High resolution particle spectroscopy in $^{208}$Pb

A Heusler$^1$, G Graw$^2$, R Hertenberger$^2$, H-F Wirth$^2$, T Faestermann$^3$, R Krücken$^3$, J Jolie$^4$, C Scholl$^4$ and P von Brentano$^4$

1 Max-Planck-Institut für Kernphysik, Heidelberg, Germany,
2 Ludwig-Maximilians-Universität, München, Germany,
3 Technische Universität, München, Germany,
4 Institut für Kernphysik, Uni Köln, Germany.

E-mail: A.Heusler@mpi-hd.mpg.de

Abstract. By using the Q3D magnetic spectrograph of the Maier-Leibnitz-Laboratorium at München, particle-hole states in $^{208}$Pb are investigated. With the reaction $^{208}$Pb$(p, p')$ at energies $14 < E_p < 18$ MeV an instrumental resolution of $\delta E_{p'}/E_{p'} = 3 \cdot 10^{-4}$ is achieved for protons without energy loss in the target. For lower energies $E_{p'}$ an exponential tail with a width proportional to the effective target thickness appears. Below $E_x = 8.2$ MeV more than 250 states in $^{208}$Pb are observed. Excitation energies are derived with uncertainties of 0.1 keV for strongly excited states by calibration with known data from Nuclear Data Sheets. $^{208}$Pb$(p, p')$ via isobaric analog resonances (IAR) in $^{209}$Bi allows to determine the neutron particle-hole components of each state in $^{208}$Pb. The selective excitation in an IAR yields the parity for each state. Spin and dominant neutron particle-hole configurations of a state are determined from the mean cross section and the shape of the angular distribution for $^{208}$Pb$(p, p')$. From about 120 particle-hole states predicted by the shell model in $^{208}$Pb below $E_x = 6.1$ MeV, about 50 states with negative parity and 30 states with positive parity are identified.

1. Introduction

Particle-hole states in the doubly magic nucleus $^{208}$Pb are investigated using the Q3D magnetic spectrograph in München at a resolution down to 3 keV. Excitation energies of more than 250 levels for $E_x < 8.1$ MeV are determined. Below $E_x < 6.1$ MeV, spin, parity and major particle-hole component of more than 50 negative parity and 30 positive parity states have been identified.

2. Experiments with the Q3D magnetic spectrograph at München

By using the Q3D magnetic spectrograph of the Maier-Leibnitz-Laboratorium in München (Fig. 1), we have studied the inelastic proton scattering on $^{208}$Pb [1, 2]. Protons are accelerated to energies between 14 and 18 MeV and detected by the Q3D magnetic spectrograph at scattering angles between $20^\circ$ and $140^\circ$. A spectrum of 1 MeV length is gathered in typically half an hour with sufficient statistics (Figs. 2, 3, 4). The line shape is asymmetric (Fig. 2). The instrumental resolution as measured for protons without energy loss in the target is 3 keV corresponding to $\delta E_{p'}/E_{p'} = 3 \cdot 10^{-4}$. Towards the right side of the peak, protons with lower energy are displayed; here an exponential tail appears, linear on the logarithmic scale. (The peak-to-valley ratio is 100.) The width of the tail depends on the target thickness, the target angle, the scattering angle, whether the target is used in transmission or reflection and whether the carbon backing...
Figure 1. Q3D magnetic spectrograph and 14 MV tandem accelerator at MLL München.

Figure 2. Spectrum of $^{208}\text{Pb}(p, p')$ for protons with energies from $E_{p'} = 11.55$ MeV (left) to $E_{p'} = 11.49$ MeV (right).

is crossed or not. In addition, satellites from the knockout of $L$-electrons with binding energies $E(L_{I,II,III}) = 13.06, 15.20, 15.86$ keV, respectively, produce satellites to each peak [1, 2]. Peaks from $L$-electrons can be distinguished from peaks of physical states (e.g. $E_x = 4895$ keV in Fig. 2) by their larger width.

Figure 3. Spectra of $^{208}\text{Pb}(p, p')$ taken on the $g_9/2$, $j_{15}/2$, $d_5/2$ IAR. Three states are exclusively excited on the $g_9/2$ IAR, five states on the $j_{15}/2$ IAR.

Figure 4. Excerpt of spectra from Fig. 3 taken on the $g_9/2$, $j_{15}/2$ IAR. Within 100 keV ten states are identified.

3. $^{208}\text{Pb}(p, p')$ via isobaric analog resonances

The lowest states in the doubly magic nucleus $^{208}\text{Pb}$ are described as particle-hole configurations, either neutrons or protons (Fig. 5). In each group of particles or holes there is an intruder. Therefore about 30% of the states have positive parity.

We studied the positive parity particle-hole states built with the intruder particle $j_{15}/2$ and the neutron holes $p_{1}/2$, $f_{5}/2$, $p_{3}/2$ and negative parity states built with all neutron particles.

We are using the method of inelastic proton scattering via isobaric analog resonances (IAR) [1, 2]. In the doubly magic nucleus $^{208}\text{Pb}$ there are 44 excess neutrons (Fig. 6). By adding one neutron a particle state in $^{209}\text{Pb}$ is created. The isobaric analog of such a state consists of 45 components. In each component one excess neutron is converted into a proton.

