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Competition between excited core states and $1\hbar\omega$ single-particle excitations at comparable energies in ^{207}Pb from photon scattering

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ABSTRACT

The $\text{Pb}(\vec{\gamma},\gamma')$ photon scattering reaction has been studied with the nearly monochromatic, linearly polarized photon beams at the High Intensity γ-ray Source (HIγS) at the DFELL. Azimuthal scattering intensity asymmetries measured with respect to the polarization plane of the beam have been used for the first time to assign both the spin and parity quantum numbers of dipole excited states of ^{206,207,208}Pb at excitation energies in the vicinity of 5.5 MeV. Evidence for dominant particle–core coupling is deduced from these results along with information on excitation energies and electromagnetic transition matrix elements. Implications of the existence of weakly coupled states built on highly excited core states in competition with $1\hbar\omega$ single particle (hole) excitations at comparable energies are discussed.

A widely used approach to understand odd-mass nuclear systems is to consider particle–core coupled wave functions $[\Psi\rangle = [\phi_j\rangle \otimes [\psi_{\text{core}}\rangle$ that enable one to conveniently consider both, core excitations and single-particle excitations. Particle–core coupled basis states are often considered to represent particularly good approximations to the actual eigenstates of the full fermionic system if either the core is very robust against small perturbations, such as a doubly-magic nucleus, or if the coupled single particle has quantum numbers different from those of the nucleons in the core. One class of such systems are odd-mass hypernuclei [1–3]. Core excitations and single particle excitations will compete, however, when, for identical quantum numbers, the energies of the two modes of excitation are almost equal and, hence, mixing may occur.

As an example, the left half of Fig. 1 shows the lowest states of ^{12}C with spin and parity quantum numbers 0^+, 2^+, and 1^- together with the known levels of the hypernucleus $^{13}_{\Lambda}$C [4,5]. The $1/2^+$ ground state of $^{13}_{\Lambda}$C represents the Λ hyperon in the $\Lambda(1s_{1/2})$ lowest shell model orbital coupled to the 0^+ ground state of its ^{12}C core. The $3/2^+$, $5/2^+$ doublet structure observed near 4.8 MeV has been interpreted as the Λ hyperon in the $\Lambda(1s_{1/2})$ orbital weakly coupled to the 2^+_1 state of ^{12}C [5,6]. The $1/2^-$, $3/2^-$ doublet near 10.8 MeV is due [6] to the Λ hyperon in the $\Lambda(1p_{1/2,3/2})$ orbitals and it provides a direct measurement of the small spin–orbit splitting [7] of 0.15 MeV between the $\Lambda(1p_{1/2})$ and $\Lambda(1p_{3/2})$ orbitals [8]. This value is appreciably smaller than the known values for nucleons and it was measured recently from (K^-,π^-) strangeness transfer reactions to the hypernucleus $^{13}_{\Lambda}$C at Brookhaven [8]. Excited $3/2^-$ and $1/2^-$ states of $^{13}_{\Lambda}$C were observed at 10.70 and 10.90 MeV. Negative parity and total angular momenta $J = 1/2$, $3/2$ are clearly assigned from p-wave strangeness transfer data.

Since the $\Lambda(1s_{1/2} \to 1p_j)$ $1\hbar\omega$ single-particle excitations occur at about the same energy as the dominant 1^- electric dipole excitation of the ^{12}C core nucleus at 10.84 MeV excitation energy, one could expect that these two structures could easily mix. These structures have been considered [5] previously but, evidently the mixing of the core excitation into the observed doublet is small [9].

