NEUTRON PICKUP REACTIONS
ON THE EVEN PALLADIUM ISOTOPES
AND THE DEEPLY BOUND HOLE-STATE EXCITATION

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Abstract: Neutron pickup was studied on all stable even-\(^{A}\) Pd isotopes via the (d, t) reaction at \(E_d = 50\) MeV and the (\(^{3}\)He, \(\alpha\)) reaction at \(E_{\text{3He}} = 70\) MeV. A systematic study of the deep-lying hole-state region is made. From a decomposition of angular distributions we obtain spectroscopic strength distributions for the \(1g_{9/2}, 2p_{1/2}, 2p_{3/2}\) and \(1f_{5/2}\) subshells which exhaust about 40% of their sum rules. Complete studies of the \(^{102,104}\)Pd(d, t) and \(^{101,103}\)Pd reactions are presented for pickup from the valence shells. For all isotopes spectroscopic information on the strongest transitions to low-lying states is obtained.

NUCLEAR REACTIONS \(^{102,104}\)Pd(d, t), \(E = 50\) MeV; measured \(\sigma(E, \theta)\). \(^{101,103}\)Pd levels deduced \(l, j, \pi, C^2S\). \(^{102,104}\)Pd(d, t), \(E = 50\) MeV; measured \(\sigma(E, \theta)\). Deduced deeply bound hole states, spectroscopic strength distributions. DWBA analysis. \(^{102,104}\)Pd(\(^{3}\)He, \(\alpha\)), \(E = 70\) MeV; measured \(\sigma(E, \theta)\); deduced deeply bound hole states.

1. Introduction

In recent years studies of neutron pickup reactions in the region around \(A = 100-130\) have brought information about the removal of neutrons from inner shells, notably the \(1g_{\frac{9}{2}}, 2p_{\frac{1}{2}}, 2p_{\frac{3}{2}}\) and \(2p_{\frac{3}{2}}\) subshells. In the particle spectra structures due to the corresponding hole states show up superimposed on a continuous background. The phenomenon has been observed in (p, d) [refs. 1-5], (d, t) [refs. 6-8] and \(^{3}\)He, \(\alpha\) [refs. 9-11] reactions.

In this paper we present the results of a study of the (d, t) reaction at \(E_d = 50\) MeV on all even palladium isotopes, together with data on the \(^{3}\)He, \(\alpha\) reaction at \(E_{\text{3He}} = 70\) MeV. Common to other investigations of the (p, d), (d, t) and \(^{3}\)He, \(\alpha\)
reactions only part of the spectroscopic strength of the inner shells is found in the gross structure. The fractions reported in literature for the 1g_{\pi} shell are 20 % in (p, d) [ref. 5], 15 % [ref. 8] and 45 % [ref. 7] in (d, t) and 45 % in ($^3$He, $^\alpha$) [ref. 11].

The aim of our study is to locate the neutron hole strength and where possible to unravel it into its different subshell components as was done in our study of the odd-$A$ tin isotopes 7). In that study envelopes of the different subshell strength could be indicated with fair accuracy. In the odd-$A$ Pd isotopes, however, the hole strength is shared by clearly isolated peaks on the one hand and a rather structureless bump on the other. This necessitated a different approach to analyzing the data, which will be described in detail in sect. 4.

Along with the evidence on inner shells, much information has been obtained on pickup from the valence shells. As this information is lacking in the literature, particularly on $^{101}$Pd, $^{103}$Pd and $^{105}$Pd, spectroscopic data on the low-lying states are presented in sect. 3.

2. Experimental method

Energy-analyzed beams of 50 MeV deuterons and 70 MeV $^3$He particles, obtained from the KVI cyclotron were used to bombard self-supporting metallic palladium targets with typical thicknesses of 500 $\mu$g/cm$^2$. Particles emerging from the target were detected with $\Delta E$-$E$ solid-state detector telescopes. The program SOFBAL 12) was used for data acquisition and software particle identification.

For the (d, t) reaction angular distributions were taken for all even Pd targets in the angular range of 6° to 22.5° except for $^{108}$Pd, for which data were taken up to 32.5°. The energy resolution was typically 65 keV. This resolution was good enough to enable us to resolve many of the low-lying transitions in $^{101}$Pd and $^{103}$Pd for which a full analysis was performed. For the heavier odd-$A$ Pd isotopes the density of the low-lying states increases to an extent that makes any attempt to resolve them hopeless. We have however obtained data on some of the more prominent transitions of different multipolarities. Spectra from the ($^3$He, $^\alpha$) reaction were recorded only at $\theta_{lab} = 15°$ and 17°.

