EPJ Web of Conferences **66**, 02049 (2014)
DOI: 10.1051/epjconf/20146602049

Complete Spectroscopy of negative parity states in ^{208}Pb with $E_x < 6.3$ MeV

A. Heusler[1,a], T. Faestermann[2], R. Hertenberger[3], H.-F. Wirth[2], and P. von Brentano[4]

[1] *Max-Planck-Institut für Kernphysik, D-69117 Heidelberg, Germany*
[2] *Physik Department E12, Technische Universität München, D-85748 Garching, Germany*
[3] *Department für Physik, Ludwig-Maximilians-Universität München, D-85748 Garching, Germany*
[4] *Institut für Kernphysik, Universität zu Köln, D-50937 Köln, Germany*

Abstract. Using the Q3D magnetic spectrograph at the Maier-Leibnitz-Laboratorium, Garching, experiments with the ^{208}Pb(p,p') reaction via isobaric analog resonances and using the ^{207}Pb(d,p) reaction have been performed with a HWHM of 1.5 keV on the low energy side. All 70 particle-hole states with negative parity predicted by the schematic shell model without residual interaction below $E_x = 6.3$ MeV are identified. Except for the states with spins 1^- and 2^-, more than 80% of the strength in each state can be described by at most four configurations; for spins 0^-, 4^-, 6^-, 7^-, and 8^- two configurations or even one configuration describe more than 95% of the strength. Natural parity configurations are more strongly mixed than unnatural parity configurations.

1 Experiments with the Q3D magnetic spectrograph at Garching

The study of the doubly magic nucleus ^{208}Pb is of key interest as more and more doubly magic nuclei come into the reach of modern experiments. The schematic shell model without residual interaction (SSM [1]) predicts 70 particle-hole states with negative parity below $E_x = 6.3$ MeV. The excitation energy in the SSM is derived from the masses of the nuclei ^{207}Tl, ^{209}Bi, ^{208}Pb and ^{207}Pb, ^{209}Pb, ^{208}Pb, the excitation energies of the particle states in ^{209}Bi, ^{209}Pb, and the hole states in ^{207}Tl, ^{207}Pb, for proton and neutron particle-hole configurations, respectively. Particle spectroscopy offers tools to determine some particle-hole components [1–5].

We have performed experiments since 2003 with the Q3D magnetic spectrograph at the Maier-Leibnitz-Laboratorium, Garching, employing the ^{207}Pb(d,p) reaction and the ^{208}Pb(p,p') reaction via isobaric analog resonances (IAR) [1]. We have especially studied the ^{208}Pb(p,p') reaction; it is equivalent to the neutron pickup reaction on a target of ^{209}Pb in an excited state. By adjusting the proton beam to a certain IAR, the neutron particle is selected. The analysis of the angular distribution allows the determination of the mixture of the neutron holes. Thus below $E_x = 6.3$ MeV, admixtures from 52 neutron particle-hole configurations of negative parity can be determined in more than 100 states (and 12 for positive parity). In contrast, the ^{207}Pb(d,p) reaction allows the determination of only fourteen components of neutron particle-hole configurations where the hole is the $p_{1/2}$ neutron. However, the sensitivity is very high, strengths down to 0.1% can be reliably measured.

