Decay spectroscopy with RILIS
Resonance Ionization Laser Ion Source

W. B. Walters, Chemistry, University of Maryland

Encompass work performed at ISOLDE (Ravn, Mishin, Fedeyosev, Köster) in collaboration with the Institute for Kernchemie in Mainz (Kratz, Pfeiffer, Wöhr, Wendt) & the IKS, Leuven, (Huyse and Van Duppen)

Motivation in Mainz was clearly to investigate the decay properties of neutron-rich nuclides involved in r-process nucleosynthesis.
Let me start by thanking DOE for many years of support, and also the Alexander von Humboldt Foundation for funding last year that permitted a 6-month stay in Mainz.

The start of RILIS work at ISOLDE was the recognition by Karl-Ludwig Kratz that the CHEMICAL SELECTIVITY needed to isolate r-process nuclides could be achieved via resonance-laser ionization. The first experiments with resonance laser ionization were conducted at GSI to separate $^{101}$Sn where the advantage over other methods was not encouraging. But, a fortuitous combination of people in Mainz, Troitsk and CERN made much more successful implementation at ISOLDE possible. Those involved included Viatcheslav Mishin and Valentin Fedoseyev from the Russian Institute for Spectroscopy, Troitsk, along with Helge Ravn and Ulli Köster at CERN/ISOLDE, Jürgen Kluge, Klaus Wendt, Andreas Wöhr, and other laser physicists in Mainz. [NIM B73, 550 (1993); ZP A 353, 9 (1995); Phys. Scr. T56, 262(1995)]

There were also parallel developments of laser ion sources led by Mark Huyse and Piet Van Duppen from the University of Leuven for Co and Ni. [NIM B 114, 350(1996)] Note that the work in Leuven was performed with an Ion Guide, not a chemical ion source. In that regard, it was possible to study the decay of heavy short-lived Ni isotopes whose release in a chemical ion source is quite slow.
Two key advantages are associated with ionization enhanced by the use of a RILIS, ....it can be turned off, and it can be tuned.

The first slide shows the gamma spectrum for Ag-126 taken last August, with the laser-on spectrum and laser-off spectrum shown together.

Tuning means that it is possible to separate isomers.

I will show the old Ag-122 spectrum from 1997 along with the neutron counting-rate as a function of laser frequency. Later on, I will present some data showing the presence of similar isomers in Ag-124 and Ag-126.

Perhaps the most impressive use of this technique has been in Leuven where the presence of 3 isomers was identified in Cu-70.
Ag-126 decay  Red/blue spectrum is with the laser on and the green spectrum is taken with the laser beam blocked.

The lines at 262 and 426 are from the decay of daughter Cd-126.
Separation of isomers with hyperfine tuning of the Resonance Ionization Laser Ion Source.

The upper spectrum was taken with the laser tuned to the central frequency (44 on this scale) ionizing both isomers.

The lower spectrum was taken with the laser tuned off center (37) ionizing only the high-spin isomer.

First shown in Sanibel in 1997.

I want to start with a RILIS story of the decay of Cu-70 levels where the miracle of the hyperfine studies made it possible to make sense of the decay of Ni-70 to levels of Cu-70 studied by Serge Franchoo in his thesis work in Leuven.

His thesis was defended in 1999 and there were data for Ni-70 that just did NOT make sense.

Finally, the RILIS hyperfine study of the Cu-70 decay made sense of the data.

AND….make it possible to make some good sense of what might be going on in Cu-76 and Cu-78.
What levels are expected in Cu-70?

\[ \begin{align*}
\text{Cu}^{
\begin{array}{c}
\text{p}_{3/2} \\
3/2^- 
\end{array}
\begin{array}{c}
1400
\end{array}
\text{p}_{5/2} \\
5/2^- 
\begin{array}{c}
915
\end{array}
\text{p}_{1/2} \\
1/2^- 
\begin{array}{c}
321
\end{array}
\text{g}_{9/2} \\
9/2^+ 
\begin{array}{c}
0
\end{array}
\text{Ni} \\
28 
\begin{array}{c}
41
\end{array}
\end{align*} \]
• Eight 1+ levels are expected. Strong beta decay should be observed to those numbered 1 through 5. Those numbered 6 and 7 are L-forbidden, and #8 should lie at a very high energy and play little role in Ni-70 decay.