Cross sections were obtained from collected charge, measured solid angle and target thickness after correcting for isotopic enrichment. The target thicknesses were measured by determining the energy loss of $^\alpha$-particles from an $^{241}$Am source passing through the targets. The cross sections were also obtained by normalizing the elastic scattering obtained with the same setup but with a different deuteron energy ($E_d = 32$ MeV) to the results of an optical-model calculation. Both results were consistent to better than 10%. In the figures we have only indicated statistical errors.
3. The evenPd(d, t)oddPd reaction to low-lying states

3.1. DATA AND DATA REDUCTION

No study of the (d, t) neutron pickup reaction has been reported so far for $^{102}$Pd. Results from $^{104}$Pd(d, t) are given in the Nuclear Data Sheets [13] but rely on unpublished work. We therefore analyzed the low-lying states in $^{101,103}$Pd in detail. For the spectra of $^{105,107,109}$Pd we only analyzed the most pronounced peaks corresponding to the different $l_n$-transfers that occur in this reaction i.e. $l_n = 0, 2, 4$ and 5. For $^{107,109}$Pd the results are compared with those of Diehl et al. [14]). This survey is necessary also for obtaining a measure of how well the angular distributions are described by DWBA calculations, since in the next section we shall heavily rely on these.

The data analysis was performed with the peak fitting program AUTOFIT [15]). Excitation energies quoted, are accurate to within 15 keV.

3.2. DWBA ANALYSIS AND RESULTS

DWBA calculations were performed with the code DWUCK4 [ref. 16]). Optical-model parameters are listed in table 1. The deuteron parameters are taken from Hinterberger et al. [17] and those for the tritons from Gibson et al. [18]. We used a finite-range correction factor of 0.845, but no non-locality corrections and no radial cut-off. The wave function of the transferred neutron was generated from a potential, the depth of which was adjusted to give the correct binding energy.

From the experimental cross sections spectroscopic factors were obtained via the relation

$$ \left( \frac{d\sigma}{d\Omega} \right)_{\text{exp}} = NC^2S \frac{1}{2j+1} \left( \frac{d\sigma}{d\Omega} \right)_{\text{DWUCK}}, $$

with $N = 3.33$.

In figs. 1, 2 and 3 the angular distributions from $^{102}$Pd(d, t)$^{101}$Pd, $^{104}$Pd(d, t)$^{103}$Pd

<table>
<thead>
<tr>
<th>Particle</th>
<th>$V_0$ (MeV)</th>
<th>$W_0$ (MeV)</th>
<th>$r_0$ (fm)</th>
<th>$a$ (fm)</th>
<th>$r_c$ (fm)</th>
<th>$V_{\lambda_0}$ (MeV)</th>
<th>$W'$ (MeV)</th>
<th>$r'_0$ (fm)</th>
<th>$a'$ (fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>deuteron</td>
<td>99.8</td>
<td>1.05</td>
<td>0.90</td>
<td>1.30</td>
<td>6.0</td>
<td>57.86</td>
<td>1.28</td>
<td>0.805</td>
<td></td>
</tr>
<tr>
<td>triton</td>
<td>170.1</td>
<td>18.32</td>
<td>1.156</td>
<td>0.689</td>
<td>1.40</td>
<td></td>
<td>1.537</td>
<td>0.876</td>
<td></td>
</tr>
<tr>
<td>neutron</td>
<td>adjusted</td>
<td>1.20</td>
<td>0.625</td>
<td></td>
<td></td>
<td>$\lambda = 25$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 1. Angular distributions from $^{102}$Pd(d, t)$^{101}$Pd for transitions to low-lying states in $^{101}$Pd. The curves are from DWBA calculations.
Fig. 2. Angular distributions from $^{104}$Pd(d, t)$^{103}$Pd to low-lying states in $^{103}$Pd. The curves are from DWBA calculations.
Fig. 3. Angular distributions from $^{106, 108, 110}$Pd(d, t)$^{105, 107, 109}$Pd for the strongest transitions with different $I_n$ transfer to low-lying states in $^{105, 107, 109}$Pd. The curves are from DWBA calculations.

and $^{106, 108, 110}$Pd(d, t)$^{105, 107, 109}$Pd are shown, respectively. It is noteworthy that the quality of the DWBA fits to the data is rather good. We list the spectroscopic factors in tables 2-4.

