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Candidates for two-phonon octupole excitations in ^{208}Pb

Minfang Yeh,* M. Kadi, P. E. Garrett, C. A. McGrath,† and S. W. Yates
Departments of Chemistry and Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506-0055

T. Belgya
Institute of Isotopes of the Hungarian Academy of Sciences, Budapest H-1525, Hungary

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Following the identification of the lowest-spin member of the two-phonon octupole quartet in ^{208}Pb, the additional members of the multiplet have been sought with the $(n,n'\gamma)$ reaction. Based on energy arguments and $E1$ transition probabilities determined from Doppler-shift lifetime measurements, the 5286- and 5216-keV states are suggested as candidates for the 2^+ and 4^+ two-phonon octupole excitations in ^{208}Pb. The difficulties of identifying the 6^+ member of this quartet are examined. [S0556-2813(98)50205-1]

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The first excited state of ^{208}Pb at 2614 keV has spin-parity 3^- and for many years has been interpreted as a surface vibration of octupole character; its collectivity is confirmed by the observed $B(E3;3^-\rightarrow0^+)$ value of 34 W.u. [1]. A quartet of two-phonon octupole states (0^+,2^+,4^+, and 6^+) is expected to occur at about twice the energy of the 3^- state, i.e., around 5.2 MeV [2]. Since the earliest experimental suggestion [3] of the existence of two-phonon excitations in ^{208}Pb more than 30 years ago, these states have been sought using a variety of techniques [4–11].

Only recently has firm evidence been provided [12], in the form of an observed cascade of two $E3$ transitions from a 0^+ state at 5241 keV, for the lowest-spin member of the two-phonon octupole quartet in ^{208}Pb. This 0^+ (2-phonon) → 3^- (1-phonon) → 0^+ (ground state) cascade represents a characteristic signature of a two-phonon octupole excitation, and the absence of other decay branches is suggestive of the collective nature of the $0^+\rightarrow3^-$ transition. While crucial transition rate data are still lacking, the identification of the 2626-keV $E3$ transition from the 5241-keV 0^+ state in ^{208}Pb is the best evidence to date for a two-phonon octupole excitation in a nucleus outside the $N=82$ region, and the $E3$-$E3$ cascade represents the first such decay leading directly to the ground state of an even-even nucleus.

The location of the other members (2^+,4^+, and 6^+) of the two-phonon octupole quartet in ^{208}Pb remains an important question in the description of these vibrational excitations. While a candidate for a higher-spin member of the multiplet has been proposed [7], recent work [8,9,11,13] has provided no support for this identification.

A unique signature for identifying members of the two-phonon octupole quartet would be the observation of enhanced $E3$ decays to the 3^- one-phonon state, with $B(E3)$ values similar in magnitude to that of the $3^-\rightarrow0^+_{\text{g.s.}}$ decay. However, for most members of the quartet, other lower-multipolarity decays are possible, thus making the observation of a two-phonon to one-phonon $E3$ transition unlikely. (An exception is the observation of the $0^+\rightarrow3^-$ $E3$ decay mentioned earlier [12].) Therefore, other signatures that can be used to identify two-phonon octupole states must be sought.

One possibility is that these states may decay by ‘‘fast’’ $E1$ transitions, as has been observed for octupole-coupled states in the $N=82$ region [14–16]. For example, the 2^+ member of the two-phonon octupole quartet of ^{208}Pb is expected to decay by an $E1$ transition to the first 3^- excited

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*Present address: Department of Chemistry, Washington State University, Pullman, WA 99164.

†Present address: Lawrence Berkeley National Laboratory, MS 88, 1 Cyclotron Rd., Berkeley, CA 94720.

