Journal of Physics: Conference Series **267** (2011) 012035 doi:10.1088/1742-6596/267/1/012035

Neutron-particle and proton-hole excitations in the N=128 isotones ^{208}Hg and ^{209}Tl from spectroscopy following ^{208}Pb+^{238}U deep-inelastic reactions

B Fornal[1], B Szpak[1], R V F Janssens[2], R Broda[1], M P Carpenter[2], G D Dracoulis[3], K H Maier[1], G J Lane[3], J Wrzesiński[1], S Zhu[2]

[1]Institute of Nuclear Physics, Polish Academy of Sciences, Kraków, Poland,

[2]Argonne National Laboratory, Argonne, IL, USA,

[3]Department of Nuclear Physics, Australian National University, Canberra, Australia

Abstract. Gamma rays in the $\pi^{-2}\nu^2$ nucleus ^{208}Hg and $\pi^{-1}\nu^2$ nucleus ^{209}Tl have been studied at Gammasphere using deep-inelastic reactions induced by a 1360 MeV ^{208}Pb beam on a thick ^{238}U target. Previously unknown yrast γ-ray cascades above the 8^+ and $17/2^+$ nanosecond isomers in ^{208}Hg and ^{209}Tl, respectively, were identified in coincidence with known γ rays deexciting the isomers. Yrast levels up to spin 13^- in ^{208}Hg have been located, and they are interpreted in light of the structure of the ^{210}Pb isotone and with the help of shell model calculations. Shell model calculations by using the V_{low-k} realistic interaction have been performed for ^{210}Pb and ^{208}Hg, and compared with experiment. The V_{low-k} effective Hamiltonian seems to account well for the properties of these neutron-rich shell model nuclei.

The nuclei ^{208}Hg and ^{209}Tl are N=128 isotones, with two neutron valence particles and two and one valence proton holes, respectively, outside doubly-magic ^{208}Pb. The structure of these nuclei is well worth studying, since it has the potential of providing information about empirical proton-neutron interactions in the as yet unexplored sector of the nuclidic chart with Z<82 and N>126. What little is known about the properties of nuclei in this region comes mainly from a recent study of ^{238}U fragmentation at relativistic energies [1], where the lowest yrast states in ^{208}Hg and ^{209}Tl were identified up to isomeric excitations with spin and parity 8^+ and $17/2^+$. In ^{208}Hg, an isomeric excitation with a half-life of 99 ns was located at 1297+x keV. It decays via a highly converted, undetected low energy transition followed by a cascade of three γ rays 203, 425 and 669 keV, which establish three other levels at 1297, 1094 and 669 keV. All those states were proposed to be members of the $\pi^{-2}(0^+)\nu g^2_{9/2}$ multiplet, with the 8^+ isomer arising from the coupling of maximally aligned spin of the two $g_{9/2}$ neutrons. Similarly, in ^{209}Tl, a cascade of three transitions 138, 324, 661 keV was found to deexcite a metastable state with a half-life of 95 ns that was placed at 1123+y keV. This isomeric state was interpreted as the highest spin member, $J^\pi = 17/2^+$, of the $\pi s^{-1}_{1/2}\nu g^2_{9/2}$ multiplet.

Another opportunity to access yrast excitations in these neutron-rich species is offered by deep-inelastic processes that occur in collisions of a ^{208}Pb beam with a ^{238}U target [2]. As shown in our earlier works, the production of neutron-rich nuclei in such processes is made

Journal of Physics: Conference Series **267** (2011) 012035 doi:10.1088/1742-6596/267/1/012035

