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Investigation of 0^+ states in mercury isotopes after two-neutron transfer

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Abstract. Using the high-resolution Q3D magnetic spectrograph at the Maier-Leibnitz Laboratory (MLL) Tandem accelerator in Munich, we studied 0^+ excitations in the mercury isotopes ^{198}Hg, ^{200}Hg, and ^{202}Hg after two-neutron transfer. We only observed 4-6 excited 0^+ states per nucleus up to about 3-MeV excitation energy, far fewer than in other experiments of this (p, t) campaign. The results reveal a sharp drop in the number of low-lying 0^+ states towards the ^{208}Pb shell closure. We discuss the low-energy 0^+ state density as a function of the valence nucleon number $N_{\rm val}$. The 0^+ excitation energies and the measured (p, t) transfer cross sections indicate a structural change throughout the Hg isotopes, with the most notable result being the peaking in the cross section of the low-lying excited 0^+_2 state in ^{200}Hg.

1 Introduction

Because of its capability to measure the characteristic forward-peaking of $L = 0$ transfers, the Q3D magnetic spectrograph [1] at the Maier-Leibnitz Laboratory (MLL) Tandem accelerator in Munich –in combination with the focal plane detector [2]– has turned out to be a very successful instrument for the identification of 0^+ excitations. This feature has been extensively used to identify 0^+ states throughout the rare-earth region from gadolinium up to platinum [3–7]. For some nuclei, the number of identified 0^+ states increased sharply with the analysis of the Q3D measurement. The large number of low-lying 0^+ states in ^{154}Gd [8] was interpreted as a new signature for the shape-phase transition from spherical to deformed nuclei [9]. The unexpected high number of observed 0^+ excitations triggered various calculations reproducing the density and distribution of 0^+ states [10–13]. Now, with the experiments on the even mercury isotopes $^{198-202}$Hg [14, 15], we move further to the ^{208}Pb shell closure. This allows us to investigate 0^+ states in the vicinity of the prolate-oblate shape-phase transition in the

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Table 1. Assigned 0^+ states in $^{198,\,200,\,202}$Hg and their relative $R(5/17.5)$ ratio. Newly assigned 0^+ states are marked with an asterisks, tentative (0^+) assignments are denoted in *italic*. Each Hg isotope is labeled with its corresponding valence neutron number N_{val}.

^{198}Hg (N_{val} = 10)		^{200}Hg (N_{val} = 8)		^{202}Hg (N_{val} = 6)	
Energy (keV)	R(5/17.5)	Energy (keV)	R(5/17.5)	Energy (keV)	R(5/17.5)
0.0 (0)	13.3 (4)	0.0 (0)	13.4 (4)	0.1 (1)	15.7 (4)
1401.0 (3)	9.4 (15)	1029.3 (1)	4.8 (2)	1411.0 (3)	12.3 (18)
1646.4 (8) *	>3.35	1515.5 (3)	10.5 (12)	1643.0 (3)	7.3 (5)
1779.6 (2)	4.9 (6)	1856.6 (2)	8.0 (21)	*1655.8 (13)*	*3.1 (13)*
		2246.1 (2) *	5.0 (7)	*1778.9 (6)*	*4.5 (15)*
		2331.8 (3)	*3.2 (9)*	*2126.7 (7)*	*3.2 (17)*
		2475.2 (1) *	4.4 (5)	*2570.7 (10)*	*2.3 (25)*
				2598.5 (2) *	4.3 (4)
				2685.7 (5)	*4.7 (32)*

Hf-Hg region [16] and to test if the prolate-oblate shape-phase transition affects the low-energy 0^+ state density of these nuclei.

2 Experiment & Analysis

To identify $L = 0$ transfers from the Hg 0^+ ground state (GS) in the target material to an excited 0^+ state of the Hg isotope of interest, e.g., a transfer from the ^{200}Hg GS to an excited 0^+ state in ^{198}Hg, we measured spectra at 5°, 17.5°, and 30° laboratory angle relative to the incoming proton beam. A more detailed description of the experimental setup at the Q3D, the specifications of the enriched Hg targets, and the analysis is given in Refs. [14, 15]. The characteristic forward-peaking of $L = 0$ transfers was determined by evaluating the ratio $R(5/17.5) \equiv \sigma(5°)/\sigma(17.5°)$ for each observed transfer. As a safe lower limit to prevent incorrect 0^+ assignments, we used $R(5/17.5) > 3$.

3 Results

The resulting 0^+ assignments for ^{198}Hg, ^{200}Hg, and ^{202}Hg –based on the $R(5/17.5)$ ratio of our data– are listed in Table 1. In total, we assigned four new 0^+ states up to $\sim$ 3-MeV excitation energy in these three Hg isotopes investigated. Tentative assignments are mostly due to a poor population of these particular states. Absolute cross sections for each state are given in Refs. [14, 15]. Some 0^+ assignments in the data sheets [17–19] were not confirmed. Whenever possible, we tested assignments from the (p,t) data for consistency with $\gamma\gamma$ coincidence data of a fusion-evaporation experiment [20] and data of a neutron-capture experiment at ILL Grenoble [21, 22].