• Five 1+ levels were observed at just about the energies and log ft values as will be suggested in the next several slides. 3 of the four members of the g-9/2 p-3/2 multiplet were identified with the aid of the laser hyperfine studies.

• A paper presenting these results is in preparation and should be available soon as J. Van Roosbroeck et al.
Magnetic moments of $^{68}\text{Cu}^{6, m}$ and $^{70}\text{Cu}^{6, m_1, m_2}$ nuclei measured by in-source laser spectroscopy

ISOLDE, CERN, 1211 Genève 23, Switzerland

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M. D. Seliverstov
Petersburg Nuclear Physics Institute, 188350, Gatchina, St. Petersburg, Russia

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Instituut voor Kern-en Stralingsfysica, University of Leuven, B-3001 Leuven, Belgium

(IS365 Collaboration and ISOLDE Collaboration)
(Received 18 September 2000; revised manuscript received 13 September 2001; published 16 January 2002)

We have obtained information on the atomic hyperfine splitting and, hence, on magnetic moments in neutron-rich $^{68, 70}\text{Cu}$ isotopes by scanning the frequency of the narrow-band laser of the first excitation step in the resonance ionization laser ion source. The deduced magnetic moments are $\mu^{(68}\text{Cu}^{6, I^{\pi}=1^+})=+2.48(2)\times(7)\mu_N$, $\mu^{(68}\text{Cu}^{m}, I^{\pi}=6^-)=+1.24(4)(6)\mu_N$, and $\mu^{(70}\text{Cu}^{m_1}, I^{\pi}=1^+)=+1.86(4)(6)\mu_N$, $\mu^{(70}\text{Cu}^{m_2}, I^{\pi}=6^-)=+1.50(7)(8)\mu_N$. The results of the scans analysis points out the existence of a new isomer, $^{70}\text{Cu}^{m_1}$. Its deduced magnetic moment is $(-)3.50(7)(11)\mu_N$, in good agreement with the $I^{\pi}=3^-$ assignment. The method of in-source atomic spectroscopy, as well as the analysis of the obtained data, is described. The results are discussed in terms of single-particle configurations coupled to the $^{68}\text{Ni}$ core.
In adding neutrons to go from Cu-70 to Cu-78 only the three boxed multiplets will invert.

$$\begin{align*}
\[p_{3/2}\] &\quad 3/2^- \quad 1400 \\
\[f_{5/2}\] &\quad 5/2^- \quad 915 \\
\[p_{1/2}\] &\quad 1/2^- \quad 321 \\
\[9g_{9/2}\] &\quad 9/2^+ \quad 69 \\
\text{Ni} &\quad 28 \quad 41 \\
\end{align*}$$

$$\begin{align*}
\[p_{3/2}\] &\quad 0^+ \quad 3/2^- \quad 1400 \\
\[f_{5/2}\] &\quad 2^+ \quad 5/2^- \quad 915 \\
\[p_{1/2}\] &\quad 2^+ \quad 1/2^- \quad 321 \\
\[9g_{9/2}\] &\quad 3^+ \quad 9/2^+ \quad 69 \\
\text{Cu} &\quad 29 \quad 41 \\
\end{align*}$$
Ni
28  41

Cu
29  49
Single odd proton levels in Cu nuclides

Filling of N = 3 oscillator shell neutrons

**Speculative**

RILIS Leuven

**Levels in odd-PROTON Cu nuclides.**

PRE dictated at Sanibel 1992
Weissman et al. DNP 2002 Cu-73 and Cu-75 showed lower moments that support the notion that Cu-75 has a 5/2- spin and parity.
(1^+, 6^-)

(5^-)

J. Van Roosboeck et al.
Hameenlinna p.327
ISOLDE RILIS Cu

Jeff Winger et al., PRC 42,958(1990).

