasing $Z$ value. This indicates that here the repulsive local s-wave part of the optical potential becomes increasingly important. All three experimental values for the absorption widths are a factor of 1.5 smaller than the calculated ones. An attempt is made by Olivier et al. [17] to relate these anomalously small widths to an increase in s-wave repulsion in the optical potential of about 20 MeV in the centre of the nucleus. The result of their calculations are in good agreement with the experimental widths for the 3d levels, but gives worse agreement for the shifts and widths of the pionic 4f orbit. Recently, in the framework of a multi-scattering theory, Karapiperis and Kobayashi [18] have successfully reproduced the observed differential cross section for the pion double charge exchange (DCX) reaction at 50 MeV. In their calculation they also need an extra s-wave repulsion (as is the case in our pionic atom data and which also is present in $\pi$ elastic scattering below 100 MeV) to reproduce the measured DCX cross sections in the optical potential responsible for the pion distortions. Such an interaction seems not to be necessary in the DCX transition operator itself, acting on nucleon pairs of isospin $T = 1$. Their [18] conclusion is that, if the additional repulsion is a dispersive effect of s-wave pion absorption, the latter has to involve predominantly proton–neutron pairs.

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