# TWO-PARTICLE, ONE-HOLE STATES IN $^{209}$Pb†

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The reactions $^{207}\mathrm{Pb}(t,p)^{209}\mathrm{Pb}$ and $^{210}\mathrm{Pb}(p,d)^{209}\mathrm{Pb}$ have been used to study the two-particle, one-hole states of $^{209}$Pb. The complementary nature of these two reactions permits identification of all but three of the observed levels below 3561 keV.

The neutron single-particle states in $^{209}$Pb have been identified by single-neutron stripping reactions on $^{208}$Pb.[1] A new class of states, the neutron two-particle, one-hole states (2p-1h), not identified in the above reaction have been investigated by means of the reactions $^{207}\mathrm{Pb}(t,p)^{209}\mathrm{Pb}$ and $^{210}\mathrm{Pb}(p,d)^{209}\mathrm{Pb}$. The former populates 2p-1h states with the configuration

$$\nu[^{207}\mathrm{Pb}(0)\{(n_1l_1j_1)(n_2l_2j_2)\}_{J_0}]_{J=J_0\pm\frac{1}{2}}$$
$$\approx \nu[(3p_{\frac{1}{2}})^{-1}\{(n_1l_1j_1)(n_2l_2j_2)\}_{J_0}]_{J=J_0\pm\frac{1}{2}},$$

where the neutron orbits 1 and 2 are in the shell $N=126$-$184$. The latter reaction populates 2p-1h states with the configuration

$$\nu[(nlj)^{-1}\,{}^{210}\mathrm{Pb}(0)]_j \approx \nu\{(nlj)^{-1}[(2g_{\frac{9}{2}})^2]_0\}_j,$$

where the neutron hole is in one of the orbits in the shell $N=82$-$126$. Thus, the $(t,p)$ reaction populates states in which the two particles are in various configurations but always coupled to the specific hole configuration $\nu(3p_{1/2})^{-1}$. Since the two-particle configurations have their parentage in $^{210}$Pb, viz. in those levels that are excited in the reaction $^{208}\mathrm{Pb}(t,p)^{210}\mathrm{Pb}$, the positions and cross sections of the corresponding $^{209}$Pb levels can be predicted. This parentage will be demonstrated here for the lowest five levels of $^{210}$Pb ($J=0^+$, $2^+$, $4^+$, $6^+$, and $8^+$) which arise primarily from the $[(2g_{\frac{9}{2}})^2]_{J=0,2,4,6,8}$ configurations. In the case of the $(p,d)$ reaction the states that are populated have various neutron hole configurations coupled to the specific two-particle configurations that exist in the ground state of $^{210}$Pb. These hole configurations have their parentage in the well-known neutron hole states of $^{207}$Pb and will be compared with them. It will be seen that in identifying these 2p-1h states, the two reactions are complementary and reveal considerable mixing of the 2p-1h states of $^{209}$Pb.

The two experiments were done using both counter-telescope techniques and a broad-range magnetic spectrograph. The full details of the experimental method are described in Ref. 1. Although absolute cross sections were obtained for the $^{207}\mathrm{Pb}(t,p)^{209}\mathrm{Pb}$ experiment, this was not possible for the $^{210}\mathrm{Pb}(p,d)^{209}\mathrm{Pb}$ measurements. Exposures on this radioactive target were checked by a monitor detector, however, and this information was used to establish relative differential cross sections. Data for the 2p-1h levels seen in the $(p,d)$ reaction were compared with distorted-wave calculations. Assignments of the orbital angular momentum, $l$, transferred in the reaction are based on these fits. The resulting spectroscopic factors, $S_j$, for the 2p-1h states are given in Table I and will be discussed below.