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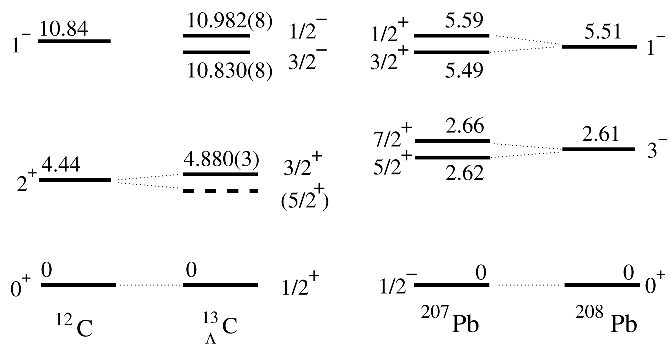

Fig. 1. *Left*: The known level scheme of the hypernucleus $^{13}_{\Lambda}$C [4,5] is compared to the relevant part of the level scheme of its core nucleus ^{12}C. *Right*: Relevant parts of the level schemes of ^{207}Pb and its core ^{208}Pb. The spin and parity quantum number assignments that are crucial to the interpretation of the doublet of strong electric dipole excitations of ^{207}Pb near 5.5 MeV are from this work. *Both*: The energy axes are scaled relative to the 1^- core states and the splittings of the doublet-level bars are increased for better visibility. The dotted lines connect established weakly coupled structures in the odd-mass systems to the corresponding core states.

It is an intriguing question whether such a small mixing between close-lying core excitations and single-particle excitations differs for hypernuclei and purely nucleonic systems. In order to draw conclusions on this question it is necessary to find and study a similar situation for a purely nucleonic environment.

The ideal test could come from high-resolution spectroscopy of ^{13}C itself with the seventh neutron occupying the $\nu(1p_{1/2})$ neutron orbital. However, ^{13}C is neutron unbound at 10.8 MeV being well above its neutron separation energy of 4.95 MeV which makes high-resolution γ-ray spectroscopy impractical. In order to study an example where a doubly-magic nucleus has a dominant E1 excitation at an energy close to the $1\hbar\omega$ neutron excitations in the neighboring even–odd spin-1/2 nucleus, we have considered the nucleus ^{207}Pb with its $\nu(3p^{-1}_{1/2})$ neutron hole in the doubly-magic core ^{208}Pb. The right half of Fig. 1 shows the 0^+ ground state of ^{208}Pb, its collective 3^- state at 2.61 MeV and the dominant E1 excitation at 5.51 MeV together with the $J \otimes 1/2^-$ weakly-coupled doublets of levels in ^{207}Pb. While the $5/2^+$, $7/2^+$ states of ^{207}Pb at 2.6 MeV were known previously [10], the $1/2^+$, $3/2^+$ states of ^{207}Pb at 5.5 MeV need to be identified experimentally.

An unambiguous identification of this doublet requires a method that is (a) selective for strong electromagnetic dipole excitations and (b) sensitive to spin and parity quantum numbers of the excited states in an odd-mass system. This possibility is given by linearly polarized intense γ-ray beams such as those that recently became available at the HIγS facility at the Duke FELL.

It is the purpose of this Letter to report on the identification of a doublet of excited states of the odd-mass proton-closed-shell nucleus ^{207}Pb at 5.5 MeV that results from the coupling of the $\nu(3p^{-1}_{1/2})$ neutron hole to the pronounced electric dipole (E1) excitation of ^{208}Pb at 5.512 MeV excitation energy. Weak coupling of the $\nu(3p^{-1}_{1/2})$ neutron hole to a 1^- state of the ^{208}Pb core results in a doublet of states of ^{207}Pb with spin and parity quantum numbers $J^\pi = 1/2^+$ and $3/2^+$. This 1^- state of ^{208}Pb has a half-life of only 16 as (attoseconds) and displays, with $B(\mathrm{E1}; 1^-_{5512} \to 0^+_1) = 0.161(12)\ e^2\,\mathrm{fm}^2 = 0.071$ W.u. the largest E1 decay transition rate of an individual bound state in a heavy nucleus known to us. Observation of similarly strong E1 decay rates in the isotone ^{207}Pb along with definite spin and parity assignments can serve as a sufficient signature for a corresponding core-coupled structure. Any energy-splitting of the core-coupled multiplet as a function of angular momentum or any modification of transition strengths represent integral measures for the interaction of the core excitation with the coupled single-particle state.

