Observation of bound and unbound $1^-$ states in $^{208}$Pb by particle spectroscopy

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Abstract. Using the Q3D magnetic spectrograph of the Maier-Leibnitz-Labaratorium at Garching (Germany), experiments on the $^{208}$Pb($d, d'$), the $^{207}$Pb($d, p$), the resonant and the non-resonant $^{208}$Pb($p, p'$) reactions were performed. The $^{208}$Pb($p, p'$) reaction was investigated near all seven known isobaric analog resonances in $^{209}$Bi. The excitation energies of about 300 states in $^{208}$Pb at $E_x < 8$MeV were determined with an accuracy of about 100eV. The mean distance between states in $^{208}$Pb is about 10keV up to the neutron threshold ($S(n) = 7368$keV). The number of $1^-$ states observed by particle spectroscopy up to the proton threshold ($S(p) = 8.00$MeV) is close to the number predicted by the schematic shell model without residual interaction. The structure of several $1^-$ states is deduced from particle spectroscopy. Four out of the seven lowest $1^-$ states contain about 80% strength of a single configuration.

1. Introduction
In $^{208}$Pb, about three hundred particle bound states with spins from $0^-$ to $14^-$ and $0^+$ to $12^+$ and, in addition, unbound states with spins up to $16^-$ and $17^+$ are known [1]. Most states below 7MeV are described by one-particle one-hole configurations [1, 2, 3, 4, 5]. Yet at rather low energies (4.8-5.3MeV) multi-particle-hole configurations are firmly identified, namely the neutron pairing vibration state and members of the double-octupole multiplet. The proton pairing vibration state is not yet known. Spin, parity, dominant configuration and several admixing configurations for 72 negative parity states with spins from $0^-$ to $8^-$ below 6.4MeV are known [5] and similarly for about 40 positive parity states with spins from $1^+$ to $11^+$ below 5.9MeV [2, 5]. Farther up many states are strongly excited by particle spectroscopy but only few spins are known [1, 6]. I will restrict my discussion to the $1^-$ states.

The schematic shell model without residual interaction (SSM) [2] predicts sixteen $1^-$ states up the neutron threshold ($S(n) = 7368$keV). Nearly the same number of $1^-$ states is more or less well known [1, 5, 7, 8, 9]. Above the neutron threshold more $1^-$ states are known from the resonant neutron capture reaction $^{207}$Pb($n, \gamma$) where $\gamma$-rays up to 0.6MeV were measured [1, 10]. Shell model calculations yield less bound $1^-$ states [11, 12]. I will discuss two questions:
(i) How many $1^-$ states are firmly identified?
(ii) Which particle-hole components are in the $1^-$ states?

2. Particle spectroscopy with the Q3D magnetic spectrograph
We are using the Q3D magnetic spectrograph of the Maier-Leibnitz-Labaratorium at Garching (Germany) for particle spectroscopy since 2003. The peak shape is highly asymmetric (Fig.1).
Figure 1. (from top to bottom) Excerpts of spectra for the $^{208}\text{Pb}(d,d')$, $^{207}\text{Pb}(d,p)$ reactions, and $^{208}\text{Pb}(p,p')$ via the $g_9/2$ and $j_{15/2}$ IAR in $^{209}\text{Bi}$. The energy resolution is 1.5 keV HWHM on the low energy side (magenta marks). The length of the tail depends on the effective target thickness (blue arrows). Each peak is followed by satellites from the electron knockout. $L$-electrons with 15 keV binding energy produce satellites with relative intensities of about 1% (green marks).

The energy resolution of 1.5 keV half-width at half-maximum (HWHM) on the low energy side is obtained only since ten years. The Q3D magnetic spectrograph itself was built forty years ago. Excitation energies below $E_x = 8\text{MeV}$ are determined with a precision of 20-500 eV. Cross sections as low as 0.1 $\mu\text{b/sr}$ are reliably measured within one hour. The peak-to-valley ratio is typically 100:1 and may become 5000:1. From the angular distributions and excitation functions