Rather than using a distorted-wave Born-approximation analysis in the case of the two-neutron stripping reaction, it was more desirable to compare the differential cross sections obtained here with previous results obtained in a $^{208}\mathrm{Pb}(t,p)^{210}\mathrm{Pb}$ study,[2] i.e., for the five states of lowest excitation energy $J=L=0$, 2, 4, 6, and 8 where $L$ is the total transferred orbital angular momentum. Thus, the $^{210}$Pb data provides measured angular distributions for a variety of $L$ values that could be used as a template to obtain, empirically, $L$ values for states observed in the $^{209}$Pb nucleus. Furthermore, the cross sections obtained for these two residual nuclei should be related in a simple manner since the final-state particle configurations are expected to be equivalent, differing only in the presence of the spectator $3p_{1/2}$ hole in the reaction $^{207}\mathrm{Pb}(t,p)^{209}\mathrm{Pb}$. Such an assumption is also in the spirit of the pairing excitation model.[3] This fact will be used below to further help identify level configurations and the assignments are given in Table II. It is important to note also that because of the identical final-state configurations, the $Q$ values to these

Table I. Levels excited in reactions $^{210}$Pb$(p,d)^{209}$Pb.

| Level No. | $E_x$ (keV) | $\ell_d$ | $J^\pi$ | Spectroscopic Factors | | | $E_x$(keV) Relative to 2152 keV Level | $E_x$(keV) in $^{207}$Pb |
|---|---|---|---|---|---|---|---|---|
| | | | | $f_{expt}$ | $\sum f_{expt}$ | Theory (2J+1) | | |
| 1[a] | 2153 | 1 | $1/2^-$ | 2.00[b] | 2.00 | 2.00 | 0 | 0 |
| 2 | 2320 | 1 | $(3/2^-)$ | 0.56 | 4.06 | 4.00 | 749 | 897 |
| 6[a] | 2906 | 1 | $3/2^-$ | 0.26 | | | | |
| 9 | 3077 | 1 | $(3/2^-)$ | 3.16 | | | | |
| 3 | 2463 | 3 | $(5/2^-)$ | 0.81 | 5.89 | 6.00 | 570 | 570 |
| 4[a] | 2741 | 3 | $5/2^-$ | 4.06 | | | | |
| 5[a] | 2873 | 3 | $5/2^-$ | 1.02 | | | | |
| 7[a] | 3031 | 3 | $7/2^-$ | 0.04 | 5.83 | 8.00 | 2048 | 2128 |
| 14 | 3499 | 3 | $(7/2^-)$ | 0.29 | | | | |
| 16 | 3902 | 3 | $(7/2^-)$ | 0.16 | | | | |
| 17 | 4222 | 3 | $(7/2^-)$ | 2.74 | | | | |
| 18 | 4270 | 3 | $(7/2^-)$ | 1.55 | | | | |
| 19 | 4309 | 3 | $(7/2^-)$ | 1.05 | | | | |
| 20 | 3659 | 6 | $(13/2^+)$ | 10.10 | 10.25 | 14.00 | 1511 | 1633 |
| 21 | 3751 | 6 | $(13/2^+)$ | 0.01 | | | | |
| 22 | 3811 | 6 | $(13/2^+)$ | 0.04 | | | | |
| 23 | 3937 | 6 | $(13/2^+)$ | 0.07 | | | | |
| 24 | 3995 | 6 | $(13/2^+)$ | 0.03 | | | | |

[a] Seen in both $(t,p)$ and $(p,d)$ reactions.
[b] Data normalized.

levels in the final nuclei are approximately equal and, thus, make the empirical comparison of cross sections and $L$ values quite reliable. Figure 1 shows the absolute differential cross sections for the $(t,p)$ measurements. The solid lines are the differential cross sections for the reaction $^{208}$Pb$(t,p)^{210}$Pb for the indicated $L$ transfer.