FIG. 4. Decay scheme for $^{76}$Cu with energies in keV. The 0.57 s half-life is probably from the decay of a high-spin isomer while the 1.27 s half-life is probably from the decay of a low-spin isomer.

g. 1. Deduced decay scheme for the $\beta$-decay of $^{78}$Cu.
The 1+ level cannot be too much above the 3-levels if it is to undergo beta decay. That limits the separation between the p-3/2 and f-5/2 proton levels and the g-9/2 and p-1/2 neutron levels.

And, the lower the 1+ level lies, the shorter will be the half-life for Ni-78.
Next, I want to review the status of the data for the RILIS studies in the Sn-132 region.
<table>
<thead>
<tr>
<th>A</th>
<th>Pₙ value in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-life in milliseconds</td>
<td></td>
</tr>
<tr>
<td>new values in red</td>
<td></td>
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<tr>
<td>old values in black</td>
<td></td>
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<tr>
<td>hopeful values in green</td>
<td></td>
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<tr>
<td>new structure in blue</td>
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<th></th>
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<th>137</th>
<th>138</th>
<th>139</th>
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<th>141</th>
<th>142</th>
<th>143</th>
<th>144</th>
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<tr>
<td>STAB</td>
<td>3.8 m</td>
<td>14 m</td>
<td>40 s</td>
<td>14 s</td>
<td>1.7 s</td>
<td>1.25 s</td>
<td>0.5 s</td>
<td>0.4 s</td>
<td>1.0</td>
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<tr>
<td>135</td>
<td>6.6 h</td>
<td>1.4 m</td>
<td>25 s</td>
<td>6.5 s</td>
<td>2.3 s</td>
<td>0.9 s</td>
<td>0.5 s</td>
<td>0.2 s</td>
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<tr>
<td>134</td>
<td>42 m</td>
<td>19 s</td>
<td>18 s</td>
<td>2.5 s</td>
<td>1.4 s</td>
<td>0.4 s</td>
<td>0.2 s</td>
<td>0.1 s</td>
<td>142</td>
</tr>
<tr>
<td>133</td>
<td>2.5 m</td>
<td>0.8 s</td>
<td>1.7 s</td>
<td>0.8 s</td>
<td>0.33 s</td>
<td>0.25 s</td>
<td>0.15 s</td>
<td>0.1 s</td>
<td>141</td>
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<tr>
<th>126</th>
<th>127</th>
<th>128</th>
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<th>130</th>
<th>131</th>
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<tbody>
<tr>
<td>132</td>
<td>133</td>
<td>2.9</td>
<td>134</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>40 s</td>
<td>1.4 s</td>
<td>1.0 s</td>
<td>0.53 s</td>
<td>0.28 s</td>
<td>0.18 s</td>
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<thead>
<tr>
<th>125</th>
<th>126</th>
<th>127</th>
<th>128</th>
<th>129</th>
<th>130</th>
<th>131</th>
<th>Q</th>
<th>132</th>
<th>133</th>
<th>134</th>
</tr>
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<tbody>
<tr>
<td>0.3 s</td>
<td>0.20 s</td>
<td>0.17 s</td>
<td>0.14 s</td>
<td>0.14 s</td>
<td>0.14 s</td>
<td>0.14 s</td>
<td>0.14 s</td>
<td>0.14 s</td>
<td>0.14 s</td>
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<td>160</td>
<td>68</td>
<td>95</td>
<td>60</td>
<td>70</td>
<td>80</td>
<td>90</td>
<td>100</td>
<td>110</td>
<td>120</td>
<td>130</td>
</tr>
</tbody>
</table>


B. Pfeiffer, K.-L. Kratz, F.-K. Thielemann and W.B. Walters, Nuclear Physics A 693, 282-324 (October 8,2001)
Sn-135 July 2000

First several hundred milliseconds

Later, but with the laser on

Laser off
Sn-135 August 2002 with the converter
The big difference between 2000 and 2002 was the use of the neutron converter which significantly lowered the spallation production of $^{135}\text{Cs}^m$. Thus, we could keep the beam gate open for much longer periods of time and collect much more $^{135}\text{Sn}$.