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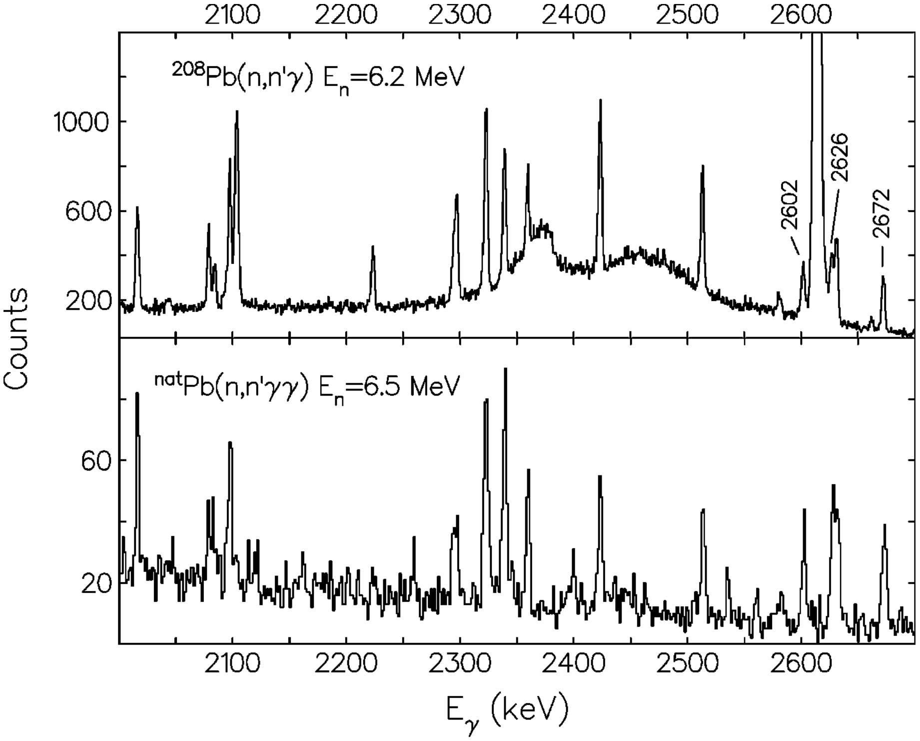

FIG. 1. Portions of the γ-ray singles spectrum (top panel) from the ^{208}Pb$(n,n'\gamma)$ reaction and the coincidence spectrum (bottom panel) obtained by gating on the 2614-keV $(3^{-}\rightarrow 0^{+}_{\rm g.s.})$ γ ray of ^{208}Pb from the $^{\rm nat}$Pb$(n,n'\gamma\gamma)$ reaction. Gamma rays of particular significance in this work (see also Table I) are indicated.

state [17], the octupole phonon at 2614 keV, by what will be referred to as an ''octupole $E1$ transition''—i.e., an $E1$ transition accompanying the destruction of an octupole phonon. Similarly, the 4^{+} multiplet member could decay by $E1$ transitions to either the 3^{-} octupole excitation at 2614 keV or the 5^{-} state at 3197 keV; although, the $4^{+}\rightarrow 3^{-}$ transition would seem more favorable, particularly in view of the energy factor and the ''octupole $E1$'' nature of the decay transition. For the spin 6^{+} state, an $E1$ transition to the 5^{-} state at 3197 keV seems most likely, although this transition would not be a two-phonon to one-phonon decay.

It is evident that a knowledge of the relevant $E1$ transition rates will play an important role in searching for the two-phonon octupole states. A possible way to identify these excitations in ^{208}Pb is to compare the $E1$ transition rates from them with those of similar ''octupole $E1$ transitions'' in neighboring odd-A nuclei such as ^{207}Pb and ^{209}Bi. In taking this approach, we admittedly ignore the importance of other contributions to the $E1$ transition rates.

Low-lying collective octupole excitations in neighboring odd-A nuclei arise from weak particle-vibration coupling of single-particle (or hole) configurations to the 3^{-} octupole vibrational state of the ^{208}Pb core. Certainly the most spectacular example of weak coupling in this region is the well-known $3^{-}\otimes h_{9/2}$ septuplet of ^{209}Bi. The members of the septuplet decay by the expected enhanced $E3$ transitions, with strengths comparable to the $E3$ decay of the octupole vibration of ^{208}Pb, and $E1$ transitions to lower-lying single-particle states. As these $E1$ transitions are orders of magnitude weaker than the giant dipole resonance, they may be very sensitive to small admixtures in their wave functions [18–20]. Unfortunately, only in ^{209}Bi are the absolute transition rates of these ''octupole $E1$'' decays known. The lifetimes of the $5/2^{+}$ and $7/2^{+}$ components of the $3^{-}\otimes p_{1/2}^{-1}$ doublet of ^{207}Pb have been measured, but $E1$ decay to the $p_{1/2}^{-1}$ single-particle state, the ground state, is forbidden.

