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Short note

Particle octupole-vibration coupling near ^{208}Pb

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Abstract. High-spin states in nuclei around ^{208}Pb were populated in deep inelastic collisions of ^{136}Xe and ^{208}Pb projectiles with ^{208}Pb targets at beam energies about 12% above the Coulomb barrier. New states in nuclei in the vicinity of ^{208}Pb have been found that result from the coupling of one and two quasi particles to the lowest 3^- excitation of the ^{208}Pb core. They show the influence of particle octupole-vibration coupling in a pronounced and clear way and verify the validity of this concept.

PACS. 21.60.-n Nuclear-structure models and methods – 23.20.Lv Gamma transitions and level energies – 25.70.Lm Strongly damped collisions – 27.80.+w $190 \leq A \leq 219$

The nucleus ^{208}Pb is one of the best known doubly magic spherical nuclei. Its lowest excited state at 2615 keV is a collective surface vibration of octupole character with a $B(E3) = 34.0(5)$ W.u. [1] for the transition to the ground state. In a shell model description, this level is composed of many particle-hole configurations, none of which does dominate. This low-lying octupole vibration of the ^{208}Pb core contributes significantly to the structure of the low-lying states in neighbouring nuclei, that have only a few valence particles, as has been shown for many cases by the Canberra group [2]. Knowledge of the interaction of the single particles with the octupole phonon is therefore required for the description of many basic states around ^{208}Pb. Of even broader interest is, that this interaction provides a favorable opportunity for an exemplary study of the coupling between vibrational quanta and single particles in general [3]; particle-phonon coupling is often a major determining factor for nuclear structure. In this work new states have been found, that present the influence of particle-octupole coupling very clearly, and therefore allow, together with previous findings, a detailed and quantitative examination of the particle-vibration coupling formalism. A thorough theoretical treatment has been presented by Hamamoto [4].

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Two experiments have been performed to study high-spin states of nuclei in the vicinity of ^{208}Pb [5]. A 30 mg/cm^2 thick ^{208}Pb target, isotopically enriched to 98.7%, was used in these experiments. It was bombarded by heavy ion beams of ^{136}Xe and ^{208}Pb, provided by the UNILAC accelerator of GSI-Darmstadt. The beam energies of 5.7 A·MeV and 6.5 A·MeV were chosen to give about $(E_{\mathrm{CM}} - V_{\mathrm{C}})/V_{\mathrm{C}} = 0.12$ relative excess energy over the Coulomb barrier, because these experimental conditions were used successfully in similar reactions involving lighter ion beams [6,7]. At these beam energies the deep inelastic reactions prevail and contribute significantly to the total reaction cross-section. They result in the transfer of many particles, high angular momentum and large excitation energy to the reaction products. It has been shown that deep inelastic reactions preferentially populate high-spin yrast states [8,6,9,10] and can be used to study excitations in stable and moderately neutron rich nuclei that cannot be reached in fusion-evaporation reactions [11,8,6].

In the experiments the thick target technique has been used. The stopping time of the recoiling nuclei is about 3 ps. Most of the γ-rays are emitted after this time and therefore no Doppler correction is required. The γ-rays emitted before the nuclei are at rest are however highly Doppler broadened and contribute only to the unresolved background.