Theoreticians had complained that the level scheme of $^{135}\text{Sb}$ was not very detailed. Our new level scheme will be much more detailed and should provide information about other low-energy levels that are important to the testing of the model.
I. Dillmann et al.

Primary beam:
1 - 1.4 GeV protons,
Intensity: ca. $10^{13}$ p/pulse

To the beamlines

ISOLDE Laser System:
- 3 copper vapor lasers
- 2 dye lasers (cw, frequency tripling by two BBO crystals → UV)

Transfer line (Nb)
~2200 K

UC$_2$-C- Target

Converter (Ta or W)
We now have excellent data for the delayed-neutron time curve for the decay of a relatively pure source of Sn-137. The weakness in our analysis that I will discuss later comes from the absence of good data for the growth and decay of the daughter Sb-137.
The good news is that we ARE able to see $^{138}\text{Sn}$ decay. But, the background is large. The laser-on--laser off difference is about less than 20%.

The bad news is that the half-lives of Sb-137 and Sb-138 are not known!!!!!

<table>
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<tr>
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<th>133</th>
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<th>135</th>
<th>136</th>
<th>137</th>
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<tbody>
<tr>
<td>A</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_{\text{meas}}$ (s)</td>
<td>1.44</td>
<td>1.12</td>
<td>530(20)</td>
<td>275(25)</td>
<td><strong>185(35)</strong></td>
<td>200(80)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{n}$ (%)</td>
<td>2.9(2)</td>
<td>13(1)</td>
<td>21(5)</td>
<td>30(5)</td>
<td><strong>50(20)</strong></td>
<td><strong>50(20)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q_{M}$ (MeV)</td>
<td>8.0</td>
<td>7.1</td>
<td>9.4</td>
<td>8.2</td>
<td>10.5</td>
<td>8.4</td>
<td>10.9</td>
<td>9.5</td>
</tr>
<tr>
<td>$Q_{\text{Audi}}$</td>
<td>7.6</td>
<td>7.2</td>
<td>8.6</td>
<td>8.0</td>
<td>9.7</td>
<td>8.9</td>
<td>10.7</td>
<td>9.8</td>
</tr>
<tr>
<td>$T_{M(GT)}$ (ms)</td>
<td>10.3 s</td>
<td>3.5 s</td>
<td>3000</td>
<td>950</td>
<td>800</td>
<td>480</td>
<td>390</td>
<td>120</td>
</tr>
<tr>
<td>$T_{\text{Hilf}}$ (ms)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>731</td>
<td>189</td>
<td>110</td>
<td>49</td>
</tr>
<tr>
<td>$T_{\text{Groote}}$ (ms)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>312</td>
<td>493</td>
<td>327</td>
<td>116</td>
</tr>
<tr>
<td>$T_{ff+GT}$ (ms)</td>
<td>[1996]</td>
<td></td>
<td></td>
<td></td>
<td>300</td>
<td>209</td>
<td>186</td>
<td>162</td>
</tr>
<tr>
<td>$T_{ff+GT}$ (ms)</td>
<td>[this work]</td>
<td></td>
<td></td>
<td></td>
<td>400</td>
<td>600</td>
<td>120</td>
<td>200</td>
</tr>
</tbody>
</table>

The lines $S_{n}$, $Q_{M}$ and $T_{M(GT)}$ are the published values from Moeller, Nix and Kratz.\(^i\)

The $T_{M(GT)}$ half lives include only for the Gamow-Teller branches.