In the two-nucleon stripping results, good agreement is seen between the angular distribution for the ground-state transition to $^{210}$Pb and to the $\frac{1}{2}^-$ level in $^{209}$Pb at 2.152 MeV. Column 5 of Table II indicates that the cross section for these two levels is identical within the ± 5% experimental error for the absolute cross sections. In addition, the two-neutron separation energy for these two levels differs by only 44 keV. These results suggest that both levels contain identical particle configurations (namely that of the ground state of $^{210}$Pb) and that the $p_{1/2}$ hole in the $^{209}$Pb case is producing at most a minor per-

Table II. Levels excited in reactions $^{207}$Pb$(t,p)^{209}$Pb.

| Level No. | $E_x$ (keV) | L | $J^\pi$ | $\frac{\sigma(209)}{\sigma(210)}$ | $\sum\frac{\sigma(209)}{\sigma(210)}$ | Centroid Relative to 2152 keV Level (keV) | $E_x$(210) (keV) |
|---|---|---|---|---|---|---|---|
| 1[a] | 2152 | 0 | $1/2^-$ | 1.02 | 1.02 | 0 | 0 |
| 4[a] | 2737 | 2 | $5/2^-$ | 0.25 | 1.02 | 697 | 795 |
| 5[a] | 2868 | 2 | $5/2^-$ | 0.38 | | | |
| 6[a] | 2902 | 2 | $3/2^-$ | 0.38 | | | |
| 7[a] | 3028 | 4 | $7/2^-$ | 0.56 | 1.00 | 955 | 1092 |
| 11 | 3206 | 4 | $(9/2^-)$ | 0.45 | | | |
| 8 | 3072 | 6 | $(11/2^-,13/2^-)$ | 0.43 | 1.00 | 1056 | 1187 |
| 12 | 3309 | 6 | $(11/2^-,13/2^-)$ | 0.58 | | | |
| 10 | 3100 | (8) | $(15/2^-,17/2^-)$ | 0.41 | 1.07 | 1198 | 1268 |
| 13 | 3432 | 8 | $(15/2^-,17/2^-)$ | 0.30 | | | |
| 15[a] | 3561 | 8 | $(15/2^-,17/2^-)$ | 0.36 | | | |

[a] Seen in both $(t,p)$ and $(p,d)$ reactions.

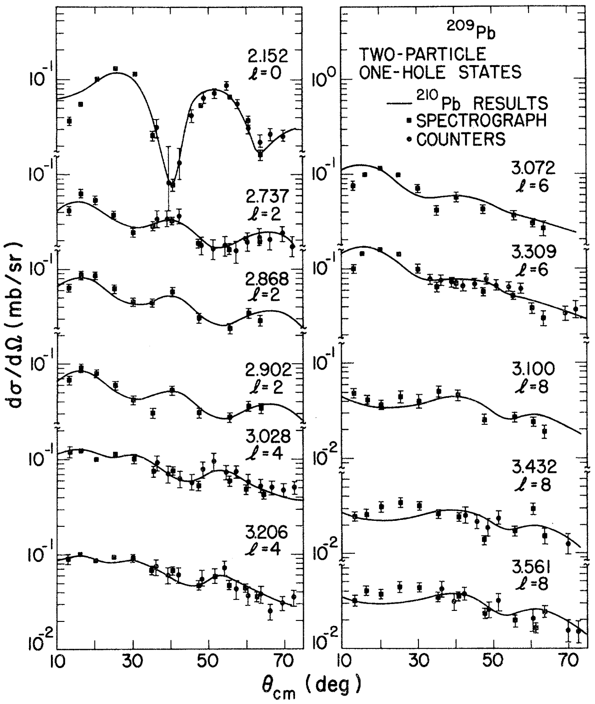

FIG. 1. $^{207}$Pb$(t,p)^{209}$Pb results.

turbation on the two-particle wave functions. It is unlikely that there would be any other $J^\pi = \frac{1}{2}^-$ levels in this energy region and no other $L=0$ transitions in the $(t,p)$ reaction were observed so it is assumed that all of the $(3p_{1/2})^{-1}$ strength lies in this level. In the pickup reaction, the angular distribution to this level is described by an $l=1$ transfer, and the spectroscopic strength is set equal to the shell-model expectation of 2 in column 5 of Table I. All other values of spectroscopic factors are quoted relative to this level.