In addition to considering the previously known $E1$ transitions from the $3^{-}\otimes h_{9/2}$ septuplet of ^{209}Bi to the $h_{9/2}$ single-particle ground state, the $E1$ decays from the $3^{-}\otimes f_{5/2}^{-1}$ sextuplet of ^{207}Pb to the $f_{5/2}^{-1}$ excitation, the first excited state, have been examined experimentally. Because these $E1$ decays in ^{209}Bi and ^{207}Pb represent the destruction of an octupole phonon, their transition rates might be expected to be similar to (two-phonon to one-phonon) octupole $E1$ transitions in ^{208}Pb.

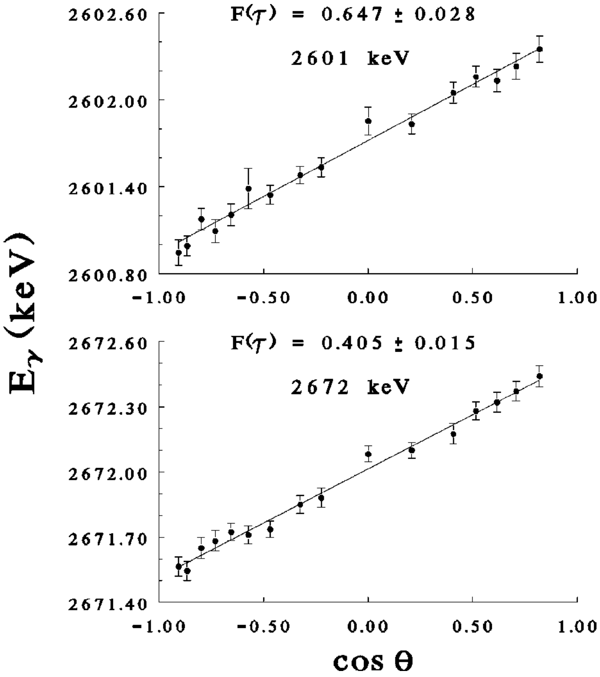

FIG. 2. Measured γ-ray energy as a function of $\cos\theta$ for selected $E1$ transitions in ^{208}Pb. Noted are the $F(\tau)$ values obtained from linear fits to the data. The level lifetimes deduced are given in Table I.

TABLE I. $E1$ transitions from positive-parity states in the 4 to 6 MeV region in ^{208}Pb

E_i (keV)	E_γ (keV)	J_i^π	J_f^π	τ (fs)	$B(E1)$ (W.u.)
4324	363	4^+	5^-	>1700	$<3.4\times10^{-4}$
4324	1126	4^+	5^-	>1700	$<1.0\times10^{-4}$
4423	1225	6^+	5^-	>700	$<2.5\times10^{-4}$
4867	386	7^+	6^-	>140	$<1.2\times10^{-4}$
5194	1996	4^+	5^-	200^{+300}_{-90}	$2.1^{+1.8}_{-1.4}\times10^{-5}$
5195	1275	7^+	6^-	50^{+100}_{-30}	$1.8^{+4.5}_{-1.3}\times10^{-4}$
5216 [a]	2602	4^+	3^-	26^{+3}_{-3}	$4.6^{+0.7}_{-0.5}\times10^{-4}$
5286 [a]	2672	2^+ or 4^+	3^-	68^{+4}_{-4}	$2.1^{+0.2}_{-0.2}\times10^{-4}$
5339	1302	8^+	7^-	35^{+46}_{-22}	$3.3^{+5.5}_{-1.9}\times10^{-4}$
5561	2947	2^+	3^-	46^{+11}_{-9}	$1.5^{+0.6}_{-0.5}\times10^{-4}$
5690	3075	4^+	3^-	42^{+8}_{-7}	$2.3^{+0.5}_{-0.4}\times10^{-4}$

[a] Candidates for the two-phonon octupole quartet.

TABLE II. $E1$ transitions in ^{207}Pb.