The values labeled $T_{\text{Hilf}}$ and $T_{\text{Groote}}$ were taken from the compilation of Staudt et al.\(^{ii}\)

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\(^{ii}\) A. Staudt et al., Atomic Data and Nuclear Data Tables, 44, (1990) 79.
<table>
<thead>
<tr>
<th></th>
<th>Counts/PSB pulse in the neutron detector</th>
<th>nuclei producec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Laser on</td>
<td>Laser off</td>
</tr>
<tr>
<td>Sn-136</td>
<td>875.3</td>
<td>4.9</td>
</tr>
<tr>
<td>Sn-137</td>
<td>39.0</td>
<td>6.8</td>
</tr>
<tr>
<td>Sn-138</td>
<td>9.6</td>
<td>8.4</td>
</tr>
</tbody>
</table>

The background at A = 138 is NOT large, the production is just quite small.
FIG. 11. Relative isotopic r-process abundances of Sn isotopes under freeze-out conditions ($T_0=1.35$) as a function of neutron density. For details, see text.

The $A = 130$ peak, Sn-136.

The $A = 190$ peak, Sn-138.

Th and U nuclides, Sn-140.
The two main features in the In-130 level scheme as known at that time were the low energy for the 1+ level shown at 2120 keV, but expected near 1400 keV, and the possible 3+ level at 388 keV. At that point we had not yet identified the 388-keV transition as a part of a large peak at 390 keV coming from In-130 decay.

In a subsequent experiment at GSI, the isomeric transition in In-130 was observed, as was a suspected transition in In-128.

With the positions of both the 1+ and 3+ levels established, it is then possible to follow the evolution of that energy difference as neutrons are added to the nucleus approaching $N = 82$. 
The transitions underlined in green were observed in MSU1015.

Probing neutron-rich In and Cd nuclei with isomer spectroscopy

M. Hellström\textsuperscript{a,b}, M.N. Mineva\textsuperscript{b}, A. Blazhev\textsuperscript{a,c}, H.J. Boardman\textsuperscript{d}, J. Ekman\textsuperscript{b}, J. Gerl\textsuperscript{a}, K. Gladnishki\textsuperscript{c,e}, H. Grawe\textsuperscript{a}, R. Page\textsuperscript{d}, Zs. Podolyák\textsuperscript{e} and D. Rudolph\textsuperscript{b} for the GSI-FRS-Isomer collaboration

Table 1: Properties of isomers observed in the present study.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$I^\pi$</th>
<th>Observed delayed $\gamma$-rays* [keV]</th>
<th>Half-life$^*,\dagger$ ((\mu)s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>This work</td>
</tr>
<tr>
<td>$^{125}\text{Cd}$</td>
<td>$(29/2^+)$</td>
<td>486, 665, \textbf{720}, 743</td>
<td>14(2)</td>
</tr>
<tr>
<td>$^{127}\text{Cd}$</td>
<td>?</td>
<td>820</td>
<td>1 - 10</td>
</tr>
<tr>
<td>$^{126}\text{In}$</td>
<td>$(1^-)$</td>
<td>201, 244, 614, 865</td>
<td>29(2)</td>
</tr>
<tr>
<td>$^{127}\text{In}$</td>
<td>?</td>
<td>221, 233</td>
<td>&lt;0.5 and 13(1)</td>
</tr>
<tr>
<td>$^{128}\text{In}$</td>
<td>$(1^-)$</td>
<td>248, 323</td>
<td>\textbf{175(90)}</td>
</tr>
<tr>
<td>$^{129}\text{In}$</td>
<td>$(17/2^-)$</td>
<td>332, 358, 994, 1352</td>
<td>11(1)</td>
</tr>
<tr>
<td>$^{130}\text{In}$</td>
<td>?</td>
<td>389</td>
<td>1 - 10</td>
</tr>
<tr>
<td>$^{129}\text{Sn}$</td>
<td>$19/2^+$</td>
<td>382, 570, 1136, 1324</td>
<td>3.9(1)</td>
</tr>
<tr>
<td>$^{130}\text{Sn}$</td>
<td>$10^+$</td>
<td>97, 391</td>
<td>1.5(1)</td>
</tr>
</tbody>
</table>

* Values are preliminary and may change as the analysis progresses.