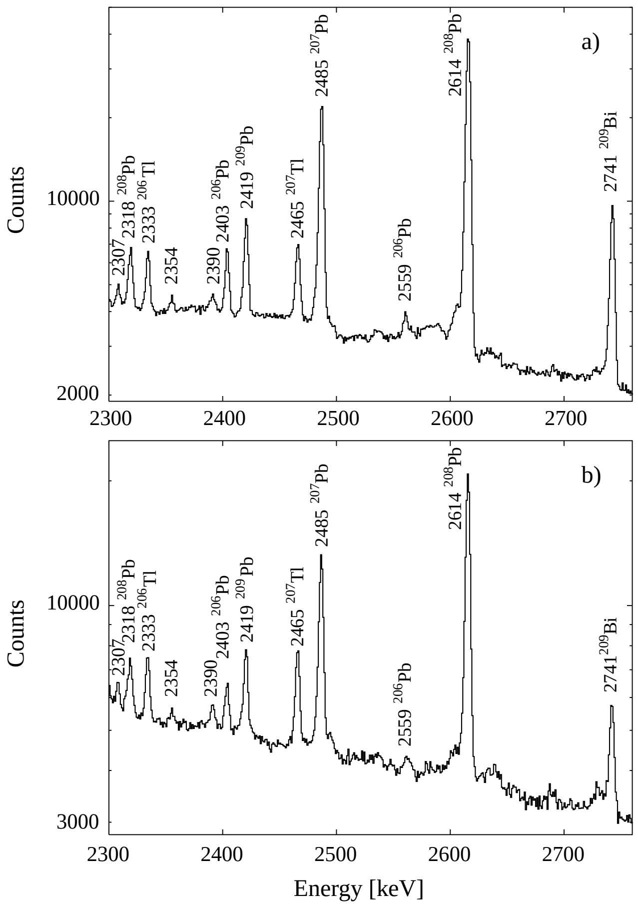

Fig. 1. The high-energy part of the total projection of the prompt-prompt E_γ-E_γ coincidence matrix from the experiment using a) the ^{208}Pb and b) the ^{136}Xe beam.

The experimental set up [12] consisted of five EUROBALL Ge-cluster detectors [13] and 132 NaI detectors of the CRYSTAL BALL [14]. The Ge-detectors, placed at $\sim 154°$ angle to the beam direction, had a total photopeak efficiency of $\sim 2.2\%$ at 1.33 MeV and the CRYSTAL BALL $\sim 53\%$. Energies and times of all Ge- and NaI-detectors were recorded. A coincidence between two Ge-detectors constituted a valid event. The beam pulse that caused the reaction was identified by detecting at least multiplicity 3 in the CRYSTAL BALL. The γ-ray efficiency was measured with standard sources at the target position. The experiment is also described in refs. [15, 16, 12]

The surprising and most striking result of these experiments is presented in fig. 1, that shows the high-energy part of the measured E_γ-E_γ projection around $\hbar\omega_3 = 2615$ keV, the excitation energy of the octupole phonon in ^{208}Pb. The figure shows results obtained in the experiment using a) the ^{208}Pb and b) ^{136}Xe beam. Many strong γ transitions are evident with both beams. Most of these transitions could be identified as indicated in the figure and explained below. All these transitions are interpreted as de-exciting the states with stretched coupling of the octupole vibration to very simple shell model states of high spin. But it should be noted, that spins and parities cannot be rigorously determined from the experimental data.

The 2741 keV line in ^{209}Bi has been known before [17], it de-excites the 3^- excitation on top of the $\pi h_{9/2}$ proton, the $15/2^+$ level. It has been shown [18,10] that the 2485 keV transition occurs in ^{207}Pb and very likely depopulates the $19/2^-$, $(\nu i_{13/2}^{-1} \times 3^-)$ state. In the present experiment [16,5] we could place the 2419 keV line in ^{209}Pb from coincidences with known lines in ^{209}Pb. It de-excites the $(21/2^+)$ state, the octupole vibration on top of the $\nu j_{15/2}$ neutron. Also the 2465 keV line could be assigned to ^{207}Tl [5] as de-exciting the $(17/2^+)$ state of the $(\pi h_{11/2}^{-1} \times 3^-)$ configuration. So the octupole excitation of stretched spin on top of a high-spin orbital is now known in all four single particle or hole neighbours of ^{208}Pb.

Broda *et al.* [10] already reported the 2318 keV transition in ^{208}Pb populating the state of $(\nu j_{15/2} i_{13/2}^{-1}, 14^-)$. It de-excites the $(\nu j_{15/2} i_{13/2}^{-1} \times 3^-, 17^+)$ state. The 2403 keV $E3$ transition has been reported earlier [19] to depopulate the $(\nu i_{13/2}^{-2} \times 3^-,\ 15^-)$ state in ^{206}Pb. In the present experiment we could observe in addition the 2559 keV transition [5] that de-excites the octupole vibration on the $(\nu i_{13/2}^{-1} f_{5/2}^{-1},\ 9^-)$ state in ^{206}Pb [19]. The 2333 keV line has now been assigned to the nucleus ^{206}Tl [5]. It de-excites the 15^+ state of $(\pi h_{11/2}^{-1} \nu i_{13/2}^{-1} \times 3^-)$ configuration. Some lines could not yet be placed. They are marked by their energies in fig. 1. As they occur with both reactions, they belong to a nucleus close to ^{208}Pb and might be also octupole excitations.