4 Discussion

Figure 1 shows the complete data set of 0^+ excitations assigned in this (p,t) campaign at the Q3D spectrograph, ranging from Gd to Hg isotopes. One notes a significantly higher 0^+ state density in ^{154}Gd, which was interpreted as a new signature for the shape-phase transition from spherical to deformed nuclei [8]. The prolate-oblate shape-phase transition observed in Ref. [16] does not show an effect on the low-energy 0^+ density. The number of low-lying 0^+ states rather declines with larger nucleon mass, down to only four low-energy 0^+ assignments in ^{198}Hg and ^{202}Hg.

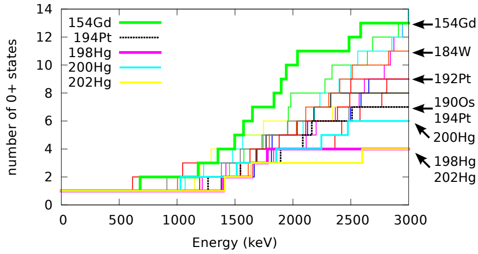

Figure 1. Histogram of low-energy 0^+ states observed in this (p, t) Q3D campaign. Data are taken from Refs. [3–7, 14, 15]. The labeled nuclei on the right-hand side show the decline of 0^+ state density throughout the prolate-oblate shape-phase transitional region, with ^{194}Pt concluded to be the closest to the critical point [16]. Figure based on Ref. [14].

The effect of a decline in the number of low-energy 0^+ states towards the ^{208}Pb shell closure is reproduced by Interacting Boson Model (IBM) [23] calculations and illustrated in Fig. 2. Please see Ref. [14] for more details on the calculations. Figure 2 shows that the number of observed 0^+ states strongly increases with N_{val} as the valence space expands, but saturates near midshell starting at about $N_{\mathrm{val}} = 22$ valence nucleons.

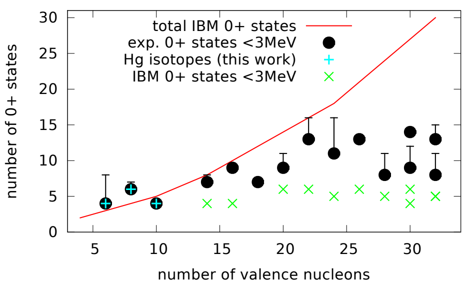

Figure 2. Number of 0^+ states up to 3 MeV assigned in this (p, t) campaign as a function of valence nucleon number N_{val}. The error bars include tentative assignments. The red line corresponds to the maximum number of *sd* IBM 0^+ states, where as the green crosses indicate the calculated number of 0^+ states using realistic parameters, if available. Based on Ref. [15].

Figure 2 shows a small peak at $N_{\mathrm{val}} = 8$, corresponding to ^{200}Hg. By directly comparing further properties of the investigated Hg isotopes one notes more differences shown in Fig. 3: the sequence and level energies of the low-lying states change rapidly at ^{200}Hg and the 0_2^+ state in ^{200}Hg is strongly populated with about 12% of the ground-state cross section. Historically, 0^+ state two-nucleon transfer cross sections approaching or exceeding 15% have signaled structural effects such as phase transitional regions or shape coexistence [9]. In Ref. [24], the enhanced 0_2^+ cross section in ^{200}Hg has been associated with an oblate single particle energy gap, but other explanations like mixing or coexistence cannot be ruled out. Another indicator for structural changes, the two-neutron separation energy S_{2n} (or the differential δS_{2n}), shows at most a weak anomaly [25, 26].

5 Conclusion

The experiments on the Hg isotopes complete a high-resolution (p, t) campaign using the Q3D spectrograph. We observe fewer low-energy 0^+ states in $^{198, 200, 202}$Hg than in other nuclei investigated in this (p, t) campaign. Plotted as a function of valence nucleon number N_{val}, we note a sharp drop in the number of 0^+ states in the near-magic region compared to the transitional and deformed regions, but a saturation towards midshell. The low-energy 0^+ density seems not to be affected by the prolate-oblate shape phase transition [16] in the Hf-Hg region.

The 0_2^+ state in ^{200}Hg has a large two-nucleon transfer cross section, which might be an indicator for a structural change throughout the Hg isotopes at $N = 120$. To understand this effect, it would be very helpful to learn more about the $E0$ ground-state transition of the 0_2^+ state.

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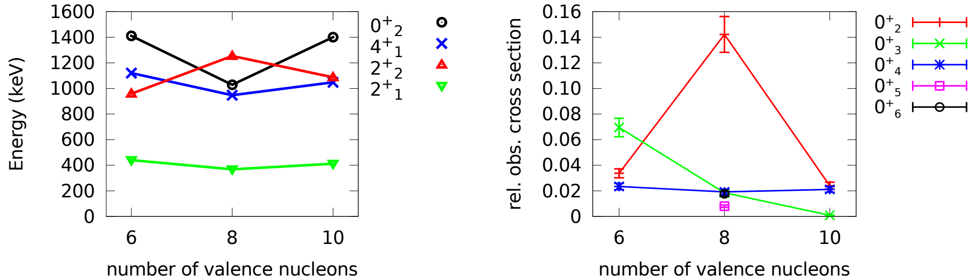

Figure 3. Low-energy states (left) and relative observed cross sections of 0^+ excitations (right) for $^{198,\,200,\,202}$Hg as a function of valence nucleon number N_{val}. The significant changes in excitation energies for the low-lying states and the unusual strong population of the 0_2^+ state at $N_{\mathrm{val}} = 8$, corresponding to ^{200}Hg, are often interpreted as an indicator for a structural change. Based on Ref. [15].

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