Monopole strength and decay out of superdeformed bands in the $A=190$ mass region from theories beyond the mean field

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(Received 5 May 1998)

The decay out of superdeformed states through $E0$ electric monopole transition is investigated for even-even nuclei in the $A=190$ mass region. Transition rates are evaluated within the generator coordinate method based on Hartree-Fock plus BCS wave functions. For light isotopes of mercury and lead, $E0$ transitions appear to be strongly enhanced due to large monopole transition matrix elements. [S0556-2813(98)01610-0]

PACS number(s): 21.60.Ev, 21.60.Jz, 23.20.−g, 27.80.+w

I. INTRODUCTION

The strength of electric monopole transitions $\rho^2(E0)$ can be used as a criterion for shape coexistence and mixing of configurations with different deformations. For instance in the neutron rich Sr, Zr, and Mo nuclei of mass closed to 100, large $E0$ strengths have been found in $0_2^+ \Rightarrow 0_1^+$ transitions suggesting that we interpret these states as due to a strong mixing of spherical and deformed configurations [1,2]. The highly deformed bands in the $A=130$ mass region are also candidates for such strong $E0$ transitions. In the decay out of ^{130}Ce highly deformed band, conversion-electron (CE) spectroscopy measurements have shown an excess of electrons with respect to the yield expected from converted γ transitions [3]. On the contrary, in ^{135}Nd no evidence for strongly enhanced $E0$ transitions depopulating the highly deformed band has been detected by Korten *et al.* [4]. In the superdeformed (SD) $A=190$ mass region Moore *et al.* [5] have measured the K x-ray yields in the SD band of ^{192}Hg. In this case the possibility of strong $E0$ decay out has been ruled out; the experimental limit to an $E0$ branch is set to be only 10%.

From a theoretical point of view, Wood *et al.* [6] suggested that the $E0$ decay mode may dominate $E2$, $M1$, or $E1$ decay out of SD bands while Krücken and Lee [7] concluded that, even if the electric monopole strengths are very large, the $E0$ transitions cannot compete with the γ transitions both in the $A=190$ and $A=130$ mass regions. In this paper, we want to determine whether in the $A=190$ mass region, the decay out of the lowest SD states to normally deformed states has a significant $E0$ electric monopole contribution. For this purpose, the generator coordinate method (GCM) [8] provides a natural extension of static lattice Hartree-Fock+BCS calculations [9] (HF+BCS). This method permits us to take into account the quantal fluctuations associated with selected collective coordinates. It is equivalent to the mixing of configurations labeled by a continuous index. We have already applied the GCM to the quadrupole and octupole modes in various studies of mercury [10,11] and lead [12] isotopes extending from normal deformation to superdeformation. We have also calculated electric monopole transitions for the heavy Zr isotopes [13], with a good qualitative agreement with the experimental data. In this paper, we exploit the matrix elements already obtained for SD Hg and Pb to determine the importance of monopole transitions. Since we have used a restricted HF+BCS set of wave functions, only collective β_2 vibrations are explored (and eventually β_3 in the case of ^{194}Pb). Any other degrees of freedom, e.g., rotational effects, pairing vibrations, single particle excitations, are not included in this work.

II. CALCULATIONS

The diagonalization of the GCM equation leads to eigenstates which are superpositions of HF+BCS states corresponding to different values of the collective coordinate. Most of them have a mean quadrupole moment corresponding to the first well and represent approximations of the ground state and of β-vibration band heads. One or two GCM states have a large quadrupole moment corresponding to the second well and are thus identified as SD states. From the GCM wave functions, matrix elements $m(E0)$ of the monopole operator between two different states are calculated as

$$m(E0)=\left\langle \mathrm{GCM}_2 \left| e\sum_i r_i^2 \right| \mathrm{GCM}_1 \right\rangle, \tag{2.1}$$

where the sum runs over protons only. The $E0$ strength is usually measured by the dimensionless quantity $\rho^2(E0)$ related to $m(E0)$ by

$$\rho^2(E0)=\left| \frac{m(E0)}{eR^2} \right|^2, \tag{2.2}$$

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TABLE I. Transitions calculated between the SD and the ground states for mercury (upper part) and lead (lower part) isotopes. For each nucleus the $m(E0)$ matrix element (in e fm^2), the strength $\rho^2(E0)$, the transition energy E (in MeV), and the decay rate $T(E0)$ (in s^{-1}) are given. The quadrupole matrix element $m(E2)$ (in e fm^2) and the corresponding $T(E2)$ decay rate (in s^{-1}) are also given for comparison.