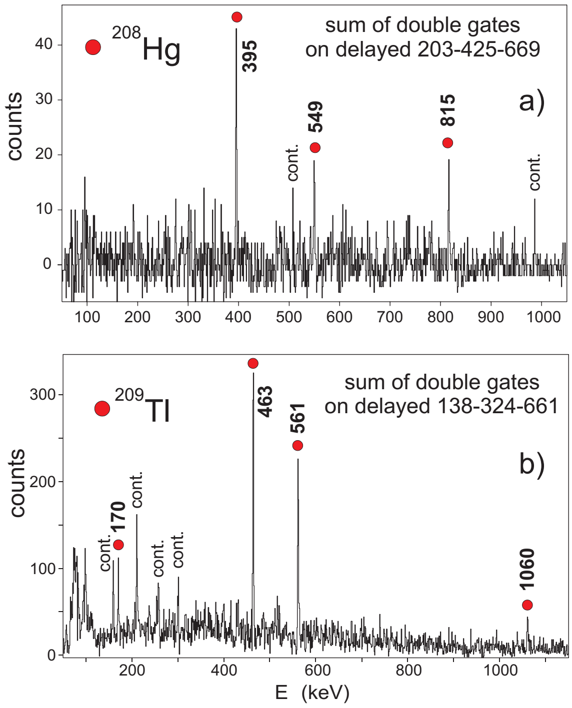

Figure 1. γ-ray coincidence spectra for (a) ^{208}Hg and (b) ^{209}Tl, showing γ rays in prompt-delayed coincidence with double gates on the transitions deexciting the known isomers. Contaminant lines of known origin are also indicated.

possible by a tendency towards N/Z equilibration of the di-nuclear system formed during the collisions [3, 4, 5, 6]. In the reactions under investigation, the lighter colliding partner, ^{208}Pb, had lower N/Z ratio than the target nucleus and, as a result, the production of nuclei with larger neutron excess than the projectile was favored. In the case of Pb products, yields sufficient for spectroscopic studies with the high detection sensitivity Gammasphere spectrometer [7] extended in neutron number up to ^{211}Pb [8].

From the observed production yields for the $^{202-211}$Pb isotopes, it became clear that Tl nuclei with masses up to at least 209 and Hg isotopes with masses up to possibly 208 had to be present in the data set with cross sections sufficient to examine in detail the coincidence relationships required to establish significant level schemes. Having all this in mind, we analyzed data from the experiment that was performed earlier at the Argonne National Laboratory using Gammasphere and a 1360 MeV ^{208}Pb beam from the ATLAS accelerator focused on a thick, 50 mg/cm^2, ^{238}U target. $\gamma-\gamma-$time coincidence data were collected with a composite trigger, requiring three or more Compton-suppressed γ rays to be in coincidence for the in-beam events, and two or more such transitions in coincidence for the out-of-beam events. A total of 2.3×10^9 events were recorded. The beam, coming in bursts with an approx. 0.3 ns time width, was pulsed with an approx. 1.6 μs repetition time, providing clean separation of prompt and isomeric events, which simplified observation of $\gamma-\gamma$ correlations across isomers.

At the beginning of data analysis, we noticed that a sizeable amount of coincidence events was present between known γ rays emitted in the decay of isomeric states located earlier in ^{209}Tl and ^{208}Hg [1]. Based on this observation, a search of γ transitions occurring above the metastable states in those two reaction products was performed by gating on γ rays deexciting the isomers. For this purpose a three-dimensional histogram which contained triple coincidence events with one prompt and two delayed γ rays was used. In the case of ^{208}Hg, all combinations of double gates set on the delayed 203, 425 and 669 keV lines [Fig. 1a] displayed new transitions at energies 395, 549 and 815 keV that definitely occur in this nucleus above the 99 ns isomer. A similar gating procedure applied to the known γ rays in ^{209}Tl revealed a sequence of transitions with energies 170, 463, 561 and 1060 keV [Fig. 1b] that undoubtedly belong to ^{209}Tl and precede in time the 95 ns isomer. By examining coincidence relationships and relative intensities of the newly identified lines, it was found that in ^{209}Tl they form a 463-561-170-1060 keV cascade feeding the isomeric state. For ^{208}Hg, such an analysis suggested that the 395 keV transition populates the 99 ns isomer from a level at 1692+x, whereas the 815 and 549 keV γ rays occur higher in the level scheme. Due to low statistics, however, it was not possible to establish firmly whether the 395, 815 and 549 keV γ rays are in mutual coincidence.