Figure 2. (from top to bottom) Excerpts of spectra near the $1^-_1$ state for the $^{208}\text{Pb}(d,d')$, $^{207}\text{Pb}(d,p)$ reactions, and for $^{208}\text{Pb}(p,p')$ via the $g_9/2$, $i_{11/2}$ and $s_{1/2}$ IAR in $^{209}\text{Bi}$. On the $s_{1/2}$ IAR the 5245 keV $3^-$ state is twenty times weaker excited, but by the $^{207}\text{Pb}(d,p)$ reaction three times stronger (blue marks). The 5280 keV $0^-_1$ state is almost exclusively excited on the $s_{1/2}$ IAR (yellow mark), the 5276 keV $4^-_{10}$ state on the $i_{11/2}$ IAR (green mark), the 5235 keV $11_1^+$ state and two members of the double-octupole multiplet (5241 keV $0^+$ and 5286 keV $2^+$) by $^{208}\text{Pb}(d,d')$ (magenta marks).
Figure 3. (from top to bottom) Excerpts of spectra near the $1^{-}$ state for the $^{207}$Pb($d,p$) reaction and for $^{208}$Pb($p,p'$) via the $g_{9/2}$ and $s_{1/2}$ IAR in $^{209}$Bi. The five states at $5.64 < E_x < 5.65$ MeV build the densest ensemble below 7 MeV while the mean distance between any two states is 10 keV. The inset shows the angular distribution of the 5640 keV $1^{-}$ state on the $g_{9/2}$ IAR, the drawn curve the calculated angular distribution for a pure configuration $g_{9/2}f_{7/2}$. The cross section for the 5640 keV $1^{-}$ state with the $^{207}$Pb($d,p$) reaction and on the $s_{1/2}$ IAR is 2 $\mu$b/sr (red marks).

up to ten particle-hole components can be determined in each state.

We have performed experiments on the $^{208}$Pb($d,d'$), $^{207}$Pb($d,p$), and the resonant and non-resonant $^{208}$Pb($p,p'$) reactions. Inelastic proton scattering via isobaric analog resonances (IAR)
Figure 5. (from top to bottom) Excerpts of spectra for the $^{208}$Pb($d,d'$), $^{207}$Pb($d,p$) reactions, and for $^{208}$Pb($p,p'$) via the $d_{5/2}$ and $g_{7/2}+d_{3/2}$ IAR in $^{208}$Bi taken above the neutron threshold $S(n)$. The $\gamma$-energies of the first four $1^-$ states above the neutron threshold from the resonant neutron capture reaction $^{207}$Pb($n,\gamma$) [10] are shown at bottom (magenta marks). Two $2^-$ states known from $^{207}$Pb($n,\gamma$) are identified, too (thin red lines).

is equivalent to a neutron pickup reaction on a target in an excited state. The doublet of the $g_{7/2}+d_{3/2}$ IARs is difficult to disentangle. Hence, in effect eight different reactions are studied.

Fig. 1-5 show excerpts from spectra for 3-5 reactions. The full length of a spectrum is about 1 MeV. The mean spacing between the states at $E_x < 7.4$ MeV is 10 keV. The background mostly corresponds to a cross section of about 0.1 $\mu$b/sr. The eight reactions excite the states in a highly selective manner. In Fig. 2, the second $1^-$ state is stronger excited on the $s_{1/2}$ IAR than other states. Several states appear essentially only with one reaction.

In Fig. 3, reliable measurements of cross sections less than 5 $\mu$b/sr decide for the identification of the $1^-_4$ state. In the $^{208}$Pb($n,\gamma$) reaction, two transitions to the ground state are observed in an ensemble of five states at $5639 < E_x < 5650$ keV [1]. The energies are determined with a precision better than 500 eV, the spins as $1^-, 2^+, 2^-, 3^-$, and $9^+$ [2, 5].

A 1% $s_{1/2}p_{1/2}$ admixture to the $5640$ keV $1^-_4$ state is derived from the mean cross section of about 2 $\mu$b/sr observed both for the $^{207}$Pb($d,p$) reaction and the $^{208}$Pb($p,p'$) reaction via the $s_{1/2}$ IAR. The angular distribution of the $1^-_4$ state on the $g_{9/2}$ IAR is well described by the configuration $g_{9/2}f_{7/2}$ (inset in Fig. 3). The $2^+$ state is much weaker excited in particle spectroscopy.
Fig. 4 shows spectra for $6.05 < E_x < 6.10$ MeV. Ref. [1] assigns spin $0^−$ or $1^−$ to the 6076 keV state and $1^−$ to the 6086 keV state, but indeed both states have spin $2^−$. The argument for assigning spin $1^−$ to the 6086 keV state was the strong excitation by the $^{208}\text{Pb}(d,p)$ reaction together with the excitation by $^{208}\text{Pb}(α,α′)$ which indicates natural parity. However, the distribution of the $d_{3/2}p_{1/2}$ strength was determined to be nearly 100% in the 5947 keV $1^−$ state, about 45% $d_{3/2}p_{1/2}$ in the 5924 keV $2^−$ state leaving another 45% $2^−$ strength in the 6086 keV state [3]. The spectra on the $d_{5/2}$ and $g_{7/2}+d_{3/2}$ IARs (Fig. 4) demonstrate the existence of a close neighbor to the 6086 keV $2^−$ state within 2 keV. It is weakly excited by the $^{208}\text{Pb}(d,p)$ reaction and has a considerable cross section on the $s_{1/2}$ IAR interpreted as a $s_{1/2}f_{5/2}$ component. Natural parity and an admixing $s_{1/2}f_{5/2}$ configuration assigns spin $3^−$.