Indeed, a doublet of strongly dipole-excited states of ^{207}Pb has previously been observed at 5.490 and 5.597 MeV [11] close to the energy of the dominant $J^\pi = 1^-$ E1 excitation of ^{208}Pb at 5.512 MeV. These states are candidates for the $1^-_{5.512} \times \nu(3p^{-1}_{1/2})$ $1/2^+$ and $3/2^+$ weakly coupled states of ^{207}Pb. Their corresponding dipole transition rates were measured in nuclear resonance fluorescence experiments at the Darmstadt S-DALINAC facility using unpolarized bremsstrahlung [11]. Spin and parity quantum numbers could not be assigned from that experiment, making it impossible to either firmly prove the quantum numbers required for the presence of weak coupling or to determine even the sign of the energy splitting $\Delta E_{\nu(p^{-1}_{1/2})}(5.512) = E(\frac{3}{2}{}^+_{\nu p}) - E(\frac{1}{2}{}^+_{\nu p})$ of the core-coupled multiplet. Odd-mass nuclei represent "unfavorable cases" [12] where spin and particularly parity assignments are difficult with traditional techniques. Therefore, experimental information is scarce. The new generation of modern light sources based on Compton back-scattering of laser light now make such studies possible.

Nuclear resonance fluorescence experiments were performed at the HIγS facility at Duke Free Electron Laser Laboratory (DFELL) using its nearly monoenergetic linearly polarized γ-ray beams. The HIγS [13] is based on the Duke/OK-4 Storage Ring FEL. Head-on collisions of the FEL photons and the relativistic electrons in the storage ring generate γ-rays in the laboratory system by the Compton effect. The wavelength of the FEL photons and the energy of the electron beam in the ring are tunable over a large range of values, which allows the production of γ rays at a corresponding range of energies. An on-axis collimator about 60 m down-stream of the Compton-collision point selects a narrow cone of linearly polarized, nearly monoenergetic γ rays from 180° Compton back-scattering processes. That beam is tunable in energy in the MeV range and is available for nuclear resonance fluorescence reactions on target nuclei placed in the γ-ray beam. Fluorescence γ-quanta result from the decay of resonantly photo-excited nuclear levels and can be observed with high energy resolution using large volume HPGe semiconductor detectors. Details of the set-up and the method have been published previously in Refs. [13–15].

The OK-4 FEL was tuned to lase at wavelengths around 450 nm. The collimator system was chosen to have a diameter of 2.54 cm, resulting in an energy resolution of about 3% for the γ-ray beams, i.e., of about 0.2 MeV FWHM for γ-ray beams of 5.6 MeV [14]. Mean energies of the γ-ray beams used for our experiments were $E_\gamma = 5.5$ and 5.6 MeV. The γ-beam intensity on target was of the order of 10^7 γ per second. Data were taken for about 6 hours. The target consisted of a 5.65-g/cm^2-thick natural Pb sample with 25.4 mm diameter (total mass 28 g). It was positioned between four coaxial HPGe detectors with efficiencies of about 60% relative to a standard $3'' \times 3''$ NaI detector at 1.3 MeV and they were mounted at a mean polar angle of $\bar{\theta} = 90°$ and at azimuthal angles of $\phi = 0°, 90°, 180°, 270°$ with respect to the (horizontal) polarization plane of the incident γ beam.

Fig. 2 displays (gain-matched and added) photon scattering spectra at a mean polar angle $\bar{\theta} = 90°$ relative to the incident beam axis and azimuthal angles $\phi_\parallel = (0°, 180°)$ in the polarization plane of the photon beam (top) and perpendicular to it $\phi_\perp = (90°, 270°)$ (bottom) using a linearly polarized incident photon beam with 5.6(1) MeV energy. The peaks at 5.490, 5.512, 5.597 and 5.611 MeV in the spectra at $\phi_\parallel$ and $\phi_\perp$ correspond to ground state decay transitions of excited states at these energies in ^{207,208}Pb. They are indicated by bigger arrows in the $\phi = 0°$ spectrum. In the spectrum at $\phi_\perp$, the peaks at 5.525, 5.580 and 5.616 MeV represent ground state decay transitions of excited states at these energies in