Further insight into the structure of ^{208}Hg could be gained by analyzing the new findings from the perspective of level arrangement in the ^{210}Pb isotone. There should be a close resemblance between the spectroscopy of yrast states in the ^{208}Hg and ^{210}Pb nuclei as in both cases the low lying structure should be dominated by excitations arising from spin recouplings of the two valence neutrons occupying the $g_{9/2}$, $i_{11/2}$ and $j_{15/2}$ single particle states. The lowest orbitals in ^{206}Hg are, in contrast, $s_{1/2}$ and $d_{3/2}$. In this case, the two-proton holes can couple to at most I=2^+ on the energy expense of approx. 1 MeV and, therefore, proton excitations are not expected to play a significant role in the low-lying yrast structure of ^{208}Hg. The ^{210}Pb level scheme, of which the high spin part was established in [9], is shown in Fig. 2. The 2^+, 4^+, 6^+ and 8^+ states are members of the $\nu g^2_{9/2}$ multiplet. Above the 8^+ isomer, three distinct yrast excitations are present at 1806, 2511 and 3152 keV with spin-parity 10^+, 11^- and 13^-, respectively. The 10^+ state arises mostly from the $\nu g_{9/2} i_{11/2}$ configuration, whereas the 11^- and 13^- excitations involve a neutron on the $j_{15/2}$ orbital and have $\nu g_{9/2} j_{15/2}$ and $\nu i_{11/2} j_{15/2}$ character, respectively.

A similar sequence of levels is expected in ^{208}Hg assuming that, to the first approximation, the two proton holes coupled to spin J^π=0^+ play a role of spectators. Indeed, as sugested in [1] the first four excited states are the 2^+, 4^+, 6^+ and 8^+ excitations having mostly a $\pi^{-2}(0^+)\nu g^2_{9/2}$ character. At higher excitation energies, a level located 395 keV above the 8^+ isomer, i.e., at 1692+x keV, and populated with a relatively high intensity is a candidate for the 10^+ state with the $\pi^{-2}(0^+)\nu g_{9/2} i_{11/2}$ dominant configuration. The decay pattern of the 10^+, 11^- and 13^- levels in ^{210}Pb suggests also that the 815 and 549 keV γ rays observed in ^{208}Hg might correspond to $11^- \rightarrow 10^+$ and $13^- \rightarrow 11^-$ transitions.

Our further efforts to interpret the high-spin levels identified in ^{208}Hg were heavily influenced by the results of shell model calculations. These calculations, in a space involving $50<Z<82$ protons and $126<N<184$ neutrons with respect to the ^{208}Pb core, have been performed with the OXBASH code [10]. The single particle energies were taken from experiment. The basis for the residual interaction was the realistic interaction calculated by Kuo and Herling, using the Kuo-Brown method [11], from the interaction between free nucleons inferred from experiments [12]. We have used it, but with the modifications applied in [13, 14] to better fit experimental energies. This covered the interactions between neutron particles, meaning orbitals above the N=126 shell gap, and those between proton holes, meaning orbitals below the Z=82 gap. But for the proton-hole – neutron-particle nucleus ^{208}Hg, the interaction between orbitals above and below the gap is of primary importance. This interaction has been calculated [15] from the H7B interaction [16].

The calculated energies of the yrast states in ^{210}Pb, shown in the left portion of Fig. 2, agree well with experiment as one may expect, since the Kuo-Herling interaction was already proven

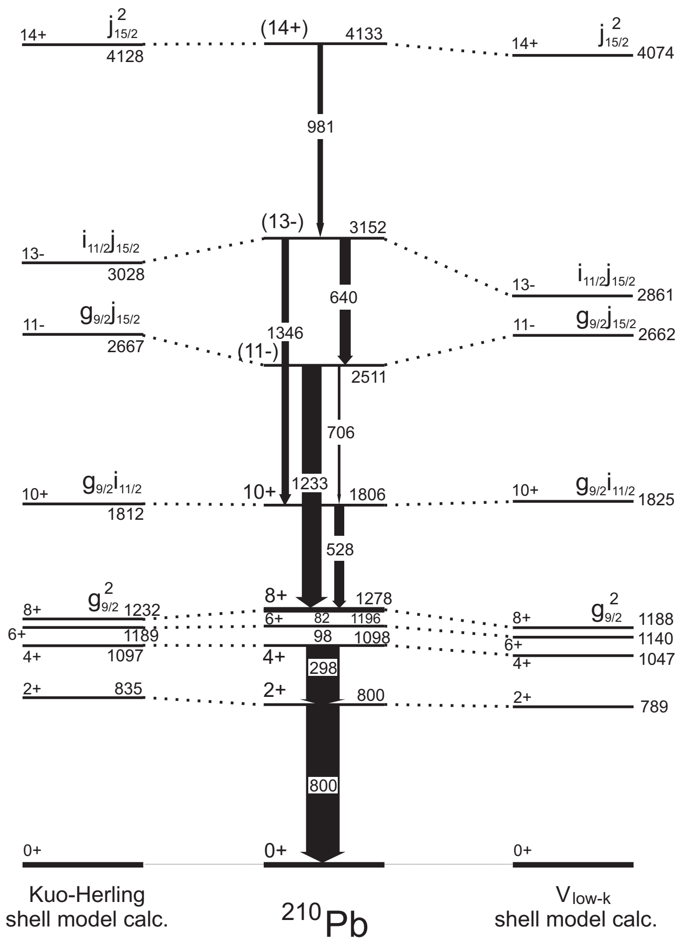

Figure 2. The ^{210}Pb level scheme from [9] with the results of shell model calculations employing the Kuo-Herling interaction (left-hand side) and V_{low-k} realistic effective interaction (right-hand side).