---

[a] e-mail: A.Heusler@mpi-hd.mpg.de

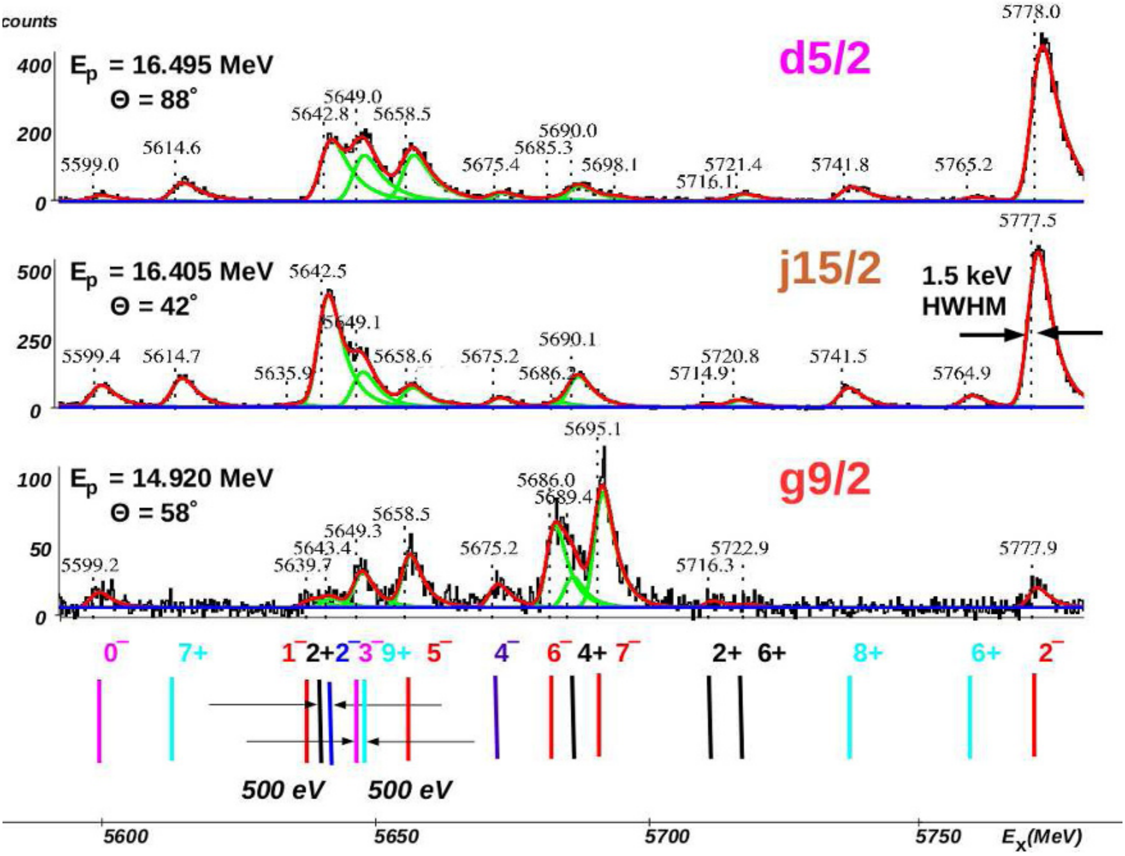

Figure 1. Spectra for the ^{208}Pb(p, p') reaction at $5.58 < E_x < 5.80$ MeV. Seventeen states are identified. Four states with the dominant configuration $j_{15/2}p_{3/2}$ are marked in cyan, five states with the dominant configuration $g_{9/2}f_{7/2}$ in red, and two states with the dominant configuration $d_{5/2}f_{5/2}$ in magenta. The state at $E_x = 5675$ keV contains about 90% of the strength of the proton particle-hole configuration $h_{9/2}d_{5/2}$.

The ^{207}Pb(d, p) and ^{208}Pb(p, p') reactions yield a mean resolution of 3 keV. Yet the line shape is asymmetric and only on the low energy side a half-width at half-maximum (HWHM) of 1.5 keV is achieved (see figure 1 at $E_x = 5778$ keV). Depending on the scattering angle ($20° \leq \Theta \leq 140°$) a long tail may be evident. Atomic electrons limit the resolution since M-electrons in lead have a binding energy of 3 keV. Excitation energies can be determined with an uncertainty of 100 eV (if the statistics are sufficiently high) because of the high linearity of the Q3D magnetic spectrograph.

2 Predictions by the Schematic Shell Model and Experimental Results

Figure 1 shows the selective excitation of states at $5.57 < E_x < 5.80$ MeV on the $g_{9/2}$, $j_{15/2}$, $d_{5/2}$ IARs. The states with dominant configuration $j_{15/2}p_{3/2}$ and spins 6^+, 7^+, 8^+, 9^+ (marked in cyan) are excited on the $j_{15/2}$ IAR but they are invisible on the $g_{9/2}$ IAR. (Near the $d_{5/2}$ IAR, the cross section has decreased to one half from the top of the $j_{15/2}$ IAR since the distance between the two IARs is less than the width of the $j_{15/2}$ IAR.)