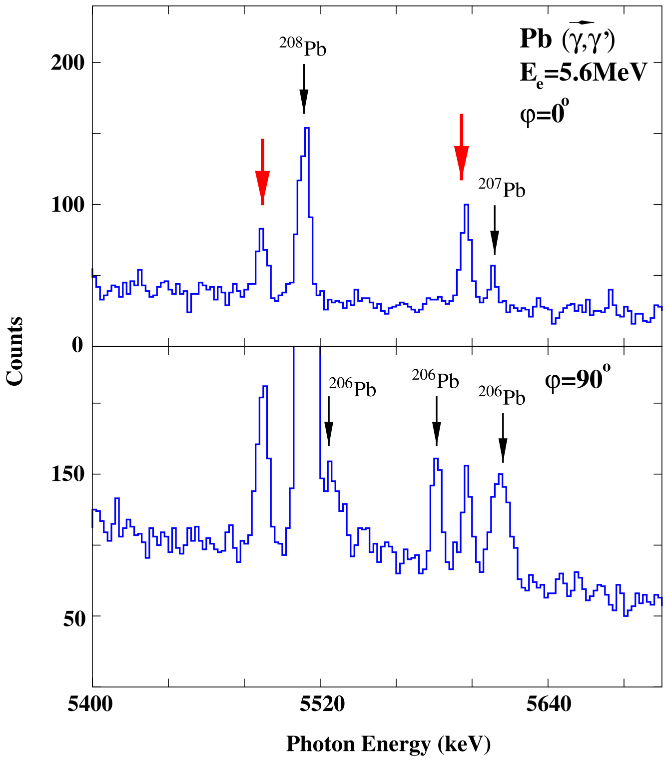

Fig. 2. (Color online.) Spectra of the Pb($\vec{\gamma},\gamma'$) reaction at a mean polar angle $\bar{\theta} = 90°$ relative to the incident photon beam and azimuthal angles $\phi_\parallel = (0°, 180°)$ (top) and $\phi_\perp = (90°, 270°)$ (bottom) relative to the polarization plane of the 5.6 MeV γ-ray beam at HIγS. The energy spread of the incident photon beam had a FWHM of 0.2 MeV. Big arrows (online red) mark the two ground state transitions of ^{207}Pb at 5.490 and 5.597 MeV. The difference of the intensity ratios of these two γ-rays is clearly visible. Other observed ground state decays are indicated by smaller arrows with the corresponding Pb isotopes labeled on top. The right most peak in the lower panel is a doublet caused by the 5.611 and 5.616 MeV lines from ^{207}Pb and ^{206}Pb, respectively.

^{206}Pb. These peaks are invisible in the $\phi_\parallel$ spectrum, which proves their E1 character.

The two states of ^{207}Pb observed at 5.490 and 5.597 MeV are of special interest. The assignment of their spin and parity quantum numbers represents a novel use of a linearly polarized photon-beam and, hence, is discussed in more detail below.

Considering dipole excitations of the $J_0^\pi = 1/2^-$ ground state of ^{207}Pb, the spins and parities of the two excited states could be $J^\pi = 1/2^\pm, 3/2^\pm$ only. The intensity distribution functions of the corresponding photon scattering cascades using a polarized incident beam can be derived within the angular correlation formalism [18]. An excited spin-1/2 state of an odd-mass nucleus radiates isotropically and hence its angular distribution ratio at any two angles is 1. The intensity distribution function of a $1/2^- \to 3/2^\pi \to 1/2^-$ photon scattering cascade using a polarized incident beam is given by

$$W(\theta,\phi) = 1 + \frac{1}{4}\left[P_2(\cos\theta) - \frac{1}{2}\pi\cos(2\phi)P_2^{(2)}(\cos\theta)\right], \qquad (1)$$

with $P_2^{(2)}$ being the unnormalized associated Legendre polynomial of second order and π being the parity quantum number of the excited $J = 3/2$ state.