For $^{101}$Pd and $^{103}$Pd the sum rules for single-neutron pickup from the valence shells are exceeded by 50% and 25%, respectively. For $^{107}$Pd and $^{109}$Pd our spectroscopic factors for the lowest $\frac{5}{2}^+$ are 15% higher than those of Diehl et al. \cite{14} but for the lowest $\frac{1}{2}^+$ state we find about 40% less. Our values for the $h_{\frac{1}{2}}$ pickup
### Table 2

\( {^{102}\text{Pd}(d, t)^{101}\text{Pd}} \)

<table>
<thead>
<tr>
<th>( E_n (\text{MeV}) )</th>
<th>( l_n )</th>
<th>( J^* )</th>
<th>( C^2S )</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s.</td>
<td>2</td>
<td>( \frac{3}{2}^+ )</td>
<td>2.43</td>
</tr>
<tr>
<td>0.26</td>
<td>4</td>
<td>( \frac{3}{2}^+ )</td>
<td>4.68</td>
</tr>
<tr>
<td>0.40</td>
<td>0</td>
<td>( \frac{1}{2}^+ )</td>
<td>0.08</td>
</tr>
<tr>
<td>0.50</td>
<td>1</td>
<td>( \frac{3}{2}^+ ), ( \frac{3}{2}^+ )</td>
<td>(0.22, 0.16)</td>
</tr>
<tr>
<td>0.66</td>
<td>5(4)</td>
<td>( \frac{3}{2}^+ ), ( \frac{3}{2}^+ )</td>
<td>(0.65, 0.91)</td>
</tr>
<tr>
<td>0.73</td>
<td>0</td>
<td>( \frac{1}{2}^+ )</td>
<td>0.15</td>
</tr>
<tr>
<td>0.98</td>
<td>2</td>
<td>( \frac{3}{2}^+ )</td>
<td>(0.17, 0.14)</td>
</tr>
<tr>
<td>1.06</td>
<td>2</td>
<td>( \frac{3}{2}^+ )</td>
<td>(0.14, 0.11)</td>
</tr>
<tr>
<td>1.25</td>
<td>2</td>
<td>( \frac{3}{2}^+ )</td>
<td>(0.22, 0.18)</td>
</tr>
<tr>
<td>1.31</td>
<td>5</td>
<td>( \frac{7}{2}^+ )</td>
<td>0.54</td>
</tr>
<tr>
<td>1.38</td>
<td>0</td>
<td>( \frac{1}{2}^+ )</td>
<td>0.08</td>
</tr>
<tr>
<td>2.05</td>
<td>1</td>
<td>( \frac{3}{2}^- ), ( \frac{5}{2}^- )</td>
<td>(0.17, 0.14)</td>
</tr>
<tr>
<td>2.12</td>
<td>(4, 5)</td>
<td>( \frac{5}{2}^+, \frac{9}{2}^+ )</td>
<td>(0.27, 0.54)</td>
</tr>
<tr>
<td>2.18</td>
<td>4</td>
<td>( \frac{5}{2}^+, \frac{9}{2}^+ )</td>
<td>(1.44, 0.72)</td>
</tr>
<tr>
<td>2.29</td>
<td>1</td>
<td>( \frac{3}{2}^- ), ( \frac{3}{2}^- )</td>
<td>(0.46, 0.38)</td>
</tr>
<tr>
<td>2.36</td>
<td>4</td>
<td>( \frac{9}{2}^+ )</td>
<td>(4.08, 1.98)</td>
</tr>
</tbody>
</table>

*) States and spin assignments adopted by Nucl. Data Sheets 13).

### Table 3

\( {^{104}\text{Pd}(d, t)^{103}\text{Pd}} \)