E_i (keV)	E_γ (keV)	J_i^π	J_f^π	τ (fs)	$B(E1)$ (W.u.)
2624	2054	$5/2^+$	$5/2^-$	90 ± 30 [a]	$4.3\pm1.4\times10^{-5}$
2624	1726	$5/2^+$	$3/2^-$	90 ± 30 [a]	$3.4\pm1.1\times10^{-4}$
2662	2093	$7/2^+$	$5/2^-$	660 ± 140 [a]	$3.0\pm0.6\times10^{-5}$
3176	836	$9/2^+$	$7/2^-$	>600	$<1.7\times10^{-4}$
3203	2633	$5/2^+$	$5/2^-$	29 ± 8	$4.5\pm1.2\times10^{-4}$
3218	2649	$7/2^+$	$5/2^-$	56 ± 17	$2.6\pm0.8\times10^{-4}$
3302	3302	$1/2^+$	$1/2^-$	11 ± 6	$5.7\pm3.1\times10^{-4}$
3302	2405	$1/2^+$	$3/2^-$	11 ± 6	$1.4\pm0.8\times10^{-4}$

[a] From Ref. [25].

Inelastic neutron scattering is expected to populate octupole-coupled states along with other low-spin excitations [13]. Therefore, to search for additional members of the two-phonon octupole quartet in ^{208}Pb and to determine the lifetimes of these states and others in ^{207}Pb, a series of $(n,n'\gamma)$ measurements was performed at the University of Kentucky Van de Graaff accelerator facility. Neutrons were produced with the ^{3}H$(p,n)^3$He or ^{2}H$(d,n)^3$He reactions, depending on the desired neutron energy. These nearly monoenergetic neutrons bombarded large, enriched isotopic samples of ^{207}Pb (40.2 g, 92.4%) or ^{208}Pb (77.6 g, 99.80%) in the form of metallic cylinders. In these singles measurements, γ rays were detected with a bismuth germanate (BGO) Compton-suppressed, n-type HPGe detector having a relative efficiency of 57% and an energy resolution of 2.0 keV at 1.33 MeV. For each nucleus, detailed excitation functions were performed by varying the incident neutron energy, and γ-ray angular distributions were measured at selected neutron energies. In addition, γ-γ coincidence measurements were performed with collimated neutrons incident on a natural Pb target surrounded by three HPGe detectors [21]. Gamma-ray singles and γ-γ coincidence spectra are illustrated in Fig. 1 for an energy region, where several γ rays of significance in this work occur. By combining the results of these measurements with previous detailed spectroscopic studies, level schemes for ^{207}Pb and ^{208}Pb were constructed [22,23].

In addition to providing spectroscopic information for the assignment of level spins and parities, the angular distribution data can be used to determine level lifetimes by the Doppler-shift attenuation method (DSAM). The γ-ray energy measured as a function of angle can be expressed as

$$E_\gamma(\theta)=E_\gamma[1+\beta F(\tau)_{\text{exp}}\cos\theta], \quad (1)$$

where $E_\gamma(\theta)$ is the measured γ-ray energy observed at an angle θ, E_γ is the unshifted energy of the γ ray, and β is the recoil velocity in units of the speed of light. $F(\tau)_{\text{exp}}$, the extracted experimental attenuation factor, can be directly compared with theoretical values calculated using the formalism of Ref. [24], and the lifetime of the excited state can be deduced. Figure 2 illustrates the measured γ-ray energy as a function of $\cos\theta$ for two important $E1$ transitions in ^{208}Pb. The in-beam energy calibrations were continuously monitored by simultaneously recording the γ rays from a ^{56}Co source along with those produced by the $(n,n'\gamma)$ reaction.

Lifetimes of many excited states in ^{207}Pb and ^{208}Pb were determined with DSAM but, for reasons described earlier, the focus was on those decaying by $E1$ transitions. Reduced transition rates for all of the $E1$ transitions observed from states in the 4- to 6-MeV range of excitation energies in ^{208}Pb are presented in Table I. By combining these data, other measured $E1$ rates in ^{208}Pb [23], and the rates of $E1$ transitions in ^{207}Pb (Table II) and ^{209}Bi (Table III), a summary of $E1$ strengths is obtained. The $B(E1)$ values of transitions from collective octupole states, the $3^-\otimes f_{5/2}^{-1}$ multiplet in ^{207}Pb and the $3^-\otimes h_{9/2}$ multiplet in ^{209}Bi, in the odd-A nuclei are illustrated by filled symbols in Fig. 3. The $E1$ transition rates from these octupole-coupled states in ^{207}Pb and ^{209}Bi are generally greater than 10^{-4} W.u. and larger than those of other $E1$ transitions in these nuclei. A notable exception is the 2583-keV transition in ^{209}Bi; this transition, which includes a significant $E3$ component [26], has been examined in detail by Hamamoto [18]. In ^{207}Pb, two $E1$ transitions exhibit decay rates comparable to those of ''octupole $E1$'' decays from the $3^-\otimes f_{5/2}^{-1}$ multiplet. These additional fast decays have been explained [20,27] by considering small admixtures into the wave functions of the initial or final states and exemplify the possible dangers of ignoring such contributions to the $E1$ transition rates.