For assigning the spin and parity quantum numbers, we form the double ratio (DR) of NRF intensities observed within the polarization plane ($\phi_\parallel$) and perpendicular to it ($\phi_\perp$). Neglecting small differences in the energy dependence of the detector efficiencies at these two nearby energies, the experimental DR is proportional to the DR of the angular distribution functions for one of the four possible photon scattering cascades $\frac{1}{2}^- \to \frac{1}{2}^\pm \to \frac{1}{2}^-$ and $\frac{1}{2}^- \to \frac{3}{2}^\pm \to \frac{1}{2}^-$. The theoretical DR is defined as

$$\mathrm{DR}_{J_1 J_2} = \frac{W_{J_1}(\phi_\parallel)}{W_{J_1}(\phi_\perp)} : \frac{W_{J_2}(\phi_\parallel)}{W_{J_2}(\phi_\perp)}, \qquad (2)$$

where $W_J(\phi)$ for any $\frac{1}{2}^- \to \frac{3}{2}^\pm \to \frac{1}{2}^-$ photon scattering cascades is given by $W(90°,\phi)$ in Eq. (1), while $W_J(\phi) = 1$ for an intermediate spin quantum number $J = 1/2$.

Table 2 lists all five possible DR values and the corresponding spin and parity combinations of the two states. Experimentally one finds

$$\mathrm{DR}_{\mathrm{expt}} = \frac{I_{5.490}(\phi_\parallel)}{I_{5.490}(\phi_\perp)} : \frac{I_{5.597}(\phi_\parallel)}{I_{5.597}(\phi_\perp)} = 0.39(4).$$

Therefore, the quantum numbers $(J^\pi_{5.490}, J^\pi_{5.597})$ are restricted to the combinations $(3/2^+, 1/2^\pm)$ or $(1/2^\pm, 3/2^-)$, only.

From the transition rates of the two states at 5.490 and 5.597 MeV, the most likely multipolarity of their ground state decays is E1. Then the measured $\mathrm{DR}_{\mathrm{expt}}$ and Table 2 leaves $J^\pi = \frac{3}{2}^+$ for the state at 5.490 MeV and $J^\pi = \frac{1}{2}^+$ for the state at 5.597 MeV.

In order to verify our conjecture of E1 radiation character, we finally deduce the angular distribution perpendicular and parallel to the polarization plane for both transitions individually. With (1) one obtains

$$\frac{W(90°,\phi_\perp)}{W(90°,\phi_\parallel)} = \begin{cases} 0.4, & J^\pi = \frac{3}{2}^-, \\ 1, & \text{for } J^\pi = \frac{1}{2}^\pm, \\ 2.5, & J^\pi = \frac{3}{2}^+. \end{cases} \qquad (3)$$

Fig. 3 displays the azimuthal intensity distribution ratios for the γ-ray transitions. The values are 2.35(66) and 0.92(25) for the states at 5.490 and 5.597 MeV, respectively. Comparing with (3) the data confirm the $(J^\pi_{5.490}, J^\pi_{5.597}) = (\frac{3}{2}^+, \frac{1}{2}^{(+)})$ assignment to better than two standard deviations. The isotropy of the angular distribution for spin-1/2 states prevents us from making parity assignments to these cases. For clarity we, therefore, stress that one out of these four quantum number assignments, namely the $\pi = (+)$ assignment for the $J = 1/2$ state at 5.597 MeV, is not based on angular distribution of photon scattering intensity but on the large decay rate of the level which leaves E1 multipolarity as the only likely possibility. These are the assignments that we adopt in Table 1.

Table 1
Excitation energy E_x, spin and parity quantum numbers J^π from this work and from Refs. [11,16,17] of excited states of ^{206,207,208}Pb. Values for E_x are taken from Ref. [11] unless otherwise noted.