Because of the $\frac{1}{2}^-$ spin and parity of the $^{207}$Pb target and the zero spin of the $^{210}$Pb target for the pickup reaction, a unique total angular-momentum assignment may be made for each level seen by both reactions. [It is assumed that the transferred neutron pair in the $(t,p)$ reaction remains in a relative $S$ state, as is most probable.] This value is

$$J^\pi = [\tfrac{1}{2}(l+L)]^{(-1)^l}, \qquad (1)$$

where $L$ is the angular-momentum change for the $(t,p)$ reaction, as identified in column 3 of Table II, and, similarly, $l$ is that for the $(p,d)$ reaction. Of course, if $|l-L|>1$ then at least two unresolved levels are being excited by the two reactions.

At about $E_x = 2900$ keV in $^{209}$Pb, two levels would be expected based on the coupling of the $2^+$ state of $^{210}$Pb to the $p_{1/2}$ hole, viz., $[(3p_{1/2})^{-1}, {}^{210}\text{Pb}(2)]_{3/2^-,\,5/2^-}$. In this same energy region another $\frac{5}{2}^-$ state would be expected based on the $[(2f_{5/2})^{-1}, {}^{210}\text{Pb}(0)]_{5/2^-}$ configuration, and this should be strongly excited in the pickup reaction. The two-nucleon stripping reaction excites three levels in this region by an $L=2$ transfer at 2737, 2869, and 2902 keV. The pickup reaction indicates an $l=3$ transfer to the lowest two levels which by Eq. (1) would require these to have $J^\pi$ of $\frac{5}{2}^-$. The third level has an $l=1$ distribution and has, therefore, $J^\pi = \frac{3}{2}^-$. [The nature of these three levels has been observed in a previous $(t,p)$ study.[4]] Column 6 of Table II shows that this exhausts the $L=2$ strength observed in $^{210}$Pb. The splitting of the $\frac{5}{2}^-$ strength is seen to be substantial for the $(t,p)$ reaction by reference to column 5 of Table II. Columns 7 and 8 indicate that the centroid of these levels lies within 100 keV of the $2^+$ level of $^{210}$Pb.

Two $L=4$ assignments in the $(t,p)$ reaction at 3028 and 3206 keV are made on the basis of the $^{210}$Pb data; these would be of the form $[(3p_{1/2})^{-1}, {}^{210}\text{Pb}(4)]_{7/2^-,\,9/2^-}$. Again the summed strength is in excellent agreement with that of $^{210}$Pb. The weak excitation of the lower state in the $(p,d)$ reaction with an $l=3$ transfer indicates a spin of $\frac{7}{2}^-$ and this suggests that the other is $\frac{9}{2}^-$. The $L=6$ doublet in the $(t,p)$ data is not excited by the $(p,d)$ reaction indicating that there is little $11/2^-$ or $13/2^-$ hole strength in this region as expected from the $^{207}$Pb spectrum. All of the $L=6$ strength appears to be in these two levels as seen in Table II.

The $L=8$ strength for the $(t,p)$ reaction was also expected to be concentrated in a doublet since no $15/2^-$ or $17/2^-$ spin states are seen in $^{207}$Pb. However, three levels at 3100, 3432, and 3561 keV were assigned $L=8$. Two possible explanations can be suggested for this threefold splitting. Possibly these are mixing with $J^\pi = 15/2^-$ or $17/2^-$ levels built from higher levels in $^{210}$Pb. However, the next $L=8$ transition is seen at 4022 keV. On the other hand, an additional $J^\pi = 15/2^-$ state is expected as a result of the missing $j_{15/2}$ particle strength which was noted in the $^{208}$Pb$(t,d)^{209}$Pb study.[1] The $(p,d)$ reaction should also weakly excite this state since there is some $(j_{15/2})^2$ strength in the ground state of $^{210}$Pb.[5] One of these three levels is observed in the $(p,d)$ data at 3561 keV, but is is quite weak and has an $l=6$ or 7 distribution. Experimental conditions in the $^{208}$Pb$(t,d)^{209}$Pb data did not permit examination of this energy region. This then must be a principal candidate for the missing $j_{15/2}$ strength.