Since most (four of the five cases considered) of the $E1$ transitions in ^{207}Pb and ^{209}Bi corresponding to the destruction of an octupole phonon are fast, the assumption that in ^{208}Pb the $B(E1)$ values from 2^+ and 4^+ members of the two-phonon octupole quartet should also be larger than those corresponding to single-particle transitions appears to be reasonably justified. Similar arguments have been used in other

TABLE III. $E1$ transitions[a] in ^{209}Bi.

E_i (keV)	E_γ (keV)	J_i^π	J_f^π	τ (fs)	$B(E1)$ (W.u.)
2564	2564	$(9/2)^+$	$9/2^-$	22 ± 5	$7.6\pm1.5\times10^{-4}$
2583	2583	$(7/2)^+$	$9/2^-$	420 ± 120	$\leqslant1.2\pm0.4\times10^{-5}$
2583	1687	$(7/2)^+$	$7/2^-$	420 ± 120	$1.0\pm0.3\times10^{-4}$ [b]
2600	2600	$11/2^+$	$9/2^-$	62 ± 18	$2.5\pm0.7\times10^{-4}$
2617	1721	$5/2^+$	$7/2^-$	>3000	$<1.2\times10^{-5}$ [b]

[a] From Ref. [26].

[b] Pure $E1$ multipolarity assumed.

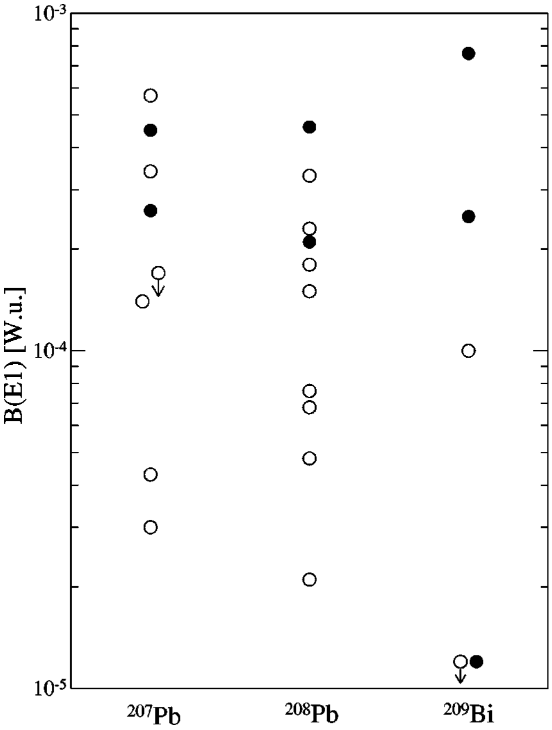

FIG. 3. $E1$ transition strengths in ^{207}Pb, ^{208}Pb, and ^{209}Bi. Transitions from two-phonon candidates in ^{208}Pb are represented as filled symbols, while other $E1$ transitions in ^{208}Pb (Ref. [23] and Table I) are shown as open symbols. For comparison, $B(E1)$ values from the $3^- \otimes f_{5/2}^{-1} \rightarrow f_{5/2}^{-1}$ transitions in ^{207}Pb (filled symbols), $3^- \otimes h_{9/2} \rightarrow h_{9/2}$ transitions in ^{209}Bi (filled symbols), and other transitions (open symbols) in these nuclei are also shown. Most of the $B(E1)$ values for transitions in ^{207}Pb and ^{208}Pb were determined in the present study.

mass regions [14–16], and a recent quasiparticle-phonon model calculation [17] of the $B(E1)$ for the 2^+ two-phonon to one-phonon transition in ^{208}Pb is in good agreement with the magnitude of these observed values. From the above assumption and the expectation that these states do not display extremely large anharmonicities in their energies, the 4^+ 5216- and $(2,4)^+$ 5286-keV states, which decay with large $B(E1)$ values compared to other $E1$ transitions in ^{208}Pb, are suggested as candidates for members of the two-phonon octupole quartet. The transitions from these states in ^{208}Pb are illustrated as filled symbols in Fig. 3. It should be noted that the $B(E1)$ value of the decay from the 5286-keV state, for which the 2^+ spin is favored, but not determined uniquely in the present work, is not as large as that for the other candidates for two-phonon octupole states. This might be attributed to the mixing of 2^+ particle-hole states in the region with the 2^+ two-phonon excitation. Other candidates for the 2^+ member of the multiplet have been observed at higher energies (see Table I), but none of these, e.g., the state at 5561 keV, exhibit considerably faster $E1$ decays.