	$m(E0)$	$\rho^2(E0)$	E	$T(E0)$	$m(E2)$	$T(E2)$
^{190}Hg	2.97	3.9×10^{-3}	3.11	9.4×10^{9}	9.84	3.43×10^{13}
^{192}Hg	0.195	1.7×10^{-5}	3.92	7.2×10^{7}	4.39	2.18×10^{13}
^{194}Hg	0.23	2.3×10^{-5}	5.13	2.2×10^{8}	2.49	2.69×10^{13}
^{196}Hg	0.21	1.9×10^{-5}	6.70	4.8×10^{8}	2.21	8.04×10^{13}
^{198}Hg	0.035	5.2×10^{-7}	8.70	3.7×10^{7}	0.075	3.41×10^{11}
^{192}Pb	0.94	3.8×10^{-4}	3.46	1.3×10^{9}	14.44	1.26×10^{14}
^{194}Pb	0.17	1.2×10^{-5}	4.99	1.2×10^{8}	7.66	2.21×10^{14}
^{196}Pb	0.56	1.3×10^{-4}	6.46	3.1×10^{9}	7.42	7.55×10^{14}
^{198}Pb	0.04	6.6×10^{-7}	8.05	3.5×10^{7}	0.12	0.59×10^{12}
^{200}Pb	0.01	4.1×10^{-8}	10.2	5.7×10^{6}	0.087	1.03×10^{12}

where $R=r_0A^{1/3}$ is the nuclear radius with r_0 equal to 1.2 fm. The absolute nuclear electric monopole decay rate $T(E0)$ is a sum of two terms,

$$T(E0)=T(E0)_{\mathrm{IC}}+T(E0)_{\mathrm{IPF}}, \tag{2.3}$$

where $T(E0)_{\mathrm{IC}}$ is the contribution involving internal conversion from K and L electron shells and $T(E0)_{\mathrm{IPF}}$ is due to the internal pair formation which is nonzero only for a transition energy larger than 1.022 MeV.

$T(E0)_{\mathrm{IC}}$ is related to the strength $\rho^2(E0)$ by the relation [14]

$$T(E0)_{\mathrm{IC}}=2.786\times10^{20}\rho^2(E0)\frac{E}{2I+1}\times[A(E0)_K+A(E0)_{L_{\mathrm{I}}}+A(E0)_{L_{\mathrm{II}}}+\cdots], \tag{2.4}$$

where $T(E0)_{\mathrm{IC}}$ is in s^{-1} and the transition energy E in MeV. The electronic coefficients $A(E0)_i$, where i represents the decay channel, i.e., one of the electronic shells $K,L_{\mathrm{I}},L_{\mathrm{II}},\ldots$, have been tabulated by Hager and Selzer [15] for a fixed value of r_0 equal to 1.2 fm and for transition energies up to 1.6 MeV. To extrapolate these numbers to higher energies, we have used the recipe given by Kantele [16,17].

The monopole decay rate due to internal pair formation $T(E0)_{\mathrm{IPF}}$ is also proportional to the strength $\rho^2(E0)$ with an electronic factor evaluated by Wilkinson [18]. With the knowledge of our microscopic $\rho^2(E0)$ strength, we have calculated these two contributions to $T(E0)$ decay rates. The $T(E0)_{\mathrm{IPF}}$ term becomes the leading contribution only for transition energies above 5 MeV for $Z=80-90$ nuclei [17].