In the proton decay of an analog resonance (Fig. 7) either the proton escapes with the unchanged energy; this corresponds to the elastic proton scattering. Or $^{208}\text{Pb}$ is left in an...
Particle-hole configurations in $^{208}\text{Pb}$ predicted by the shell model without residual interaction [1, 2]. Amplitudes of the configurations $j_{15/2}p_{1/2}$, $j_{15/2}f_{5/2}$, $j_{15/2}p_{3/2}$ are deduced from $^{208}\text{Pb}(p, p')$ via IAR for 30 states of $^{208}\text{Pb}$ below $E_x = 6.0$ MeV.

Figure 6. Creation of an isobaric analog resonance (IAR) in $^{209}\text{Bi}$. The IAR consists of 45 components.

Figure 7. Proton decay of an IAR in $^{209}\text{Bi}$.
Figure 8. Excitation functions of $^{208}$Pb$(p, p')$ for the 4668, 5127, 5374 5615 keV states with proton energy $15 < E_p < 18$ MeV [2].

Figure 9. Angular distributions of $^{208}$Pb$(p, p')$ for the 6$^-$, 7$^-$, 8$^-$ states with dominant configuration $g_9/2f_7/2$ [3]. Near $\Theta = 40^\circ$ the cross section for the 6$^-$, 7$^-$ configurations differs by a factor two.

4. Identification of states in $^{208}$Pb below $E_x = 6.1$ MeV

Fig. 3 shows spectra of $^{208}$Pb$(p, p')$ taken on the $g_9/2$, $j_{15/2}$, $d_{5/2}$ IAR. Among about 50 identified states in the shown region of 600 keV, many states are strongly excited in the $d_{5/2}$ IAR. Five states are exclusively excited on the $j_{15/2}$ IAR, three states on the $g_9/2$ IAR. They contain large fractions of the configuration $j_{15/2}p_{3/2}$.

Fig. 4 shows an excerpt of only 100 keV length fitted by the deconvolution program GASPAN [2]. At $E_x = 5615$ keV the 7$^+$ state with dominant structure $j_{15/2}p_{3/2}$ is excited. To the right, the outer states in a triplet have spin 6$^-$, 7$^-$ and dominant structure $g_9/2f_7/2$. The middle member with spin 4$^+$ does not show any resonant behaviour. Within 10 keV five states are seen at $E_x = 5.65$ MeV. The highest state of the quintuplet with spin 9$^+$ is excited by the intruder IAR only. The next state is excited both on the $g_9/2$ and $d_{5/2}$ IAR; it has spin 4$^-$. The distance between the 4$^-$ and the 9$^+$ states is $400 \pm 100$ eV.

Fig. 9 shows angular distributions for the 5686 6$^-$, 5694 7$^-$, 5836 8$^-$ states [3]. The 6$^-$, 7$^-$ states are well described by the single configuration $g_9/2f_7/2$. They contain 10% of a proton configuration which is not excited. The 8$^-$ state contains no other configuration; the deep minimum at scattering angle $\Theta = 90^\circ$ is characteristic for the configuration with the highest spin of a particle-hole multiplet [1].

Excitation functions were taken from 14 to 18 MeV proton energy [2]. The parity of more than 100 states is unambiguously determined. In Fig. 8 the 5127 state with spin 2$^-$ or 3$^-$ [4] is excited exclusively in the $d_{5/2}$ IAR, three 7$^+$ states in the $j_{15/2}$ IAR; they have the structure $j_{15/2}$ coupled to $p_{1/2}$, $f_{5/2}$, $p_{3/2}$. The width of the $j_{15/2}$ resonance is 210 keV while the distance between the $j_{15/2}$ and $d_{5/2}$ IAR is 120 keV [2].

For positive parity states with spins 5$^+$, 6$^+$, 7$^+$, 8$^+$, 9$^+$, 10$^+$, almost all states below 6 MeV predicted by the shell model are identified. In Fig. 10 the energies predicted by the shell model without residual interaction (SM) are shown at left, the experimental energies at right. For each state several particle-hole configurations are determined. The states containing the strongest component of the configurations built with a $j_{15/2}$ particle and $p_{1/2}$, $f_{5/2}$, $p_{3/2}$ holes are identified.

Similarly, for negative parity states almost all states below 6 MeV predicted by the shell model are identified [1, 3, 2]. More negative parity states up to 7.5 MeV are being identified.
5. Conclusion
Below $E_x < 6.1\text{ MeV}$ in $^{208}\text{Pb}$, from the study of the $^{208}\text{Pb}(p, p')$ reaction via isobaric analog resonances in $^{209}\text{Bi}$, more than 50 negative parity states with spins $0^-$ to $8^-$ and 30 positive parity states with spins $5^+$ to $10^+$ have been identified. The high resolution of the Q3D magnetic spectrograph in München yields a half width at half maximum of 1.5 keV for scattered protons without energy loss ($E_{p'} \geq E_p - E_x$) and 2-6 keV for $E_{p'} < E_p - E_x$.

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