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# $(2^+ \bigotimes 3^-)$ TWO-PHONON STATES AND FAST E1 TRANSITIONS IN $^{144}$Sm

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The nuclear field theory approach to the treatment of two-phonon excitations in the nuclear spectrum is applied to the $(2^+ \bigotimes 3^-)$ two-phonon multiplet states in the nucleus $^{144}$Sm. Theory provides a quantitative account concerning the energies and gamma-decay rates.

## 1. *Introduction*

The search and the study of multiphonon states is a central issue in the understanding of many-fermion systems, giving, in particular, a direct check on the degree of anharmonicity of the vibrational motion. There are a lot of examples of two-phonon states of quadrupole type in even-even nuclei. On the other hand, data on multiphonon states involving octupole excitations are quite rare.

In the present paper, recent experimental results about the nucleus $^{144}$Sm [1,2] are analyzed within the framework of nuclear field theory (NFT) [3].

For the quintuplet of negative parity states the excitation energies strongly suggest an interpretation as $(2^+ \bigotimes 3^-)$ levels. A very important feature of the decay of these states is associated with the observation of fast $E1$ transitions ($B(E1) \approx 10^{-3}$

Weisskopf units) that are much faster than the majority of $E1$ transitions in this mass region [1].

## 2. Theory

Nuclear field theory provides a systematic method to analyse the various facets of collective states in nuclei. In it the free fields, corresponding to vibrational (boson) and quasi-particle (fermion) degrees of freedom and containing a large fraction of the many-body nuclear correlations, interact through both the model bare interaction and the particle-vibration coupling vertices. Unlike other systems with many degrees of freedom, the nuclear bosonic fields are built out of the quasiparticle degrees of freedom. So it is a characteristic of the basis to be overcomplete and to contain states violating the Pauli principle. It has been shown that the NFT correctly treats these effects to all orders of perturbation theory.

In NFT one can construct diagrammatically the interaction among phonons. Due to the rapid convergence of the NFT perturbative expansion, only the lowest order diagrams are in general important [4].

The nucleus $^{144}$Sm is a semi-magic nucleus with 82 neutrons and 62 protons. To determine the single-particle properties, we use a standard Woods-Saxon potential. For the protons, a static deformation of the pairing field is established and for the calculation we use the quasiparticle representation in the nuclear BCS approximation [5]. The residual particle-hole interaction is of a multipole-multipole type, and the coupling constants are determined from the experimental data for the energies

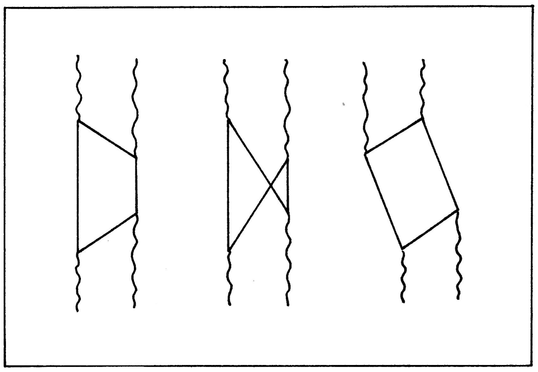

*Fig. 1. Diagrams representing the basic topologies which contribute to the energy shift in the case of two-phonon interaction. The arrows corresponding to the fermion states have been omitted in the figure, so the drawing should represent all possible combinations of particle-hole lines and quasiparticles lines.*

and the electromagnetic transition $B(E\lambda)$ values for the lowest states of a given multipolarity in the random phase approximation. The particle-vibration coupling vertices are, in this way, fully determined [3]. In Fig. 1, the diagrams contributing to the energy shift in the case of phonon-phonon interaction are shown. Comparison between the resulting single phonon spectrum and the experimental findings is shown in Table 1.