In order to compare with electric quadrupole $E2$ and dipole $E1$ γ-decay rates, let us recall the expressions of the corresponding $T(E2)$ and $T(E1)$:

$$T(E2)=1.223\times10^{9}E^5B(E2),$$

$$T(E1)=1.587\times10^{15}E^3B(E1), \tag{2.5}$$

where $T(E2)$ and $T(E1)$ are expressed in s^{-1} and E the γ transition energy in MeV. The transition probabilities $B(E2)$ (in e^2 fm^4) and $B(E1)$ (in e fm) are related to the square of the transition matrix elements $m(E2)$ and $m(E1)$ defined as Eq. (2.1) with the usual quadrupole or dipole operators.

III. RESULTS AND DISCUSSION

In the present work, we calculate $E0$ transition rates for the even-even isotopes of mercury ($A=190-198$) and lead ($A=192-200$) for which Hartree-Fock energy maps, GCM states, and $E2$ decay out of SD bands were given in Refs. [11] and [12], respectively. As in these earlier works, SkM* effective force [19] is used and only quadrupole axial deformations are taken into account. In the case of ^{194}Pb, the influence of octupole deformations has also been investigated [12].

The monopole transitions are calculated between the SD collective state and states in the first well. First we compare electric $E0$ and $E2$ rates for the transitions to the ground state. Table I presents (lower part) the values of $m(E0)$, $\rho^2(E0)$, E, $T(E0)$, $m(E2)$, and $T(E2)$ obtained for mercury (upper part) and lead isotopes. Though less unfavored for lighter isotopes mainly in mercury, our calculations do not predict significant $E0$ transitions. Note that these rates are determined for band heads and would be decreased by a factor $(2J+1)$ for higher spins.

To study the dependence of decay rates on the excitation energy of the state in the first well, we have chosen the two lightest isotopes ^{190}Hg and ^{192}Pb. The results are reported in Table II. The striking feature of our results is a gradual increase of the $\rho^2(E0)$ with the excitation energy of the states in the first well. This leads to huge values greater than 1.0 [20] for transitions to the fourth excited state. In that case, the corresponding $T(E0)$ rate becomes of the same order of magnitude than the $T(E2)$ one and the $E0$ monopole decay out appears to compete with the $E2$ quadrupole decay. The $E2$ transition rate decreases with increasing excitation energy. This is mostly due to the variation of the transition energy which enters into the transition rate with a power 5 [see Eq. (2.5)].

In Ref. [12], we studied the coupled axial quadrupole and

TABLE II. Transitions between the SD state and other GCM states for ^{190}Hg (upper part) and for ^{192}Pb (lower part). The mixing angle θ is expressed in degrees; see Table I for other notations.

	$m(E0)$	$\rho^2(E0)$	θ	E	$T(E0)$	$m(E2)$	$T(E2)$
4th	82.16	2.98	57	0.29	6.1×10^{11}	649.0	1.05×10^{12}
3th	16.46	0.12	85	1.02	6.2×10^{10}	103.2	1.43×10^{13}
2nd	5.49	1.3×10^{-2}	89	1.76	1.6×10^{10}	8.76	1.58×10^{12}
1st	4.68	9.7×10^{-3}	88	2.69	1.7×10^{10}	24.69	1.05×10^{14}
g.s.	2.97	3.9×10^{-3}	90	3.11	9.4×10^{9}	9.84	3.43×10^{13}
4th	73.43	2.34	62	0.11	4.7×10^{11}	718.3	1.18×10^{10}
3th	19.54	1.66×10^{-1}	86	0.99	1.1×10^{11}	72.82	6.15×10^{12}
2nd	5.84	1.48×10^{-2}	89	1.94	2.1×10^{10}	11.84	4.70×10^{12}
1st	6.33	1.74×10^{-2}	89	2.48	7.7×10^{8}	31.74	1.15×10^{14}
g.s.	0.94	3.85×10^{-4}	89	3.46	1.3×10^{9}	14.44	1.26×10^{14}

octupole dynamics of ^{194}Pb. States of both parities were obtained. One of each parity was located in the second well, corresponding to positive and negative parity band heads. The negative parity intrinsic state is excited by about 2 MeV with respect to the positive parity state. Using transition matrix elements of the dipole operator, we have estimated the $T(E1)$ decay rate to compare it to the $T(E0)$ rate. For the SD^+ state, our present calculation of $T(E0)$ confirms our previous result [12]: its decay out is dominated by $E2$ transition. The $E0$ transitions are found comparable with the $E1$'s but still two order of magnitude too low. For the SD^- state, the $E0$ transition rate is negligible and the decay out of the SD excited negative parity band remains dominated by $E1$ transitions to yrast SD states.