$^\dagger$ From fitting decay time distributions of the $\gamma$-rays indicated in bold type.
g7/2 to d3/2 versus 3+ to 1+ difference
= 1100 1090 914 ~800 700
Alex Brown’s OXBASH separation for the 1\(^+\) and 3\(^+\) is only 910 keV, which is about half of the observed 1732-keV difference.

As beta decay to this 1\(^+\) level is the main driving force for r-process waiting-pont nuclides, this high energy for the 1\(^+\) level implies LONGER half-lives for N = 82 r-process isotones.

As E-beta for Cd-130 decay is about 6 MeV, a 15% lower energy would means a half-life that is twice as long.

What saves the day here is that, along with the higher energy for the 1\(^+\) level, the Q\(_\beta\) also turns out to be about 1 MeV higher than expected by many mass models. Two wrongs can, sometimes, still get it right.
This graph incorporates the new mass for Cd-130 (Dillmann et al.) and shows the strong drift of the higher observed masses (lower binding energy) for the heavier Cd nuclides, consistent with a weakened interaction. Note that it starts above Cd-124 (N = 76 N/Z = 1.58).
There are people out there who do not believe the Cd-128 and Cd-130 results. Including the late S. Raman, who did not include Cd-128 in his ANDT compilation.
IS-333 Ag-130 decay RILIS

First 100 ms
Second 100 ms
Residual before beam gate
One of the reasons for disbelieving the rather sparse data for the levels in Cd-128 is their anomalous behavior as N = 82 is approached.
Given the skepticism about the structure for Cd-128 that has been presented, and to also provide some more insight into structure of neutron-rich nuclides, I will show some data from another source.
Data from the fantastic beta-gamma counting system at MSU built by the Mantica group and used for experiment MSU 1015 (2003).

Session DF - Nuclear Structure: 94 $\leq$ A < 160.
ORAL session, Friday afternoon, October 31
Canyon B, TM

[DF.006] Level structures of $^{120}$Pd, $^{126}$Cd, and $^{128}$Cd from beta decay and isomeric decay


Nuclides in the 114<A<129 mass region were studied at the NSCL following fragmentation of a 120-MeV/A $^{136}$Xe beam. Time-correlated gamma-ray singles and coincidence spectra following both beta decay and isomeric gamma decay were collected as a function of Z and A for the implanted fragments using the MSU beta counting system and 12 SeGA Ge detectors. The first $2^+$ level in $^{120}$Pd was identified at 438 keV following beta decay of $^{120}$Rh. Previously reported gamma rays were observed within 20 microseconds of implantation of $^{128}$Cd and $^{126}$Cd fragments. In addition, a new gamma ray was observed at 219 keV in the decay of the $^{126}$Cd isomer. The structures of the even-even Pd and Cd nuclides will be discussed in the framework of both the Interacting Boson Model and the Shell Model. This work was supported by the U. S. NSF and U. S. DOE.
$^1g_{9/2} -5^1h_{11/2} + ^1h_{11/2} + ^6 g_{7/2} + ^8 g_{7/2} + ^8 p_{1/2} + ^1d_{3/2} + ^1 1^- \ldots$

$t = ??? \text{ s}$

$\nu = -57$

$120 \text{ Rh}$

$75$

$Q_\nu = \sim 11.1 \text{ MeV}$

$S_n = \sim 6.7 \text{ MeV}$

$P_n = \sim 3\%$

$Q_b = \sim 11.1 \text{ MeV}$

$D = -57$

$D = -68$

$^7g_{9/2} \rightarrow ^7g_{9/2} + ^7p + ^7n$

first forbidden branch

$log f_t = 5.5$

$log f = 5.41$

$log t = 0.09 \text{ t = 1.2 s}$

$^7g_{7/2} -1 \rightarrow ^7g_{9/2} + ^7p + ^7n$

G-T allowed branch

$log f_t = 4.2$

$log f = 5.03$

$log t = -0.83 \text{ t = 148 ms}$

$^9g_{9/2} -4 ^9h_{11/2} + ^9h_{11/2} + ^6 g_{7/2} + ^7 g_{7/2} + ^7 p_{1/2} + ^1 d_{3/2} + ^1 g_{7/2} + ^7$