The 6076 keV state is weakly excited by $^{207}\text{Pb}(d,p)$. The peak to valley ratio is still 20:1 (blue mark in Fig. 4). The assignment of spin $0^−$ or $1^−$ [1] is based on the interpretation of the angular distribution for the polarization power in $^{207}\text{Pb}(d,p)$ as $s_{1/2}p_{1/2}$. However, the 6076 keV state is not excited on the $s_{1/2}$ IAR. The vanishing polarisation power is due to an even mixture of $d_{3/2}p_{1/2}$ and $d_{5/2}p_{1/2}$, hence the spin is $2^−$.

Fig. 5 shows excerpts of spectra which cover the $1^−_{15}, 1^−_{16}, 1^−_{17}, 1^−_{18}$ states. They correspond to the four lowest $1^−$ states above the neutron threshold observed by $^{207}\text{Pb}(n,γ)$ with $E_γ = 41, 102, 181, 209$ keV [10]. In particle spectroscopy, at least up to the proton threshold ($S(p) =$

Figure 6. (from left to right) Level scheme of $1^−$ states in $^{208}\text{Pb}$ calculated by the SSM [2] and the SSM extended by including the surface delta interaction (SDI) [4], from experiment [1, 5, 7, 8, 9], and from shell model calculations with realistic forces [11, 12]. The blue dashed line shows the neutron threshold $S(n)$, the yellow region unbound $1^−$ states. More $1^−$ states are expected around $E_x = 6.5 − 7.5$ MeV (red dotted lines). Four states are shown to consist by more than 80% of a single configuration (red lines). The yrast $1^−$ state calculated by Kuo et al [11] at $E_x = 4279$ keV is not shown.
8.00 MeV), the resolution and the background do not change. Excitation energies are determined with a precision better than 0.5 keV (blue marks).

3. Conclusion

Fourteen bound states are firmly assigned the spin of 1− [1, 5, 7, 8, 9] and several 1− states above the neutron threshold are confirmed [1, 10] (Fig. 6). Their excitation energies are determined with an accuracy better than 0.5 keV. The level at $E_x = 6076$ keV assigned spin 0− or 1− [1] is shown to have spin 2−. The level at $E_x = 6.09$ MeV assigned spin 1− [1] is shown to be a doublet with two states of spin 2− and 3− in less than 2 keV distance.

For most of the low-lying 1− states, up to ten particle-hole components are determined from the analysis of the angular distributions and excitation functions. The angular distributions for $^{207}$Pb(d, p) yield the strengths of the configurations where a particle is coupled to the $p_{1/2}$ hole. The comparison of the cross section to calculations yields the orbital angular momenta of the particle(s), the comparison of the analyzing power the spins of the particle(s). For the resonant $^{208}$Pb(p, p′) reaction, the particle in a particle-hole configuration is determined by the excitation on a certain IAR. The mixing of the hole components is determined from the fit of the angular distribution by a series of Legendre polynomials where the coefficients are products of the well known single-particle widths [6], geometrical coefficients depending on the various spin factors, and the phases between the outgoing proton waves. The strengths of the configurations where a particle is coupled to the $p_{1/2}$ hole agree with values derived from $^{207}$Pb(d, p).

Four 1− states contain more than 80% of a single configuration (Fig. 6). Indeed the transformation matrix from the configurations to these states is close to unity; yet the diagonal is shifted by one: The states with order numbers 2, 3, 4, 7 mainly consist of the configurations $g_7/2f_{5/2}$, $d_3/2f_{5/2}$, $g_7/2p_{3/2}$, and $d_3/2p_{3/2}$ have rather large cross sections [6]. Three of these configurations may couple to spin 1−.

The very first calculation of the bound 1− states in $^{208}$Pb by T. T. S. Kuo, J. Blomqvist and Gerry Brown [11] does not differ much from the newest calculation by Alex Brown [12]; both indicate only twelve particle bound 1− states (Fig. 6).

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