Particle octupole vibration coupling (POVC) is pronounced, if two orbitals satisfy the $\Delta j \equiv \Delta l \equiv 3$ rule. This is the case for the new data, namely $g_{9/2}$ and $j_{15/2}$ for ^{209}Pb, $f_{7/2}$ and $i_{13/2}$ for ^{207}Pb, and $d_{5/2}$ and $h_{11/2}$ for ^{207}Tl. Also the structure of these nuclei, with only one single particle or hole, is so simple, that POVC manifests itself most clearly, very little obscured by any other phenomena. Therefore the POVC model is tested in the following, first for ^{209}Pb as an example.

The relevant levels of ^{209}Pb and their properties are determined by the energies of the pure single particle orbitals $g_{9/2}$ and $j_{15/2}$ (more directly by their energy difference), the known energy of the 3^- vibration in ^{208}Pb (2615 keV), and only one coupling matrix element $h(j_{15/2},\ g_{9/2} \times 3^-)$. From the experimental energies of the $9/2^+$, $15/2^-$, $21/2^+$ states the coupling strength of $h(j_{15/2},\ g_{9/2} \times 3^-) = -591$ keV and $E(j_{15/2}) - E(g_{9/2}) = 1557$ keV for the energy difference of the unperturbed states of the single neutron are derived. The results are depicted in fig. 2b) for the coupled states and c) for the uncoupled states. The sizeable energy shifts of levels due to POVC are evident in the figure. The wave functions are

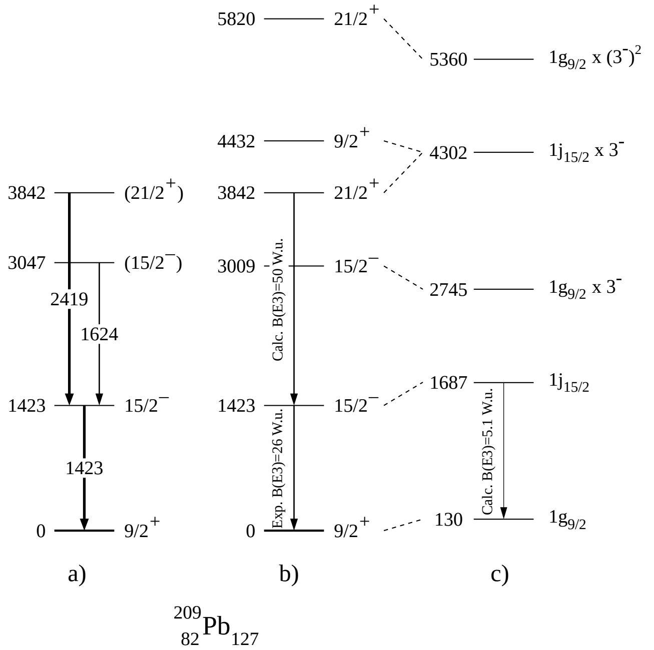

Fig. 2. a) The part of the experimental level scheme of ^{209}Pb. b) Levels in ^{209}Pb as calculated in the frame of POVC model. The energies of levels $E(9/2_1^+)$, $E(15/2_1^-)$, $E(21/2_1^+)$ are from the experiment and have been used in the calculation. c) The energies of the uncoupled states given relative to the ground state of ^{209}Pb.

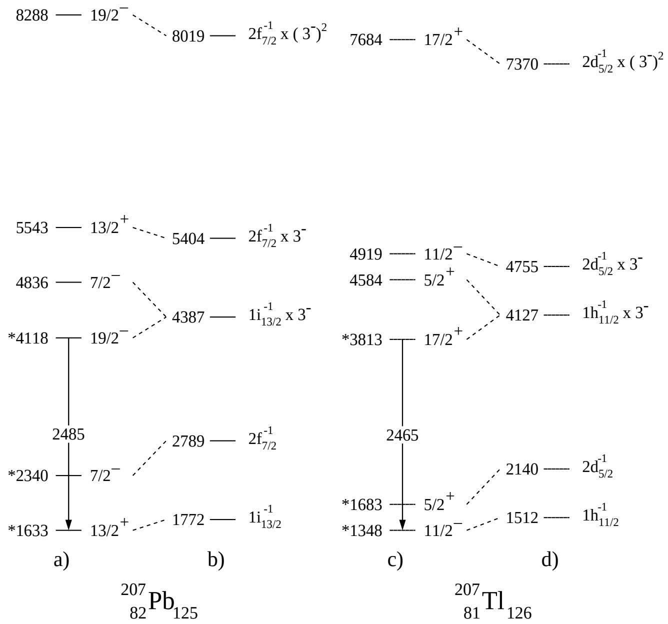

Fig. 3. a), c) Levels in ^{207}Pb and ^{207}Tl, respectively as calculated in the frame of POVC model. The energies of levels marked by * are from the experiment and have been used in the calculation. b), d) The energies of the uncoupled states given relative to the ground state of ^{207}Pb and ^{207}Tl, respectively.