to describe particle-particle excitations. What is more interesting, the results of Kuo-Herling calculations for ^{208}Hg, shown in Fig. 3, account well for the structure proposed from experiment, supporting the assignments of 10^+, 11^- and 13^- quantum numbers to the levels located in the present work above the 99 ns isomer.

It has occurred to us, that the new findings in nuclei belonging to the yet unexplored region of the nuclidic chart with Z<82 and N>126, could serve as a testing ground for the so called V_{low-k} realistic shell model interactions that became recently available. These interactions are derived from realistic nucleon-nucleon (NN) potentials without any adjustable parameters.

We have obtained V_{low-k} effective interaction for the 50<Z<82 and 126<N<184 model space by using the Computational Environment for Nuclear Structure (CENS) by T. Engeland, M. Hjorth-Jensen and G.R. Jansen [17], based on [18]. First, the high-momentum repulsive components of the CD-Bonn NN potential were renormalized by way of the so-called V_{low-k} approach [19, 20], with a momentum cut-off Λ=2.2 fm^{-1}. Next, the V_{low-k} potential was used,

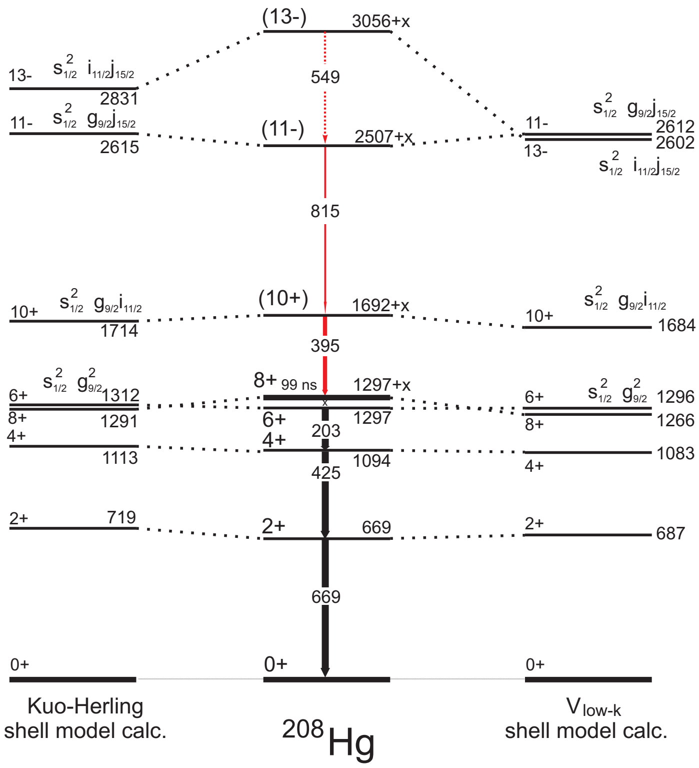

Figure 3. The proposed level scheme for ^{208}Hg. Also shown are the results of shell model calculations performed with the Kuo-Herling interaction (lef-hand side) and V_{low-k} realistic effective interaction (right-hand side).