In Table III are summarized the evolutions of $m(E0)$ and $\rho^2(E0)$ for the transition between the SD state and the state in the first well for which the matrix element is the largest. In all cases, this state is the one the closest in energy to the SD state. The strongest $\rho^2(E0)$ values occur for the lightest Hg and Pb isotopes. The $T(E2)$ decay rates between the same states are also given in Table III. Both these $E0$ and $E2$ rates are significantly lower than the $E2$ rates to the ground states given in Table I. This result agrees with the main conclusions of Krücken *et al.* [7], although there are several significant differences between our model and the calculation of this reference.

TABLE III. Monopole matrix elements $m(E0)$ (in e fm^2), strengths $\rho^2(E0)$, transition energies (in MeV), $T(E0)$, and $T(E2)$ (in s^{-1}) for mercury (upper part) and lead (lower part) isotopes. For each nucleus these quantities are given for the transition between the SD and the states in the first well where the matrix element takes the largest value.

	$m(E0)$	$\rho^2(E0)$	E_γ	$T(E0)$	$T(E2)$
^{190}Hg	82.16	2.98	0.29	6.1×10^{11}	1.1×10^{12}
^{192}Hg	33.72	0.49	0.41	1.2×10^{11}	1.2×10^{12}
^{194}Hg	7.82	2.62×10^{-2}	0.94	1.3×10^{10}	1.1×10^{13}
^{196}Hg	27.62	0.32	0.08	4.7×10^{10}	0.3×10^{9}
^{198}Hg	6.38	0.17	0.40	4.2×10^{9}	5.4×10^{10}
^{192}Pb	73.43	2.34	0.11	4.8×10^{11}	1.2×10^{10}
^{194}Pb	16.24	0.11	0.35	3.4×10^{10}	6.4×10^{11}
^{196}Pb	17.13	0.12	2.30	2.2×10^{11}	3.2×10^{14}
^{198}Pb	0.91	3.46×10^{-4}	1.84	4.6×10^{8}	7.5×10^{13}
^{200}Pb	8.38	2.91×10^{-2}	0.20	6.9×10^{9}	2.2×10^{9}

The transition matrix elements that we have determined result from a microscopic self-consistent calculation, with an effective nucleon-nucleon interaction as only phenomenological input. It gives us the opportunity to test the phenomenological two-level model used by Krücken *et al.* [7] and by Wood *et al.* [6]. In this model, all the strength results from the mixing of two states with very different deformations. The amplitudes a and b of both components in the physical state are parametrized by an angle θ, with $a=\sin\theta$ and $b=\cos\theta$. Assuming θ closed to 90° the $E0$ strength can be expressed as

$$\rho^2(E0)=a^2b^2[\langle r^2\rangle_1-\langle r^2\rangle_2]^2\frac{Z^2}{R^4}. \tag{3.1}$$

It only depends on the mixing angle and on the square of the difference between the rms radii of the states which are mixed. Using a second order expansion of the radii in the deformation parameter β, this expression can also take the form

$$\rho^2(E0)=a^2b^2(\beta_1^2-\beta_2^2)^2\left(\frac{3Z}{4\pi}\right)^2. \tag{3.2}$$