	E_x (MeV)	J^π This work	J^{π} [a] ($\hbar$)	$B(E1)\downarrow$ (10^{-3} e^2 fm^2)[b]
^{206}Pb	5.5251(3)	1^-	$1^\pm$	2.3(3)
	5.5811(3)	1^-	1^-	8.1(9)
	5.6161(3)	1^-	$1^{(-)}$	11.6(13)
^{207}Pb	5.4897(3)	$\frac{3}{2}^+$	$\frac{1}{2}^-, \frac{3}{2}^\pm$	33.4(40)
	5.5974(3)	$\frac{1}{2}^{(+)}$	$\frac{1}{2}^\pm, \frac{3}{2}^\pm$	65.8(76)
	5.611(2)[c]	$\frac{3}{2}^+$	$(\frac{1}{2}, \frac{3}{2})$	14.9(24)
^{208}Pb	5.5121(3)	1^-	1^-	161(12)

[a] Taken from Ref. [11] unless otherwise noted.
[b] Taken from Ref. [11].
[c] Taken from Refs. [16,17]. According to Ref. [16], the existence of this state was uncertain because that γ-ray could be interpreted as a transition from the possible 6.179 MeV level to the first excited state at 0.57 MeV. However, 6.179 MeV was beyond our excitation energy region of 5.6 ± 0.1 MeV, which proves existence of the excited state at 5.611 MeV for which $J^\pi = 3/2^+$ can be assigned from our data after subtraction of the ^{206}Pb contaminant at this energy.

Table 2
Given is a total of 16 possible spin and parity combinations for the two states of ^{207}Pb, which correspond to different values of the double ratio (DR). Combinations restricted to E1 excitations of the two states are specified on the right

DR	(J_1^π, J_2^π)	for E1 only
0.16	$(\frac{3}{2}^+, \frac{3}{2}^-)$	–
0.40	$(\frac{3}{2}^+, \frac{1}{2}^\pm)$, $(\frac{1}{2}^\pm, \frac{3}{2}^-)$	$(\frac{3}{2}^+, \frac{1}{2}^+)$
1.00	$(\frac{3}{2}^+, \frac{3}{2}^+)$, $(\frac{3}{2}^-, \frac{3}{2}^-)$, $(\frac{1}{2}^\pm, \frac{1}{2}^\pm)$	$(\frac{3}{2}^+, \frac{3}{2}^+)$, $(\frac{1}{2}^+, \frac{1}{2}^+)$
2.50	$(\frac{3}{2}^-, \frac{1}{2}^\pm)$, $(\frac{1}{2}^\pm, \frac{3}{2}^+)$	$(\frac{1}{2}^+, \frac{3}{2}^+)$
6.25	$(\frac{3}{2}^-, \frac{3}{2}^+)$	–

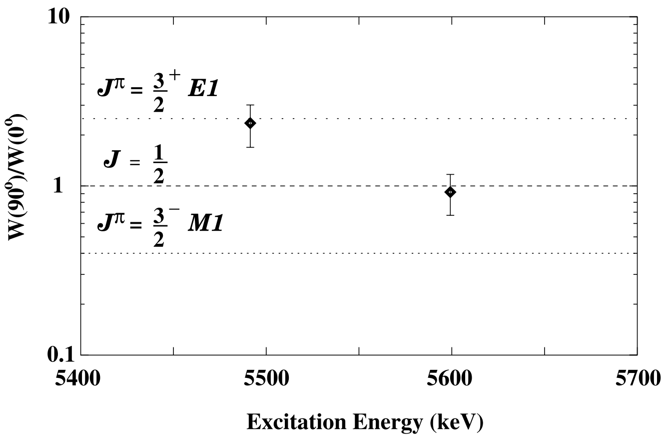

Fig. 3. Azimuthal intensity distribution for $J^\pi \to \frac{1}{2}{}^-_1$ of the two states in ^{207}Pb at 5.490 and 5.597 MeV. The horizontal lines mark the ratios for possible spins, $\frac{1}{2}$ and $\frac{3}{2}$.