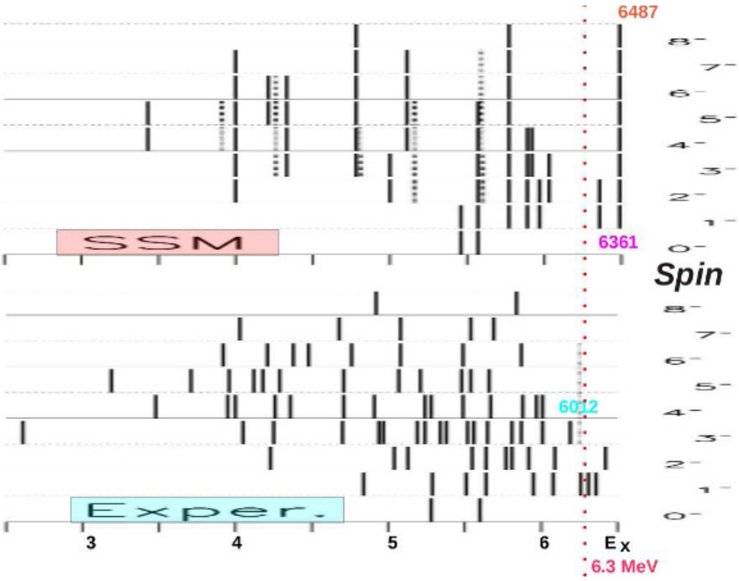

Figure 2. States with negative parity below E_x =6.3 MeV. (top) Prediction by the SSM; neutron and proton configurations are marked by solid and dotted lines, respectively. (bottom) Experimentally identified states. At E_x = 6243, 6251, 6256 keV states with major strength from the configurations $g_{7/2}f_{5/2}$ and $d_{3/2}f_{5/2}$ but unknown spins in the range 3^- - 6^- are identified (dotted line).

The ensemble of five states within 10 keV at $5.39 < E_x < 5.50$ MeV is disentangled. Namely, the 5640 1^- state is excited on the $g_{9/2}$ IAR only, the 5643 2^- state on the $d_{5/2}$ IAR only, the 5648 3^- state both on the $g_{9/2}$ and the $d_{5/2}$ IARs, the 5649 9^+ state on the $j_{15/2}$ IAR only. Finally, the 5642 2^+ state is excited by the direct-(p, p') reaction; it has a smooth excitation function. The distance between the 5642 2^+ and 5643 2^- states and between the 5648 3^- and 5649 9^+ states is about 500 eV.

The SSM predicts 70 particle-hole states with negative parity below E_x = 6.3 MeV, two states with spins of 0^- and 8^- and up to fourteen states for spins 1^- - 7^- (top of figure 2). For spins 1^- and 2^- the next configuration is $s_{1/2}p_{3/2}$ at E_x = 6361 keV, for spins 3^- - 8^- $j_{15/2}i_{13/2}$ at E_x^{SSM} = 6487 keV, and for the spin of 0^- $g_{9/2}h_{9/2}$ at E_x^{SSM} =6844 keV.

We have identified all 70 negative parity states predicted by the SSM below E_x = 6.3 MeV (bottom of figure 2). At $6.02 < E_x < 6.35$ MeV (above the 6012 4^- state) only three states with the spin of 1^- and one state with a spin of 2^- are known. The gap corresponds to the predicted gap in the SSM space at $6033 \le E_x^{SSM} \le 6487$ keV. The sum rules for 64 out of 70 particle-hole configurations with spins 0^-- 8^- are found to be complete within about 10%. A one-to-one correspondence between the 70 SSM configurations and 70 experimentally observed states can be established. By this means complete spectroscopy of negative parity states in ^{208}Pb with $E_x < 6.3$ keV is obtained.

The left side of figure 3 shows the distribution of the strengths for the lowest fourteen 4^- configurations in the lowest fourteen 4^- states. More than 80% of the strength of any state is described by two configurations, in the case of the 3475, 3947, 3995, and 4911 keV states even one configuration contains more than 90% strength. The proton configurations $f_{7/2}s_{1/2}$ and $f_{7/2}d_{3/2}$ are not detectable. Yet since all other twelve configurations predicted below E_x = 6.3 MeV are almost completely identified, and the large gap predicted towards the fifteenth configuration $j_{15/2}i_{13/2}$ at E_x^{SSM} = 6487 keV is verified (there is no 4^- state between E_x = 6012 keV and 6243 keV), the transformation matrix between the configurations and states for a spin of 4^- may be assumed to be orthogonal [7]. Thus the strength of the undetectable proton configurations can be also determined (marked by open rectangles).

The configuration mixing in the 5^- states is much larger (right side of figure 3). Except for the 4710 and 5075 keV states, no state contains more than 80% of a single configuration. The yrare state is the most strongly mixed state; five configurations contribute 10% - 30% each.