with the addition of the Coulomb force for protons, to calculate the effective interaction V_{eff} within the framework of the Q-box folded-diagram expansion [21]. The computation of the Q-box was performed at second order in V_{low-k}. It included four two-body terms: the V_{low-k}, the two core polarization diagrams V_{1p1h} and V_{2p2h}, corresponding to one particle-one hole and two particle-two hole excitations, and a ladder diagrams accounting for excluded configurations above the chosen model space. The shell model calculations have been performed using the OXBASH code [10]. We let the valence protons occupy the five levels $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$, and $0h_{11/2}$ of the Z=50-82 shell, while for valence neutrons the model space included the $2g_{9/2}$, $1i_{11/2}$, $1j_{15/2}$, $3d_{5/2}$, $4s_{1/2}$, $2g_{7/2}$, and $3d_{3/2}$ orbitals of the N=126-184 shell. We used the experimental single particle energies defined with respect to the ^{208}Pb core. The results for ^{210}Pb are displayed on the right hand side in Fig. 2. Considering that no adjustable parameters have been involved in the procedure of deriving the shell model two-body matrix elements from the NN potential, the agreement between experimental and calculated level energies is noteworthy. The only major discrepancy, of the order of 300 keV, occurs for the 13^- excitation which involves two neutrons on high spin orbitals, $\nu i_{11/2}j_{15/2}$, coupled to the maximum spin: 13^-.

A similar comparison done for ^{208}Hg and displayed in Fig. 3, shows that energies of the 2^+,

4^+, 6^+, 8^+, 10^+, and 11^- states are also reproduced well by the V_{low-k} effective interaction. Significant deviation is observed only for the 13^- state originating mostly from the $\pi^{-2}(0^+)\nu$ $i_{11/2}j_{15/2}$ configuration, as it was in the case of the corresponding state in ^{210}Pb.

In summary, detailed γ-ray coincidence measurements using Gammasphere for the reaction system ^{208}Pb+^{238}U have provided much information about γ-ray transitions and yrast excitations in ^{208}Hg and ^{209}Tl above the known nanosecond isomers. The new findings include high-spin states in ^{208}Hg arising from two-proton-hole, two-neutron-particle couplings. Considerable similarities between the yrast structure of the ^{210}Pb isotone, as well as comparisons with results of shell model calculations with the Kuo-Herling interaction were important in the interpretation of the ^{208}Hg levels. The newly identified structure was confronted with results of shell model calculations employing realistic V_{low-k} interaction. The satisfactory agreement that was observed between experiment and theory demonstrates noticeable predictive power of shell model calculations based on V_{low-k} realistic Hamiltonian in neutron-rich nuclei.

Acknowledgments
This work is supported by the Polish Ministry of Science and Higher Education under contract N-N202-263238 and by the US Department of Energy, Office of Nuclear Physics, under contract DE-AC02-06CH11357.

References

[1] Al-Dahan N et al. 2009 *Phys. Rev.* C **80** 061302(R)
[2] Fornal B et al. 2001 *Phys. Rev. Lett* **87** 212501
[3] Freiesleben H, Kratz J V 1984 *Phys. Rep.* **106** 1
[4] Broda R 2006 *J. Phys. G* **32** R151
[5] Krolas W et al. 2003 *Nucl. Phys.* A **724** 289
[6] Fornal B et al. 1995 *Acta Phys. Pol.* B **26** 357
[7] Lee I Y 1990 *Nucl. Phys.* A **520** 641c
[8] Lane G J et al. 2005 *Phys.Lett.* B **606** 34
[9] Rejmund M et al. 1997 *Z. Phys.* A **359** 243
[10] Brown B A, Etchegoyen A, Rae W D M, Godwin N S 1984 OXBASH (unpublished).
[11] Kuo T T S, Brown G E 1966 *Nucl. Phys.* **85** 40
[12] Kuo T T S, Herling G H 1975 US Naval Research Laboratory Report No. 2258 (unpublished)
[13] Warburton E K, Brown B A 1991 *Phys. Rev.* C **43** 602
[14] Rydström L, Blomqvist J, Liotta R J, Pomar C 1990 *Nucl. Phys.* A **512** 217
[15] Rejmund M 1998 *PhD thesis* (Warsaw :Institute of Experimental Physics, Warsaw University)
[16] Warburton E K 1991 *Phys. Rev.* C **44** 233
[17] Engeland T, Hjorth-Jensen M and Jansen G R, CENS, a Computational Environment for Nuclear Structure, in preparation.
[18] Hjorth-Jensen M, Kuo T T S, Osnes E 1995 *Physics Reports* **261** 125
[19] Bogner S, Kuo T T S, Coraggio L 2001 *Nucl. Phys.* A **684** 432c
[20] Bogner S, Kuo T T S, Coraggio L, Covello A and Itaco N 2002 *Phys. Rev.* C **65** 051301(R)
[21] Coraggio L, Covello A, Gargano A, Itaco N and Kuo T T S 2009 *Prog. Part. Nucl. Phys.* **62** 135 and references therein.