<table>
<thead>
<tr>
<th>( E_n (\text{MeV}) )</th>
<th>( l_n )</th>
<th>( J^* )</th>
<th>( C^2S )</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s.</td>
<td>2</td>
<td>( \frac{3}{2}^+ )</td>
<td>2.09</td>
</tr>
<tr>
<td>0.24</td>
<td>4</td>
<td>( \frac{3}{2}^+ )</td>
<td>4.28</td>
</tr>
<tr>
<td>0.50</td>
<td>(0, 2)</td>
<td>( \frac{1}{2}^+, \frac{3}{2}^+, \frac{5}{2}^+ )</td>
<td>(0.32, 0.36, 0.31)</td>
</tr>
<tr>
<td>0.61</td>
<td>2</td>
<td>( \frac{1}{2}^- ), ( \frac{3}{2}^- )</td>
<td>(0.38, 0.29)</td>
</tr>
<tr>
<td>0.70</td>
<td>2</td>
<td>( \frac{3}{2}^+, \frac{5}{2}^+ )</td>
<td>(0.74, 0.61)</td>
</tr>
<tr>
<td>0.76</td>
<td>5</td>
<td>( \frac{1}{2}^-, \frac{3}{2}^- )</td>
<td>1.05</td>
</tr>
<tr>
<td>0.80</td>
<td>2</td>
<td>( \frac{3}{2}^+, \frac{5}{2}^+ )</td>
<td>(0.16, 0.13)</td>
</tr>
<tr>
<td>1.03</td>
<td>2</td>
<td>( \frac{3}{2}^+, \frac{5}{2}^+ )</td>
<td>(0.24, 0.20)</td>
</tr>
<tr>
<td>1.17</td>
<td>2</td>
<td>( \frac{3}{2}^+, \frac{5}{2}^+ )</td>
<td>(0.20, 0.16)</td>
</tr>
<tr>
<td>1.28</td>
<td>5</td>
<td>( \frac{3}{2}^- )</td>
<td>0.40</td>
</tr>
<tr>
<td>1.57</td>
<td>2</td>
<td>( \frac{3}{2}^+, \frac{7}{2}^- )</td>
<td>(0.20, 0.16)</td>
</tr>
<tr>
<td>1.64</td>
<td>0</td>
<td>( \frac{5}{2}^- )</td>
<td>0.08</td>
</tr>
<tr>
<td>1.75</td>
<td>2</td>
<td>( \frac{5}{2}^+, \frac{7}{2}^- )</td>
<td>(0.08, 0.07)</td>
</tr>
<tr>
<td>1.82</td>
<td>0</td>
<td>( \frac{5}{2}^- )</td>
<td>0.07</td>
</tr>
<tr>
<td>1.90</td>
<td>1</td>
<td>( \frac{7}{2}^-, \frac{9}{2}^- )</td>
<td>(0.10, 0.08)</td>
</tr>
<tr>
<td>1.96</td>
<td>2</td>
<td>( \frac{7}{2}^+, \frac{9}{2}^- )</td>
<td>(0.11, 0.09)</td>
</tr>
<tr>
<td>2.10</td>
<td>1</td>
<td>( \frac{7}{2}^-, \frac{9}{2}^- )</td>
<td>(0.19, 0.17)</td>
</tr>
<tr>
<td>2.18</td>
<td>1</td>
<td>( \frac{7}{2}^-, \frac{9}{2}^- )</td>
<td>(0.08, 0.07)</td>
</tr>
<tr>
<td>2.28</td>
<td>4</td>
<td>( \frac{7}{2}^+, \frac{9}{2}^- )</td>
<td>(0.60, 0.30)</td>
</tr>
<tr>
<td>2.48</td>
<td>4</td>
<td>( \frac{7}{2}^+, \frac{9}{2}^- )</td>
<td>(0.82, 0.42)</td>
</tr>
<tr>
<td>2.60</td>
<td>4</td>
<td>( \frac{7}{2}^+, \frac{9}{2}^- )</td>
<td>(2.26, 1.14)</td>
</tr>
<tr>
<td>2.66</td>
<td>4</td>
<td>( \frac{7}{2}^+, \frac{9}{2}^- )</td>
<td>(1.51, 0.75)</td>
</tr>
<tr>
<td>2.76</td>
<td>1</td>
<td>( \frac{7}{2}^-, \frac{9}{2}^- )</td>
<td>(0.24, 0.22)</td>
</tr>
<tr>
<td>2.88</td>
<td>1</td>
<td>( \frac{7}{2}^-, \frac{9}{2}^- )</td>
<td>(0.26, 0.24)</td>
</tr>
</tbody>
</table>

*) States and spin assignments adopted by Nucl. Data Sheets 13).
4. Deep-lying hole states

4.1. THE (d, t) REACTION

Spectra of tritons taken at $\theta_{\text{lab}} = 15^\circ$ are shown in fig. 4 for all targets. The following characteristics are evident:

(i) At very low excitation energies strong peaks are found that carry most of the hole strength associated with the valence shells. States of higher excitation energy are of more complicated nature and are weakly excited.

(ii) Around $E_x = 2.5$–$3.0$ MeV an abrupt enhancement is seen in all spectra. Within a range of less than $1$ MeV a number of almost isolated peaks is found. Guided by the results of experiments on neighbouring nuclei $^{1-11}$, we associate this structure with neutron pickup from the next lower shells.

(iii) At about $E_x = 4$–$5$ MeV except perhaps for $^{101}$Pd, another much smoother enhancement is observed, separated from the first by a local minimum.