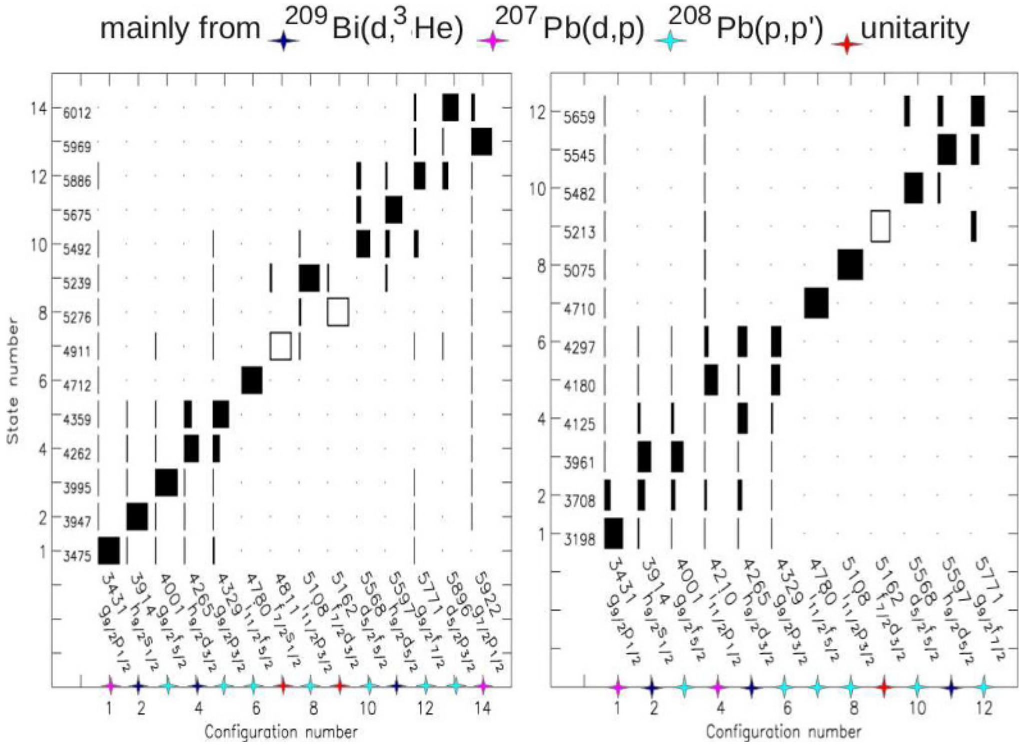

Figure 3. Strengths of SSM configurations in states below $E_x = 6.3\,\text{MeV}$, (left) for the fourteen configurations and fourteen states with the spin of 4^-, and (right) for the twelve configurations and twelve states with the spin of 5^-. Strengths of the configurations with a $p_{1/2}$ hole are determined to 0.1% by the $^{207}\text{Pb}(d,p)$ reaction. The configuration with the dominant strength is determined by the indicated reaction.

Similarly, as for the lowest twenty states [7], the determination of more amplitudes in the transformation matrices will allow us to deduce matrix elements of the residual interaction among particle-hole configurations in ^{208}Pb from the wave functions of the states below $E_x = 6.3\,\text{MeV}$ where the configuration space may be considered to be complete. The transformation matrices for spins 0^-, 4^-, 5^-, 6^-, 7^-, 8^- are indeed complete; for the spins of 1^- and 2^- the completeness is less evident.

References

[1] A. Heusler *et al.*, Phys. Rev. C 74, 034303 (2006); Phys. Rev. C 75, 024312 (2007); Eur. Phys. J. A 44, 233 (2010); Phys. Rev. C 82, 014316 (2010); Eur. Phys. J. A 46, 17 (2010); Eur. Phys. J. A 47, 22 (2011); J. Phys. (London) G 38, 105102 (2011); Yad. Fiz. 76, 860 (2013).
[2] C. F. Moore, J. G. Kulleck, P. von Brentano, and F. Rickey, Phys. Rev. 164, 1559 (1967).
[3] P. Grabmayr, G. Mairle, U. Schmidt-Rohr, *et al.*, Nucl. Phys. A 469, 285 (1987).
[4] M. Schramm, K. H. Maier, M. Rejmund, *et al.*, Phys. Rev. C 56, 1320 (1997).
[5] B. D. Valnion, V. Yu. Ponomarev, Y. Eisermann, *et al.*, Phys. Rev. 63, 924318 (2001).
[6] M. J. Martin, Nucl. Data Sheets 108, 1583 (2007).
[7] A. Heusler and P. von Brentano, Ann. Phys. (NY) 75, 381 (1973).