$8^+ 2000$

$6^+ 1800$

$4^+ 1000???$

$2^+ 400 \text{ or } 450???$

$0^+ 0$

$120 \text{ Pd} \nu = -68$

$46 \text{ 74}$

$120(10) \text{ ms}$

NEW DATA

$\begin{align*}
(4^+) & \quad 618 \quad 1056 \\
(2^+) & \quad 912 \\
(2^+) & \quad 438 \\
0^+ & \quad 0 \\
120 & \quad 46 \text{ Pd} \nu = -68 \\
46 & \quad 74
\end{align*}$
IBM-2 calculations of even–even Pd nuclei

Ka-Hae Kim\textsuperscript{a}, Adrian Gelberg\textsuperscript{a,b}, Takahiro Mizusaki\textsuperscript{a}, Takaharu Otsuka\textsuperscript{a}, Peter von Brentano\textsuperscript{b}

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\textsuperscript{b} Institut für Kernphysik der Universität zu Köln, 50937 Cologne, Germany

Received 1 March 1996
The new data from MSU experiment 1015 in which the decay of Rh-120 to Pd-120 was sought provided not only the new data for the 2+ and 4+ energies in Pd-120, but confirmation of the low 2+ energy in Cd-128.

Hence, the Cd data remain “ugly” in the sense that the 2+ energies do not rise toward the n = 82 closed shell.

In contrast, the new data for Pd-120 are found almost exactly where 1996 IBM-d calculations had predicted.

On the next slide are shown the degree to which the rather complete structures of the even-even Pd nuclides tend to mirror each other around a 2+ minimum at Pd-114(N = 68).

The levels of the Pd nuclides have been broken down into a “shell-model region caused by the N = 56 subshell, a transition region, and a symmetric collective region centered at N = 68.
I would like to conclude with a short summary of what I believe is the “case” for the weakening of the nucleon-nucleon interaction for nuclides with high N/Z where higher N/Z means over 1.6.

I would argue that the first sign of something new were the data for Sn-134, 1997, but it has been the recent new data for B(E2) values in Sn and Te found here at Oak Ridge that have made such talk more respectable.
Experimental and Calculated levels for $^{134}$Sn.

**Calculated**

Chou & Warburton

**Experiment**

Zhang *et al.*

Experiment

$(\pi f_{7/2})^2$  $(\pi g_{7/2})^2$

The caption does not point out that the OXBASH interactions were multiplied by 0.6!!!!!!!
Anomalous behavior of $2^+$ excitations around $^{132}$Sn

J. Terasaki, J. Engel, W. Nazarewicz, and M. Stoitsov

Abstract:

In certain neutron-rich Te isotopes, a decrease in the energy of the first excited $2^+$ state is accompanied by a decrease in the $E2$ strength to that state from the ground state, contradicting simple systematics and general intuition about quadrupole collectivity. We use a separable quadrupole-plus-pairing Hamiltonian and the quasiparticle random phase approximation to calculate energies, $B(E2,0^+ \rightarrow 2^+)$ strengths, and $g$ factors for the lowest $2^+$ states near $^{132}$Sn ($Z \geq 50$). We trace the anomalous behavior in the Te isotopes to a reduced neutron pairing above the $N=82$ magic gap.

In this paper the argument is made for a reduced neutron pairing gap.
How anomalous????
As can be seen, the 2+ levels in the Hg nuclides are also significantly lower than the adjacent closed shell nuclides.