The level energies agree within 22 and 85 keV, respectively, with the excitation energy of the predominant bound E1 excitation of the neighboring doubly-closed shell nucleus ^{208}Pb at 5.512 MeV. I.e., the energy splitting of the doublet $\Delta E_{\nu(p_{1/2}^{-1})}(5.512) = E_{3/2^+} - E_{1/2^{(+)}} = -107$ keV is less than 2% of the centroid value. This is comparable to the relative splitting of the well-established $3^- \otimes \nu(p_{1/2}^{-1})$ weakly coupled doublet at 2.6 MeV [10,19]. However, literature values for transition rates indicate more pronounced deviation from weak coupling at 5.5 MeV. Like the 1^- state of ^{208}Pb at 5.512 MeV, that doublet of individual quantum states of ^{207}Pb dominates its dipole excitation strength distribution with E1 decay rates to the ground state of 18(4) and 29(4) mW.u. [11]. While these are the largest E1 strengths from the ground state to excited states up to 6.2 MeV, which is the energy up to where data on ^{207}Pb are available, these values are a factor of three smaller than in the ^{208}Pb core indicating a substantial deviation from pure weak coupling.

In order to investigate this theoretically the dipole excitation strength distributions of ^{207,208}Pb have been calculated using the Quasiparticle Phonon Model (QPM) in a fashion similar to what has been described in Ref. [11]. The analysis of the QPM wave functions yields the following picture: The wave function of the strongest-dipole excited 1^- state of ^{208}Pb calculated at 5.35 MeV is $|\Psi_{1^-}|^2 = 11\% \cdot 1_1^- + 85\% \cdot 1_2^-$ where 1_i^- is the ith one-phonon configuration [11]. The corresponding $1/2^+$ and $3/2^+$ states of ^{207}Pb at about the same excitation energy are calculated to have small admixtures of neutron-hole excitations to the nearby $\nu(4s_{1/2})$ and $\nu(3d_{3/2})$ orbitals. Their wave functions are $|\Psi_{1/2^+}|^2 = 3.4\% \cdot 4s_{1/2} + 40.9\% \cdot [3p_{1/2} \otimes 1_1^-]_{1/2^+} + 34.3\% \cdot [3p_{1/2} \otimes 1_2^-]_{1/2^+}$ and $|\Psi_{3/2^+}|^2 = 4.7\% \cdot 3d_{3/2} + 35.4\% \cdot [3p_{1/2} \otimes 1_1^-]_{3/2^+} + 38.8\% \cdot [3p_{1/2} \otimes 1_2^-]_{3/2^+}$, respectively. These wave functions show an overlap of 40% ($1/2^+$) and 46% ($3/2^+$) with the particle-coupled 1^- core excitation. In other words, the interaction of the unpaired neutron with the ^{208}Pb core excitation leads to a substantial modification of the latter in terms of the relative weight of the ith one-phonon contribution to the dominant core excitation. Since $B(\mathrm{E1}, 1_2^- \to 0^+_{g.s.(^{208}\mathrm{Pb})}) \gg B(\mathrm{E1}, 1_1^- \to 0^+_{g.s.(^{208}\mathrm{Pb})})$, the $1/2^+$ and $3/2^+$ states of ^{207}Pb under discussion near 5.5 MeV are dipole-excited about twice weaker than expected if the unpaired neutron was considered as a pure spectator. This can indeed be quantitatively observed from the absolute E1 transition rates to the ground states of ^{207,208}Pb, respectively. The missing strength of the core excitation is expected to be fragmented over nearby states with identical quantum numbers. Our data include a nearby $3/2^+$ state at 5.61 MeV with smaller E1 strength than the states discussed so far. The QPM calculations suggest it as another fragment of the particle-coupled 1^- core excitation with a squared amplitude of 33% while it simultaneously shows an enhanced character of a $\nu(3d_{3/2})$ particle excitation of 34.6%.