calculated as

$$
\begin{aligned}
\left|9/2_1^+\right\rangle &= 0.99\cdot\left|g_{9/2}\times 0^+\right\rangle + 0.17\cdot\left|j_{15/2}\times 3^-\right\rangle ,\\
\left|15/2_1^-\right\rangle &= 0.91\cdot\left|j_{15/2}\times 0^+\right\rangle + 0.41\cdot\left|g_{9/2}\times 3^-\right\rangle ,\\
\left|21/2_1^+\right\rangle &= 0.88\cdot\left|j_{15/2}\times 3^-\right\rangle + 0.48\cdot\left|g_{9/2}\times (3^-)^2\right\rangle .
\end{aligned}
$$

With the measured reduced transition probabilities of $B(E3, 15/2_1^- \rightarrow 9/2_1^+) = 26(4)$ W.u. [20] in ^{209}Pb and $B(E3, 3^- \rightarrow 0^+) = 34.0(5)$ W.u. [1] in ^{208}Pb, these wave functions give the unknown $B(E3, j_{15/2} \rightarrow g_{9/2}) = 5.1$ W.u. for the transition between pure shell model orbitals. The corresponding effective $E3$ charge is $e_{\text{eff}} = 1.35\ e$ and represents the coupling to the higher frequency 3^- core excitations. This value compares well to $e_{\text{eff}} = 1.5\ e$ derived for a very similar $E3$ transition $i_{13/2} \rightarrow f_{7/2}$ in the one neutron nucleus ^{147}Gd [21]. From this the transition strength $B(E3, 21/2_1^+ \rightarrow 15/2_1^-) = 50$ W.u can be predicted, which is largely determined by the double octupole admixture of the $21/2_1^+$ state. The calculated wave functions compare well with the measured spectroscopic factors. Kovar *et al.* measured in the ^{208}Pb(d, p)-reaction $S(l = 7) = 0.77$ for the 1423 keV level and a sum of 0.17 for levels at 3052, 3556, and 3716 keV; the model wave functions give 0.83 and 0.17. The splitting of the higher $15/2^-$ state involves different interactions, that are not considered here.

The situation in ^{207}Pb and ^{207}Tl is very similar to that in ^{209}Pb. The relevant orbitals are here $\nu i_{13/2}$ and $\nu f_{7/2}$, or $\pi h_{11/2}$ and $\pi d_{5/2}$. Again the free parameters can be determined from 3 measured level energies, as indicated in fig. 3. The coupling strengths are calculated as $h(i_{13/2}^{-1}, f_{7/2}^{-1} \times 3^-) = +725$ keV for ^{207}Pb and $h(h_{11/2}^{-1}, d_{5/2}^{-1} \times 3^-) = +747$ keV for ^{207}Tl. Figure 3 shows the derived energies, and the deduced wave functions are:

^{207}Pb:

$$
\begin{aligned}
\left|13/2_1^+\right\rangle &= 0.98\cdot|i_{13/2}^{-1}\times 0^+\rangle - 0.19\cdot|f_{7/2}^{-1}\times 3^-\rangle ,\\
|7/2_1^-\rangle &= 0.91\cdot|f_{7/2}^{-1}\times 0^+\rangle - 0.42\cdot|i_{13/2}^{-1}\times 3^-\rangle ,\\
|19/2_1^-\rangle &= 0.97\cdot|i_{13/2}^{-1}\times 3^-\rangle - 0.25\cdot|f_{7/2}^{-1}\times (3^-)^2\rangle ,
\end{aligned}
$$

^{207}Tl:

$$
\begin{aligned}
|11/2_1^-\rangle &= 0.98\cdot|h_{11/2}^{-1}\times 0^+\rangle - 0.21\cdot|d_{5/2}^{-1}\times 3^-\rangle ,\\
|5/2_1^+\rangle &= 0.92\cdot|d_{5/2}^{-1}\times 0^+\rangle - 0.40\cdot|h_{11/2}^{-1}\times 3^-\rangle ,\\
|17/2_1^+\rangle &= 0.96\cdot|h_{11/2}^{-1}\times 3^-\rangle - 0.29\cdot|d_{5/2}^{-1}\times (3^-)^2\rangle .
\end{aligned}
$$

In these cases, in contrast to ^{209}Pb, the orbitals of lower spin $\nu f_{7/2}$ and $\pi d_{5/2}$ respectively, are at higher energy and the corresponding states decay by M1-transitions; no E3 transitions can be observed. Two experiments [22,23] give different results for the spectroscopic factors of the $f_{7/2}$ neutron hole in ^{207}Pb, but agree that about 20% of the strength is shifted to the region of the $\nu i_{13/2} \times 3^-$ state, as predicted by the model. The ^{208}Pb$(d,{}^3$He)-reaction [24] shows also, that about the predicted amount of $d_{5/2}$ strength is shifted to energies around the calculated octupole state.