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**Table 4**

$^{106, 108, 110}$Pd(d, t)$^{105, 107, 109}$Pd

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$l_n$</th>
<th>$J^\pi$</th>
<th>$C^2 S$</th>
<th>$C^2 S$ $^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s.</td>
<td>2</td>
<td>$\frac{1}{2}^+$</td>
<td>2.05</td>
<td></td>
</tr>
<tr>
<td>0.32</td>
<td>$2+4$</td>
<td>$\frac{1}{2}^+$ $\frac{3}{2}^+$</td>
<td>0.56 + 4.54</td>
<td></td>
</tr>
<tr>
<td>1.44</td>
<td>5</td>
<td>$\frac{11}{2}^-$</td>
<td>0.90</td>
<td></td>
</tr>
</tbody>
</table>

$^{108}$Pd(d, t)$^{107}$Pd

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$l_n$</th>
<th>$J^\pi$</th>
<th>$C^2 S$</th>
<th>$C^2 S$ $^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s.</td>
<td>2</td>
<td>$\frac{1}{2}^+$</td>
<td>1.62</td>
<td>1.39</td>
</tr>
<tr>
<td>0.11</td>
<td>0</td>
<td>$\frac{1}{2}^+$</td>
<td>0.20</td>
<td>0.37</td>
</tr>
<tr>
<td>0.21</td>
<td>5</td>
<td>$\frac{11}{2}^-$</td>
<td>2.70</td>
<td>1.67</td>
</tr>
<tr>
<td>0.31</td>
<td>4</td>
<td>$\frac{7}{2}^+$</td>
<td>3.75</td>
<td>2.78</td>
</tr>
</tbody>
</table>

$^{110}$Pd(d, t)$^{109}$Pd

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$l_n$</th>
<th>$J^\pi$</th>
<th>$C^2 S$</th>
<th>$C^2 S$ $^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s.</td>
<td>2</td>
<td>$\frac{1}{2}^+$</td>
<td>1.30</td>
<td>1.16</td>
</tr>
<tr>
<td>0.12</td>
<td>0</td>
<td>$\frac{1}{2}^+$</td>
<td>0.29</td>
<td>0.43</td>
</tr>
<tr>
<td>0.19</td>
<td>5</td>
<td>$\frac{11}{2}^-$</td>
<td>3.42</td>
<td>2.6</td>
</tr>
<tr>
<td>0.41</td>
<td>4</td>
<td>$\frac{7}{2}^+$</td>
<td>3.89</td>
<td>4.0</td>
</tr>
</tbody>
</table>

$^a$) States and spin assignments adopted by Nucl. Data Sheets $^{13}$).

$^b$) Diehl et al. $^{14}$.}

are higher by 60 % ($^{107}$Pd) and 30 % ($^{109}$Pd), whereas for the g.s. we find a 35 % higher value for $^{107}$Pd and good agreement for $^{109}$Pd. In view of the above it may be that our spectroscopic factors come out somewhat too high as a result of our choice of optical-model and bound-state wave-function parameters. The same family of optical-model parameters has been used in the analysis of the Sn(d, t) data $^{7}$. 
(iv) At higher excitation energies the spectra are almost flat and for all isotopes the cross section is about equal, \( \approx 0.7 \text{ mb/sr \cdot MeV} \) at \( Q = -14 \text{ MeV} \). See also fig. 5.

The main objective of this study was to reconstruct the neutron pickup strength distributions of the different subshells. A possible way to attain this goal would have been the decomposition of the spectrum into several broad peaks as was done in ref. 7. It turned out however, that for the Pd isotopes this procedure would only work for the region around 2.5–3.0 MeV excitation energy where the spectra show pronounced structures. For the other region of concentrated strength around
Fig. 5. Triton spectrum from the $^{108}\text{Pd}(d, t)^{107}\text{Pd}$ reaction. Indicated as bg 1 and bg 2 are two different choices of background subtraction. The different areas, for which angular distributions are obtained with the choice bg 1, are indicated by different shadings.

Fig. 6. Angular distributions for the hatched areas from fig. 5 after subtraction of bg 1. Fits with $l_n = 1$ and $l_n = 4$ curves obtained from DWBA are indicated.
$E_x = 4$–$5$ MeV the spectra are too smooth with energy and vary too little in shape with angle to make such an approach feasible. We have therefore chosen for a more straightforward method in which we cut the spectra into energy bins. Angular distributions were obtained for the cross sections contained in each of these bins above a background that was subtracted similarly as in ref. 7). These angular distributions were then subjected to a least-squares fit with a linear superposition of DWBA angular distributions that correspond to the different expected $l_n$ values, $l_n = 1, 4$ and maybe $l_n = 2, 3$. This method can be expected to yield rather reliable results, since on the basis of the fits to the low-lying levels we can have some confidence in the predicted DWBA angular distributions. Moreover, the angular distributions for $l_n = 1$ and $l_n = 4$, expected to be the main components, are different enough in shape to allow a $\chi^2$ fit. The cuts were made at local minima in the spectra to minimize uncertainties. At higher excitation energies where the spectra are smooth, the cuts were taken 1 MeV apart.

