Talk presented at the HRS workshop
at GSI Darmstadt, Germany

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High resolution particle spectroscopy of $^{208}\text{Pb}$
with the MLL Q3D magnetic spectrograph

50 years ago isobaric analog states in medium heavy nuclei were discovered. Shortly later, accelerators were built with the power to excite such resonances in $^{209}\text{Bi}$; the proton decay then populates states in the doubly magic nucleus $^{208}\text{Pb}$.

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Immediately after the first successful studies of $^{208}\text{Pb}$ a magnetic spectrograph with high resolution and high performance was demanded. Harald Enge found the design of the Q3D magnetic spectrograph.

The first Q3D was realized at the MPIK (HD). Already in 1973 an energy resolution of $2 \times 10^{-4}$ was obtained. Alas, the length of the detector was only 5 cm, whereas 2000 cm are needed.

Several detectors were successfully developed during 30 years until H.-F. Wirth at the MLL built the final detector. Since 2003 we are using the Q3D to study $^{208}\text{Pb}$.

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This ($d, d'$) spectrum covers about 4% of the total region of interest, namely excitation energies from 3 to 8 MeV. The mean spacing of the states is 10 keV. In total we observe more than 300 states in $^{208}\text{Pb}$.

The peak shape is highly asymmetric. On the low energy side, the HWHM resolution is 1.5 keV. The width on the high energy side depends on the scattering angle and the target thickness.

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Inelastic proton scattering via an IAR corresponds to a neutron pickup reaction with a target in an excited state or in the g.s.

There are seven known IARs in $^{209}\text{Bi}$. The parent states in $^{209}\text{Pb}$ are shown at right: $g_{9/2}$ and $g_{7/2}$, $d_{5/2}$ and $d_{3/2}$, $s_{1/2}$, $i_{11/2}$, and $j_{15/2}$. Hence together with the off-resonance proton scattering at $14 < E_p < 18$ MeV, and with the $(d, p)$ and $(d, d')$ reactions, we studied ten different particle reactions.
The \((p, p')\) reaction via IARs is highly selective. Here, the 4206 \(6^-\) state is excited solely on the \(i_{11/2}\) IAR, the 4230 \(2^-\) state essentially only on the \(d_{5/2}\) IAR, and the 4180 \(5^-\) state both on the \(g_{9/2}\) and \(i_{11/2}\) IARs.

I am using the GASPAN code developed by Friedrich Riess (Garching) to analyze the spectra. Each peak is fitted by an individual GAUSSIAN and a common exponential tail. The dotted line shows the GAUSSIAN peak. Each fitted level is drawn green, the sum of all levels red, and the background blue; the original spectrum black.

Here I show more of the \((d, d')\) spectrum. A more careful look reveals several peaks which were not fitted. (You have to tell where GASPAN should try to fit a peak.) GASPAN could easily fit a dozen more peaks in this spectrum, some of them I have marked with magenta arrows.

The distance to the next peak at lower excitation energies is similar, namely about 10-20 keV. Indeed, these satellites derive from the knockout of atomic electrons.

The binding energy of the 13-15 keV for the 8 L-electrons. Evidently the observed HWHM of 1.5 keV is due to knockout of the M-electrons with a mean binding energy of 2.9 keV. The instrumental resolution is better.

The binding energy of the atomic electrons is 88 keV for the 2 K-electrons, and 0.5 and 0.1 for the other electrons.

The position of twelve satellites for the knockout of up to 2 K-electrons and up to 4 L-electrons is indicated in a schematic way.

The spectrum shows just three states and a close ensemble of another three states at the far right. The display is logarithmic. The peak to valley ratio is about 1000:1.

Clearly GASPAN finds up to eight satellites for the three strongly excited states.

The analysis thus seems rather hopeless: The mean spacing of the states in \(^{208}\text{Pb}\) is 10 keV and there are resolved satellites in 15 and 30 keV distance to each peak.

The big problem is: How may one distinguish satellites from peaks of physical states?
A pragmatic method has been developed to distinguish satellites from physical states.

First of all you must know that GASPAN is able to fit two peaks at the same position if the GAUSSIAN widths differ.

Because of the energies for the L-electrons in the three subshells differ by about 2 keV, the width of a peak with a L-satellite is always broader than a peak of a physical state.

The first L-satellite is about 2 keV broader, the 2nd one about 4 keV; at the same time the probability of the knockout diminishes starting with a few percent for the first L-satellite. Therefore you need a peak-top-valley ratio higher than 100:1.

K-satellites are seldom observed because of the low probability and since near 88 and 176 keV distance mostly another physical state is present.

Peaks from L-satellites are tagged like contaminations from light nuclei ($^{12}\text{C}$, $^{14}\text{N}$, $^{16}\text{O}$) and ignored in the subsequent analysis.

Here I show a typical example. For the huge central peak, three satellites are needed; they are marked by yellow ovals.

The residuum spectrum at bottom shows the result of the fit; there are no wiggles exceeding the $2\sigma$ levels. The goodness of the fit is measured with $\chi^2/f = 0.98$.

If you omit the seven peaks marked magenta, the lower residuum spectrum is obtained. Now you find wiggles near the seven peaks marked by black arrows and you obtain $\chi^2/f = 1.37$.

The results from the fit by GASPAN are analyzed by another program.

First of all the correct calibration is done using values from the Nuclear Data Sheets as of 2007 (NDS2007). Three successive fits with a parabola of second order are done. By this means the typical uncertainties $d$-$Ex$ in excitation energies diminish from about 2 to 1 and 0.5 keV.

The calibration is inspected by plotting the momentum of the particle corresponding the excitation energy versus the detector position.

The deviations from a linear fit should have a similar shape everywhere, because the magneto-optic aberrations are highly stable.

Here you see the plot for 300 runs. The excitation energies for each run follow an almost straight line. It is the result of ten years of work.
The mean distance between the states in $^{208}$Pb is about 10 keV. GASPAN can fit doublets with spacings down to about 2 keV if the statistics are sufficient. Yet about one quarter of the states belong to doublets with a spacing of less than 2 keV. The comparison of the energies obtained from the ten different reactions allows to disentangle such doublets.

Here you see the energies determined in 120 runs for a range of 5 keV from 5810 to 5815 keV. They are ordered by the beam energy as indicated by the IAR and for each IAR by the scattering angle.

Clearly near the $d_{5/2}$ IAR only the higher state is excited and near the $g_{9/2}$ IAR the lower state becomes visible. The distance between the two states is determined with 400 eV.

We have identified the 150 lowest states in $^{208}$Pb up to 6.2 MeV and determined the excitation energies. The uncertainties for ($p, p'$) are from 20 eV to 500 eV. The median uncertainty is 70 eV. Half of the values are up to an order of magnitude better than NDS2007, the precision of the other half is comparable to NDS2007.

**Summary**

We have studied ten different particle transfer reactions, especially the inelastic proton scattering via an IAR in $^{209}$Bi.

The energy resolution on the low energy side is 1.5 keV. The annoying effect of the knockout of atomic electrons is handled in a pragmatic manner.

Excitation energies of the 150 states in $^{208}$Pb below $E_x = 6.2$ MeV are determined with a median uncertainty of 100 eV and for another 200 states up to 8 MeV with slightly less precision.

Thank you for your attention.