In summary, we have demonstrated a new method for spin and parity quantum number assignments to highly excited particle-bound dipole excitations of odd-mass nuclei based on the measurement of azimuthal nuclear resonance fluorescence-intensity asymmetries about an incident linearly polarized γ-ray beam. This method has been used to identify the doublet of energy levels of ^{207}Pb that predominantly originates in the weak coupling of the $\nu(3p_{1/2}^{-1})$ neutron hole to the strongest neutron-bound electric dipole excitation of the doubly closed shell ^{208}Pb core at 5.51 MeV. The observed energy splitting of this $J = 1/2$, $3/2$ doublet at an excitation energy of more than $30A^{-1/3}$ MeV amounts to less than 2% of its excitation energy with the $J = 3/2$ state being the lower lying level. Deviations from the pure weak-coupling scenario show up in the absolute transition rates due to the particle–core interaction. Consequently, some E1 strength is shifted to other lower-lying levels of ^{207}Pb by the particle–core interaction.

The particle-excited $J^\pi = 1/2^-$, $3/2^-$ doublet in the hypernucleus $^{13}_{\Lambda}$C occurs at an excitation energy of $25A^{-1/3}$ MeV with, once again, the $J = 3/2$ state being the lower lying level. Its energy splitting also amounts to less than 2%. The fact that the weakly coupled structure of $^{13}_{\Lambda}$C built on the 10.8-MeV 1^- state of ^{12}C has not yet been observed suggests that the mixing between core-excited states and single-particle excitations is weaker in the Λ-nuclear system than in the purely nucleonic system ^{207}Pb that we have studied here. In ^{207}Pb its E1 core excitation is not shifted in energy with respect to the 1^- state of ^{208}Pb. A modification of the core excitation $\psi(1^-[\mathrm{core}(^{13}_{\Lambda}\mathrm{C})]) \neq \psi(1^-[^{12}\mathrm{C}])$ induced by the hyperon and a corresponding increase in energy of the core excitation [9] would indeed lift the degeneracy of single-particle and core excitations that is suggested by Fig. 1 and that often suffices as a condition for strong mixing. More data, such as magnetic moments of the $^{13}_{\Lambda}$C states, are highly desirable to quantify the amount of weakly coupled admixtures to the doublet of states at 10.9 MeV.

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References

[1] W. Brückner, et al., Phys. Lett. B 55 (1975) 107.
[2] H. Tamura, et al., Phys. Rev. C 40 (1989) 479.

[3] O. Hashimoto, et al., Prog. Part. Nucl. Phys. 57 (2006) 564.
[4] H. Kohri, et al., Phys. Rev. C 65 (2002) 034067.
[5] E. Hiyama, M. Kamimura, T. Motoba, T. Yamada, Y. Yamamoto, Nucl. Phys. A 639 (1998) 173c.
[6] M. May, et al., Phys. Rev. Lett. 47 (1981) 1106.
[7] W. Brückner, et al., Phys. Lett. B 79 (1978) 157.
[8] S. Ajimura, et al., Phys. Rev. Lett. 86 (2001) 4255.
[9] E. Hiyama, M. Kamimura, T. Motoba, T. Yamada, Y. Yamamoto, Phys. Rev. Lett. 85 (2000) 270.
[10] O. Häusser, F.C. Khanna, D. Ward, Nucl. Phys. A 194 (1972) 113.
[11] J. Enders, et al., Nucl. Phys. A 724 (2003) 243.
[12] U. Kneissl, N. Pietralla, A. Zilges, J. Phys, G: Nucl. Part. Phys. 32 (2006) R217.
[13] V.N. Litvinenko, et al., Nucl. Instrum. Methods Phys. Res., Sect. A 407 (1998) 8.
[14] N. Pietralla, Z. Berant, et al., Phys. Rev. Lett. 88 (2002) 12502.
[15] H.R. Weller, et al., Prog. Part. Nucl. Phys. 62 (2009) 257.
[16] T. Chapuran, R. Vodhanel, M.K. Brussel, Phys. Rev. C 22 (1980) 1420.
[17] M.J. Martin, Nucl. Data Sheets 70 (1993) 315.
[18] L.W. Fagg, S.S. Hanna, Rev. Mod. Phys. 31 (1959) 711.
[19] J. Ungrin, R.M. Diamond, P.O. Tjom, B. Elbek, Mat. Fys. Medd. Dan. Vid. Selsk. 38 (8) (1971).