The choice of the background is an heuristic one. For $^{107}$Pd, the isotope on which we have the most extensive data two different choices of the background were tried. In fig. 5 they are indicated as bg 1 and bg 2.

Angular distributions obtained for the shaded areas in the spectrum (fig. 5) are shown in fig. 6 and spectroscopic factors, assuming only one $l_n$ value are listed in table 5. This analysis done with bg 1 shows that the peaks at $E_x = 2.72$ MeV and 3.39 MeV are almost pure $l_n = 4$ transfer, while the peak at $E_x = 3.00$ is an $l_n = 1$ transition. This analysis must be seen as a check because we consider bg 2 as a more realistic choice. The characteristics of bg 2 are:

**TABLE 5**
Spectroscopic factors derived for energy-bins in $^{108}$Pd$(d, t)^{108}$Pd after subtraction of the background bg1

<table>
<thead>
<tr>
<th>Energy bin (MeV)</th>
<th>Assumed $l_n$ transfer</th>
<th>$C^2S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.49–2.91</td>
<td>4</td>
<td>1.0</td>
</tr>
<tr>
<td>2.91–3.14</td>
<td>1</td>
<td>0.13</td>
</tr>
<tr>
<td>3.14–3.53</td>
<td>4</td>
<td>1.0</td>
</tr>
<tr>
<td>3.77–6.00</td>
<td>4</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**TABLE 6**
Parameters $E_{x0}$ and $E_{x1}$ defining the assumed background bg 2

<table>
<thead>
<tr>
<th>Daughter nucleus</th>
<th>$E_{x0}$ (MeV)</th>
<th>$E_{x1}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>2.0</td>
<td>4.16</td>
</tr>
<tr>
<td>103</td>
<td>0.98</td>
<td>2.42</td>
</tr>
<tr>
<td>105</td>
<td>0.0</td>
<td>1.54</td>
</tr>
<tr>
<td>107</td>
<td>0.0</td>
<td>1.00</td>
</tr>
<tr>
<td>109</td>
<td>0.0</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Fig. 7. Angular distribution for different energy bins after subtraction of bg 2 for the $^{106}$Pd(d, t)$^{105}$Pd reaction. Best fits with a mixture of pure $l_n$ angular distributions calculated with DWBA are indicated.
Fig. 8. Distribution functions of spectroscopic neutron pickup strength derived from angular distributions of energy bins from the $^4\text{Pd}(d, t)^{10}$Pd spectra after subtraction of bg 2. The details of the procedure with the help of which these fits were performed are described in the text and an example is given in fig. 7.
(i) It has the value of the cross section found in the flat region at \( E_x = 15 \text{ MeV} \) and higher down to an energy \( E_{x_1} \).
(ii) From \( E_{x_1} \), the background \( bg \ 2 \) drops down linearly to zero at an excitation energy \( E_{x_0} \).

The values of \( E_{x_0} \) and \( E_{x_1} \) for all isotopes are listed in table 6. With this background the analysis for all Pd isotopes was done along the lines indicated above.

In fig. 7 the angular distributions for the different slices, after subtraction of \( bg \ 2 \) are given for the \(^{106}\text{Pd}(d, t)^{105}\text{Pd}\) reaction. These angular distributions were fitted with a mixture of pure \( l_n \) DWBA shapes obtained with the same optical model parameters as used for the low-lying states. The resulting strength functions are shown in fig. 8. The error bars indicated in the figure are the ones that follow from the least-square procedure and include the “goodness-of-fit” correction. It is indeed observed that for \(^{107}\text{Pd}\) the pronounced structures assigned \( l_n = 4 \) and \( l_n = 1 \) in the analysis with \( bg \ 1 \) are reproduced (see fig. 8).

As a further check on this procedure we analyzed in one case, \(^{102}\text{Pd}\), the region of 1–3 MeV excitation both with the above method and with the usual peak fitting to separate levels as described in sect. 3. There we found that many of these peaks are well fitted by pure \( l_n \) transitions and we obtained spectroscopic factors for them. With the above method in which we lump all peaks together and try to deduce contributions of various \( l_n \) transfers by \( \chi^2 \) fitting we obtained quantitatively consistent results within 20%.