Table 1. The energy shifts for the states resulting from particle octupole-vibration coupling in nuclei with two quasi-particles outside the ^{208}Pb core. The following shorthand was used for the energy shifts $\Delta E = E_\gamma - \hbar\omega_3$: $\Delta E_1 \equiv \Delta E(^{209}\text{Pb},\ 21/2^+)$, $\Delta E_2 \equiv \Delta E(^{207}\text{Pb},\ 19/2^-)$, $\Delta E_3 \equiv \Delta E(^{207}\text{Pb},\ 11/2^+)^\dagger$, $\Delta E_4 \equiv \Delta E(^{207}\text{Tl},\ 17/2^+)$. All energies are given in keV.

Nucleus	^{208}Pb	^{206}Tl	^{206}Pb	^{206}Pb
State	9062	4976	6430	5218
Spin	(17^+)	(15^+)	15^-	12^+
Configuration	$\nu 1j_{15/2}1i^{-1}_{13/2} \times 3^-$	$\pi 1h^{-1}_{11/2}\nu 1i^{-1}_{13/2} \times 3^-$	$\nu 1i^{-2}_{13/2} \times 3^-$	$\nu 1i^{-1}_{13/2}2f^{-1}_{5/2} \times 3^-$
E_γ	2318	2333	2403	2559
ΔE_{EXP}	−297	−282	−212	−56
ΔE_{CAL}	−326	−280	−200	−92
Comments	$\Delta E_1 + \Delta E_2$	$\Delta E_4 + \Delta E_2$	$20/13 \cdot \Delta E_2$	$\Delta E_2 + \Delta E_3$
	$(-196) + (-130)$	$(-150) + (-130)$	$20/13 \cdot (-130)$	$(-130) + (38)$

† The candidate for the state of $(\nu 2f^{-1}_{5/2} \times 3^-,\ 11/2^+)$ configuration in ^{207}Pb has been observed at 3223(2) keV in the ^{207}Pb(p, p′) reaction [25].

If the concept of POVC is appropriate, it should also be applicable, if more than one particle is involved. Figure 1 shows octupole-transitions on two particle states of very pure and simple structure. These states are yrast and result from stretched coupling of the orbitals, that have been discussed above. Table 1 compares the energy shifts of the octupole vibration based on these states with two excited particles or holes with that of the individual particles (holes). It turns out that the individual shifts can be simply added for stretched configurations or more generally calculated by simple angular momentum recoupling. The accuracy of this approach ranges from 2 to 36 keV. The interaction is weak enough, that the linear terms only give a good description, but it also exceeds any other interactions so much, that they do not spoil the agreement between theory and experiment.

So far it has been shown, that POVC reproduces the measured energies of octupole states built on two-particle states from parameters (primarily the coupling strengths), that are derived from the observed couplings with single particle states; in other words the model is consistent in itself. The coupling strength can however also be independently calculated [4] from a standard single particle potential and the amplitude of the octupole vibration in ^{208}Pb, that is determined by the $B(E3, 3^- \to 0^+, {}^{208}\text{Pb})$. The results of Hamamoto [4]

$$h(i^{-1}_{13/2}, f^{-1}_{7/2} \times 3^-) = +710 \text{ keV (exp. 730)}\,,$$
$$h(h^{-1}_{11/2}, d^{-1}_{5/2} \times 3^-) = +760 \text{ keV (exp. 750)}\,,$$
$$h(j_{15/2},\ g_{9/2} \times 3^-) = -770 \text{ keV (exp. 590)}\,,$$

are in astonishingly good agreement with the experimental data.

In summary, using the inelastic heavy ion reactions to produce nuclei around ^{208}Pb, levels have been eminently populated, that result from the octupole vibration built on high-spin one and two particle states. Several previously unknown states of this nature have been identified. They show the influence of particle-vibration coupling most clearly and verify that the theoretical description of this phenomenon is valid also quantitatively.

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