The only ingredient that is not obviously given by our method is the mixing angle. To determine it, we have to define two decoupled states. A simple way to proceed which does not require any new calculation is to use the quadrupole coupling between GCM states located in the two wells that we have discussed in our previous papers (see, for instance, Ref. [21]). We define decoupled states as the states obtained by the diagonalization of the quadrupole coupling matrix between the SD state and the states located in the first well. The actual GCM states can be then mixtures between these decoupled states, with a mixing angle θ. We use it together with the radii of the decoupled states to evaluate what would be the monopole transition in a two-level model. The mixing angles are given in Table II for ^{190}Hg and ^{192}Pb using a diagonalization of the quadrupole matrix between the SD state and each of the first four eigenstates of the first well. Table II indicates that the SD state is fully decoupled with the ground state but significantly coupled to the nearest state:

TABLE IV. Comparison between monopole strengths $\rho^2(E0)$ calculated within the two-level model and the full GCM calculation for ^{190,198}Hg and ^{192,200}Pb. For each nucleus are given root mean square radii (in fm^2) for the ground state, the SD state and the state in the first well that is closest in energy, $\Delta\langle r^2\rangle^2$ (in fm^4), mixing angle θ (in degrees). The two last columns give, respectively, the strengths $\rho^2(E0)$ calculated in the two-level model and in the full GCM calculation.

	$\langle r^2\rangle_{\text{g.s.}}$	$\langle r^2\rangle_{\text{SD}}$	$\langle r^2\rangle_{\text{near}}$	$\Delta\langle r^2\rangle^2$	θ	$\rho^2(E0)$ two-level	$\rho^2(E0)$ GCM
^{190}Hg	28.79	31.44	29.09	5.525	57	3.257	2.98
^{198}Hg	29.02	32.56	29.62	8.620	88	0.028	0.017
^{192}Pb	28.78	31.86	29.47	5.759	62	3.716	2.34
^{200}Pb	29.15	32.98	30.12	8.203	89	0.028	0.029

θ varies from 90° to around 60° which explains the large differences between the $\rho^2(E0)$ values. Similar results are obtained for all nuclei, although the couplings are significantly smaller for the heavy isotopes reflecting the increase of the barrier height between the two wells as a function of the neutron number.

In Table IV we compare the monopole strengths calculated within the two-level model to the full calculation GCM values for all the isotopes and only for the nearest state in energy. The agreement between the two models is fairly good in all cases. Although the assumption of a mixing of the SD state with a single state is valid, the value of the mixing angle is strongly case dependent: the squared mixing amplitude a^2 varies from 29.6% in ^{190}Hg to 0.12% in ^{198}Hg. The largest values seem to be still compatible with the assumption of weak mixing made to derive Eq. (3.1).

The values of the monopole matrix element that we have found are in qualitative agreement with the estimates of Krücken *et al.* [7]. However, in our calculation, the difference in energy between the states in the two wells may be up to a few hundred keV, compared to a few keV in Krücken's model. In our case, this energy difference is a result of the calculation and not an assumption of the model. Nevertheless, this larger energy difference is not sufficient to create significant $E0$ decay rates.

IV. CONCLUSIONS

Within the framework of the generator coordinate method, we have investigated the electric monopole strength in the decay out of SD bands in the $A=190$ mass region. Our calculations show that $E0$ transitions cannot compete with $E2$ transitions to low-lying states even in the lightest isotopes ^{190}Hg and ^{192}Pb, where $E0$ transitions are enhanced. Transitions to excited states in the first well are more favored and if there is any chance for $E0$ transitions to be detected one should search for γ rays of energy lower than 1 MeV. Several factors have not been taken into account in our calculations. We have only introduced collective vibrational modes and not individual excitations, such as two quasiparticle states. Thus our model does not allow us to reproduce the $E1$ transition rates, which up to now seem to correspond to the dominant decay mode of SD bands [22,23]. Furthermore we have not taken into account the rotational degree of freedom. That we have only considered vibrational band heads may affect partly our results but probably not the isotopic and the energy dependences of $E0$ transition rates.

ACKNOWLEDGMENTS

We thank A. Astier, W. Korten, S. Perriès, and N. Redon for fruitful discussions about the possible proposal for an experimental evidence of these transitions. Thanks are also due to R. Béraud and I. Berkès for discussions about the definition of the monopole transition decay rates. Part of the numerical calculations were carried out by the CRAY vector facilities of the IDRIS-CNRS center.

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