From fig. 8 we conclude the following.
(i) The \( l_n = 1 \) strength distribution is rather structureless in contrast to the \( l_n = 4 \) distribution.
(ii) The \( l_n = 4 \) distribution consists of two regions, one narrow and structured, the other at higher excitation energy smooth and wide. Especially in the case of \(^{104}\text{Pd}\)

![Figure 9. Fractions of the subshell strength relative to the sum rule (2j+1) as obtained for the 2p_{1/2} + 2p_{3/2} shells (l_n = 1) and the 1g_{9/2} shell (l_n = 4).](image-url)
the narrow region seems to consist of only one isolated state. With increasing neutron number the strength in this region fragments more and more.

(iii) The results obtained for $^{107}$Pd with the higher background bg 1 (table 5) are consistent with the results of fig. 8, as they show that the most pronounced structures are predominantly $l_n = 4$.

(iv) For lower excitation energies evidence for $l_n = 2$ transfer is observed.

(v) For higher excitation energy we have allowed for $l_n = 3 (f_\frac{3}{2})$ transfer, though except for $^{101}$Pd there is no clear evidence for it. This observation is consistent with our previous results on the Sn isotopes where also no strong evidence for $f_\frac{3}{2}$ was found. In fig. 9 the integrated spectroscopic factors are shown for $l_n = 4$ and $l_n = 1$. It shows that roughly 50% and 40% of the spectroscopic strength is exhausted for $l_n = 4$ and $l_n = 1$, respectively.

![Fig. 10. Alpha-particle spectra from the $^3$Pd($^3$He, $^\alpha$) reaction at $E_{^3$He} = 70 MeV for all even-$A$ palladium isotopes, taken at $\theta_{lab} = 15^\circ$.](image)
4.2. THE \(^3\text{He}, \alpha\) REACTION

In order to have an independent and more unambiguous determination of the g\(_\frac{5}{2}\) strength distribution we have studied the \(^3\text{He}, \alpha\) reaction at \(E_{\text{3He}} = 70\) MeV on all even-\(A\) Pd isotopes. Due to its high \(I\)-mismatch this reaction strongly favours the \(I_n = 4\) transfer over \(I_n = 1\) and 2. For this reason it is to be expected that the strength standing out over the background should be a fair image of the \(I_n = 4\) distribution.

Spectra were taken at two angles, \(\theta_{\text{lab}} = 15^\circ\) and \(17^\circ\). The \(15^\circ\) spectra are shown in fig. 10. The similarity between the structures observed in fig. 10 and the \(I_n = 4\) strength distributions deduced from the (d, t) reaction data (fig. 8) adds to the confidence in the reliability of the latter.

5. The \(g_{\frac{5}{2}}\) hole strength in the IBFA model

In the interacting boson-fermion approximation (IBFA) model \(^{19}\) odd-\(A\) nuclei are described by coupling the odd particle (hole) to the s- and d-bosons of the IBA model \(^{20}\), describing the even-even case. Restricting ourselves to one shell-model state with angular momentum \(j\), the hamiltonian can be written as

\[
H = H_n + H_f + V_{\text{bf}},
\]

with

\[
V_{\text{bf}} = A\sqrt{5}[(d^\dagger a^\dagger)^{(0)}(a^\dagger a)^{(0)}]_o^0 + B\sqrt{5}[(a^\dagger a)^{(2)}(d^\dagger d)^{(2)}]_o^0
+ A(2j + 1)^{-\frac{1}{2}}[(a^\dagger a)](d^\dagger d)]_o^0,
\]

where

\[
Q_b^{(2)} = (s^\dagger d^\dagger + d^\dagger s) + \chi(d^\dagger d^\dagger).
\]

We specify that the odd fermion is a hole in the \(g_{\frac{5}{2}}\) shell. From microscopic considerations \(^{21}\) it follows that the exchange term in the hamiltonian is important only for partially occupied shells. Therefore we put \(A = 0\). The parameters of the boson hamiltonian, \(H_n\) have been obtained from a best fit to the even PD isotopes \(^{21}\). The parameters of \(V_{\text{bf}}\) were taken constant for all isotopes, \(B = +0.45\) MeV, \(A = +0.40\) MeV and \(\chi = -\frac{1}{2}\sqrt{7}\). These values are very similar to the ones used in a calculation of the low-lying negative-parity states in the odd-\(A\) Eu isotopes \(^{22}\).