And, there is a slight drop in energy as $N = 126$ is approached.
<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Isotopes</th>
<th>Spin</th>
<th>States</th>
</tr>
</thead>
<tbody>
<tr>
<td>([g_9/2])^{-2}</td>
<td>8^+ 2874</td>
<td>6^+ 2812</td>
<td>4^+ 2002</td>
</tr>
<tr>
<td>([g_9/2])^{+2}</td>
<td>8^+ 2760</td>
<td>6^+ 2612</td>
<td>4^+ 2268</td>
</tr>
<tr>
<td>([d_{5/2}]g_{7/2})</td>
<td>8^+ 2956</td>
<td>6^+ 2872</td>
<td>6^+ 2422</td>
</tr>
<tr>
<td>([d_{5/2}])^{+2}</td>
<td>4^+ 1574</td>
<td>2^+ 871</td>
<td></td>
</tr>
<tr>
<td>([g_9/2])^{-2}</td>
<td>8^+ 3589</td>
<td>6^+ 3448</td>
<td>4^+ 3076</td>
</tr>
<tr>
<td>([g_9/2])^{+2}</td>
<td>8^+ 3309</td>
<td>6^+ 3304</td>
<td>6^+ 2958</td>
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<tr>
<td>([d_{5/2}]g_{7/2})</td>
<td>4^+ 1495</td>
<td>2^+ 934</td>
<td></td>
</tr>
<tr>
<td>([d_{5/2}])^{+2}</td>
<td>4^+ 1495</td>
<td>2^+ 934</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Isotopes</th>
<th>Spin</th>
<th>States</th>
</tr>
</thead>
<tbody>
<tr>
<td>88 Zr</td>
<td>0^+ 0</td>
<td>88 Zr</td>
</tr>
<tr>
<td>40 Zr</td>
<td>0^+ 0</td>
<td>40 Zr</td>
</tr>
</tbody>
</table>
Here, the 2+ energy in Sr clearly rises as N = 50 is approached.
The question was raised as to how $2^+$ energies vary as the $N = 82$ shell is approached. Below is the chart showing how strange the behavior of the $2^+$ energies in Cd are!!!
Fig. 3. Charge radius change in the tin isotopes. The line relies all the ground-states nuclei.
I am not certain as to how to interpret these Cd radii. These data go out to Cd-120. It certainly looks inviting to take advantage of the good Cd RILIS yields to extend these out, at least to Cd-126.

They might be showing larger radii owing to the intruder admixtures.
It is possible to interpret the lowered 2+ energies in the even-even Cd nuclides (lowered relative to the isotonic Te nuclides) as arising from a lowered proton pairing, or, perhaps the proton pairing is normal, and it is just a consequence of the lowered neutron pairing noted in the previous paper!!!!

And, there are also the lowered total binding energies for all of the Cd nuclides, relative to the FRDM masses. Perhaps FRDM is not the best comparison, but those values are used extensively for calculations where no data are available.

And, the absence of isomerism in Cd-130 and the suggested lower energy for the 2+ energy in Cd-130. A reliable determination for the 2+ energy in Cd-130 and B(E2) values for the heavy Cd nuclides may be better measures for proton pairing in these nuclides.
Then, there is the position of the 1+ level in In-130.

The remedy in OXBASH is a significant lowering of the pn interaction strength…..same as for Sn-134.

In other words, much of the new data for neutron-rich Cd and In nuclides could be accommodated by lowered interaction strengths for these very neutron-rich nuclides.
Where does RILIS go? Remember, RILIS gives chemical selectivity, but it can’t beat diffusion…..as for Ni nuclides.

Each time we have started a new element, 2 or three new isotopes have been found.

At ISOLDE, Cd-133 is in sight, In-136 and In-137 are possible hopefully we will get better data for Ag-130, both neutron and gamma ray data. From In-136 and In-137, we could get structure in Sn-136, for example.

We are approved for antimony and should get Sb-137 and Sb-138 with neutrons. Cs-138 will overwhelm the gamma rays.

And, there was the Mn-66 study that revealed the low 2+ energy in Fe-66 that provided strong evidence for deformation in Ca-48 to Ni-78 region. There is much more spectroscopy that could be done with Mn.
If TRIUMF initiates a RILIS program, with their larger beam currents, they might be able to move to more out one two additional neutrons.

Thank you for your attention.