The identification of a reasonable 6^+ two-phonon candidate from the available data is difficult, as direct decay of such a state to the 3^- octupole phonon is neither anticipated nor observed. Schramm *et al.* [28] have identified a 6^+ state at 5213 keV, very close to the two-phonon energy, but the large spectroscopic factor observed in the (t,α) single-nucleon transfer reaction indicates that this state is primarily of proton particle-hole character. With neutron transfer and inelastic light-ion scattering reactions, Valnion [29] has recently performed a detailed examination of this excitation region in ^{208}Pb. While concluding that two or more close-lying states are present, he was unable to confirm the 6^+ assignment. We observe a state at this energy, but the decay γ rays are not completely resolved from other γ rays in our data and this spin-parity assignment cannot be verified. Therefore, we must conclude that the 5213-keV state, while consistent in energy with a two-phonon octupole interpretation, is not a good candidate for the highest-spin member of the quartet. This conclusion is consistent with the results of recent Coulomb excitation measurements [30] which should have been sensitive to an unfragmented two-phonon octupole 6^+ state at this energy.

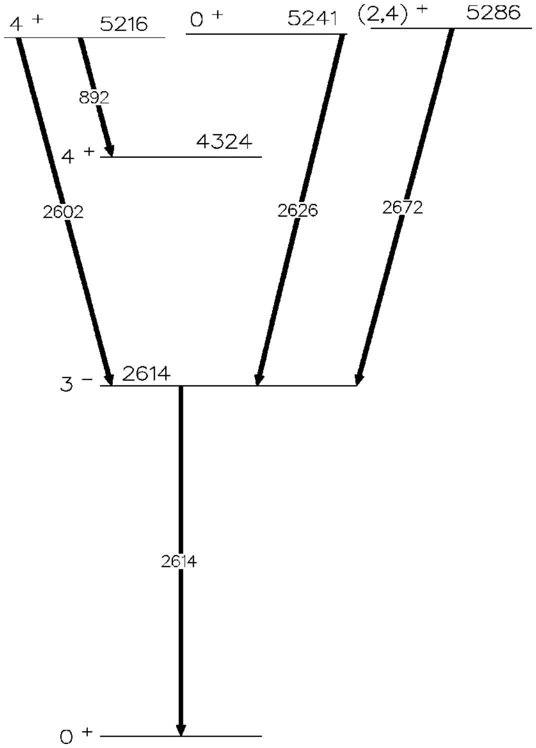

FIG. 4. Suggested candidates for the two-phonon octupole states in ^{208}Pb.

When the above observations are combined with those for the aforementioned 0^+ 5241-keV state, the suggested two-phonon octupole structure shown in Fig. 4 emerges. In this picture, the anharmonicity of the suggested two-phonon states at about twice the energy of the one-phonon excitation is quite small.

Recent attempts to excite members of the two-phonon multiplet through heavy-ion Coulomb excitation [7,8,11,30] have not led to the population of any of the candidates shown in Fig. 4, or to a 6^+ candidate which should have the largest Coulomb excitation probability. It should also be noted that the absence of a transition from the 2^+ state at 5286 keV to the ground state appears to make the population of this level with the (γ,γ') reaction, as suggested by Enders *et al.* [17], highly unlikely.

In summary, candidates for members of the two-phonon octupole multiplet in ^{208}Pb have been sought with the $(n,n'\gamma)$ reaction. Based on excitation energy arguments and

$E1$ transition rates determined through Doppler-shift lifetime measurements, the states at 5286 and 5216 keV are suggested as candidates for the 2^+ and 4^+ members of the quartet. When combined with the earlier identification of the 0^+ member [12], candidates for the lowest-spin members of the quartet are proposed. The anharmonicity of these states at about twice the energy of the one-phonon excitation is remarkably small. No compelling candidate for the 6^+ member of the quartet has been identified.

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