In fig. 11 are shown the resulting strength distributions for the \(g_{\frac{5}{2}}\) hole state, compared with the corresponding distributions obtained from the analysis of the experimental data. The hole strength distributed over the collective states of the IBFA model is calculated. These can be viewed as doorway states. Further coupling to the underlying non-collective 3- and 5-quasiparticles states as well as collective states based on coupling with valence particles will result in an additional spreading which however will not change the picture in its essence.
It is observed from fig. 11 that the major features of the strength distribution are reproduced by our calculation:

(i) The lowest major fragment of $g_{9/2}$ hole strength has the right excitation energy for all isotopes.

(ii) The calculated spreading increases with neutron number in a manner rather comparable to the experimentally observed distribution.
6. Summary and conclusions

Neutron pickup through the (d, t) reaction has been studied on all even-$A$ Pd isotopes at $E_d = 50$ MeV, supplemented by data from the ($^3$He, x) reaction at $E_{^3}$He = 70 MeV.

Pickup from next lower shells is observed in all spectra. At higher excitation energies, $E_x = 4-5$ MeV a smooth bump stands out over the continuous background. At lower excitation energies, $E_x = 2.5-3.5$ MeV, a region with (almost) isolated peaks is seen. Between these two regions there is a gap. This picture is different from what was found for the Sn isotopes, where such a separation into two regions was not so clear. Analogously to the Sn case, however, is the fact that with increasing neutron number the structures get broader and coalesce. Here $^{107}$Pd is possibly an exception.

The part of the spectra above our assumed background was analyzed with the use of a least-squares fit with a mixture of different $(l,j)$ transfer DWBA curves to the experimental angular distributions for different energy bins. Thus we were able to recover the spectroscopic strength distributions for pickup from the $1g_{\frac{3}{2}}$ shell and from the $2p_{\frac{3}{2}}$ shell.

About 40–50% of their total sum rules is found for each isotope. This is consistent with the case of the tin isotopes, where we found 45%, but still it is significantly below the sum-rule limit. The percentage of the spectroscopic strength sum rules of 40–50% might even have to be reduced further to 30–40% if one renormalizes this percentage by the same factor needed to bring the strength for pickup from the valence shells in agreement with complete exhaustion of their sum-rule limit. In sect. 3 it was indicated that for $^{101}$Pd and $^{103}$Pd these sum-rule limits were exceeded by about 50% and 25%, respectively.

It is still an open question where the remaining strength is located. Recently Ishimatsu et al. have attempted to account for the full strength in a systematic study of the (p, d) reaction by not subtracting a background but on the other hand choosing a fixed energy interval and identifying the strength in it with that of the next lower shells. We have shown in our previous work on the Sn(d, t) reaction that it is indeed conceivable that the missing strength resides in the background, but in contrast to the result of Ishimatsu et al. we cannot account for the total background in terms of direct single-particle pickup from inner shells.

The fair agreement between the calculations with the IBFA model and the data seems to support the picture of the $g_{\frac{3}{2}}$ hole strength being distributed over simple collective states that act as doorways to underlying states of more complex configurations (3-, 5-quasiparticle states). In our calculation only the spectrum of doorway states was calculated. It exhibits an increasing fragmentation of $g_{\frac{3}{2}}$ hole strength when going from $^{101}$Pd to $^{109}$Pd. This is due to the increasing collectivity of the low-lying states of the palladium isotopes with increasing mass number. Since the spreading of the strength over the doorway states is already of the order of several MeV, the spreading
over the non-collective states contributes little to the width of the strength distributions but will merely smoothen the spectrum. This picture has been advocated by Koeling and Iachello \textsuperscript{24} to explain the g\textsubscript{3} neutron hole strength distributions observed in the tin isotopes. Also Wagner \textit{et al.} \textsuperscript{25} apply it to the 1d proton hole state distribution seen in the (d, \textsuperscript{3}He) reaction on even-\textit{A} \textit{Ar} and Ca isotopes. Recently Soloviev \textit{et al.} \textsuperscript{26} have pointed out that quasi-hole+phonon states with phonons of other multipolarities than quadrupole can be important. One might be tempted to identify the lowest two major g\textsubscript{3} fragments with the g\textsubscript{3} \textsuperscript{-1} and g\textsubscript{3} \textsuperscript{-1} \otimes quadrupole phonon, respectively, since their splitting in for example \textsuperscript{107}Pd is close to the phonon energy. However, the strengths of these two fragments are roughly equal indicating that the weak coupling scheme is not applicable here.

In conclusion we remark that in our opinion the two main puzzles in this field remain the location of the full spectroscopic strength and an answer as to the origin of the continuum part of the spectrum. Further experimental effort to clarify these points remains highly desirable.

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