Thus, the levels shown in Table II contain all of the two-particle strength observed in $^{210}$Pb. Also their centroids have about the same spacing as $^{210}$Pb although some compression is apparent. Table II lists all levels observed in $^{207}$Pb$(t,p)^{209}$Pb up to 3600 keV. The exceptions are the single-particle levels and a weakly excited level at 2584 keV. The splitting of the expected doublets is of the order of 200-300 keV.

All levels observed in the $(p,d)$ reaction up to 3600 keV are indicated in Table I except for the seven known single-particle states and the 2584-keV state referred to above which were omitted for the sake of brevity. Since the lowest three $l=3$ transitions essentially exhaust the shell-model sum rule $\sum_i S_j^i = 2j+1 = 2J+1$ for $j=\frac{5}{2}$, all other $l=3$ transitions were treated as $j=\frac{7}{2}$ transitions. Columns 6 and 7 indicate that all of the $p_{3/2}$ strength was observed, 75% of the $f_{7/2}$ strength, 70% of the $i_{13/2}$ strength. Columns 8 and 9 compare the centroids of the single-particle strength with that observed in $^{207}$Pb. The agreement is good to about 100 keV.

Several new strong states appear in the $^{210}$Pb$(p,d)^{209}$Pb data which were previously unreported and are also not seen in the present $^{207}$Pb$(t,p)$ $^{209}$Pb results. These levels, seen at 2320 and 2463 keV, have $l=1$ and $l=3$ angular distributions and appear to be needed to satisfy the sum rules for the $p_{3/2}$ and $f_{5/2}$ strengths, respectively, as shown in Table I. These states may be members of a $(g_{9/2}, 3^-)$ multiplet similar to the multiplet in $^{209}$Bi, which is based on $h_{9/2}$ proton coupled to the $3^-$ octupole state of $^{208}$Pb.[6] This multiplet would have spins from $\frac{3}{2}^-$ to $15/2^-$. The $3^-$ level is made up of many particle-hole pairs (such as $p_{3/2}{}^{-1}g_{9/2}$), which would mean the multiplet has the construction of two-particle, one-hole states not directly formed by the $(t,p)$ reactions under consideration. However, the $(p,d)$ reaction would be expected to excite such states. Thus, it is suggestive that these new levels ($j=\frac{3}{2}$ and $\frac{5}{2}$) are part of this multiplet which also could include the $15/2^-$ levels at 1.428 keV and the $15/2^-$ state which is tentatively assigned to the level at 3561 keV. The only other member of the multiplet expected to be excited by the $(p,d)$ reaction has $J^\pi = \frac{7}{2}^-$ and can perhaps be associated with one of the lower fragments of the $f_{7/2}$ strength.

The only level which was observed and not explained up to 3600 keV was the level at 2584 keV which appears to have a complex structure because the angular distribution obtained in the $(p,d)$ and $(t,p)$ reactions did not compare with others seen. It is perhaps a mixture of several states of different spin (such as the $f_{7/2}$ and $h_{9/2}$) and it lies approximately at the unperturbed position of the $3^-$ suggesting it could indeed contain several of the multiplet members. Many more levels are seen in the $^{207}$Pb$(t,p)^{209}$Pb and in the $^{210}$Pb$(p,d)^{209}$Pb experiments at higher excitations, but they were not pertinent to the discussion here and will be presented in a more complete form in a later publication.

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