*TABLE 1.*
*Experimental [2] and calculated energies of the $(2^+ \bigotimes 3^-)$ two-phonon states.*

| $J^\pi$ | $E_{exp}$ | $E_{cal}$ |
|---|---|---|
| $1^-$ | 3.22 | 3.14 |
| $2^-$ | 3.39 | 3.49 |
| $3^-$ | 3.53 | 3.50 |
| $4^-$ | 3.59 | 3.47 |
| $5^-$ | 3.67 | 3.35 |

## 3. The E1-transitions

The NFT allows to construct diagrammatically the effective electromagnetic matrix elements corresponding to the transitions between the basic states. The external field is modified by the mediation of the collective states, in particular of the giant dipole resonance (GDR) for the $E\lambda$ transition, as shown in Fig. 2.

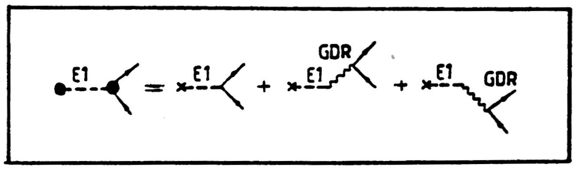


*Fig. 2. Renormalization of single-particle E1 moment due to particle-vibration coupling.*

These graphs lead to a simple renormalization of the coupling, given by

$$c_{eff} = e(1 + \chi(\Delta E)) ,$$

where the polarizability can be written as [5]

$$\chi(\Delta E) \approx -0.76 \frac{(\hbar\omega_D)^2}{(\hbar\omega_D)^2 - (\Delta E)^2} .$$

The quantity $\Delta E = E - \hbar\omega_{3^-}$ is the energy of the dipole transitions, very small in our cases as compared to the GDR energy $\hbar\omega_D \approx 15$ MeV. Consequently, one can use the static value of the polarizability

$$\chi(\Delta E = 0) \approx -0.76.$$

Adding the corrections for the center of mass motion, we obtain

$$\epsilon_{eff}(E1) = -\frac{1}{2}e\left(\tau_2 - \frac{N-Z}{A}\right)(1+\chi).$$

In the case of $^{144}$Sm one finds $\epsilon_{eff}(E1) \approx 0.17e$ for protons and $\epsilon_{eff}(E1) \approx -0.13e$ for neutrons.

The NFT diagrams used in the calculation of the transition matrix elements are shown in Fig. 3.

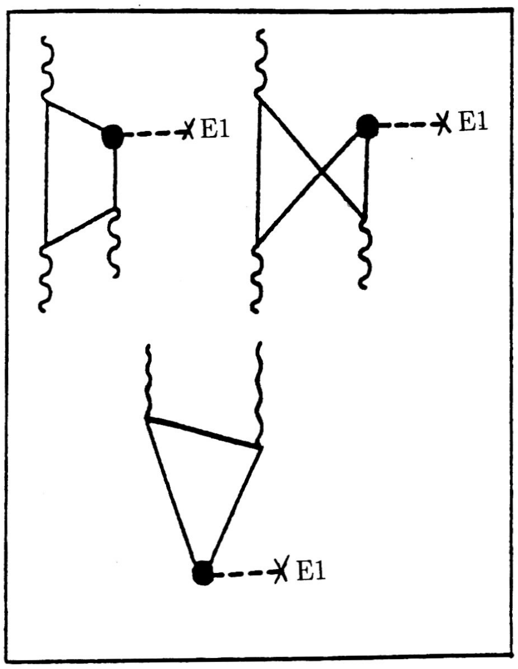


*Fig. 3. Diagrams representing the basic topologies that are used in the calculation of transition matrix elements. The arrows corresponding to the fermion states have been omitted. Therefore, the drawing should represent all possible combinations of particle and hole lines.*

The $B(E\lambda)$ calculated values are the result of a strong cancellation among the contributions displayed above. The transition probabilities for $1^-$, $2^-$ and $3^-$ are compared in Figs. 4 – 6. In the cases of $2^-$ and $3^-$ states the experimentally observed transition strengths are accounted for. In the case of the $1^-$ state, the experimental data are accounted for not only in the case of the transition from th two-phonon $(2^+ \otimes 3^-)_{1^+}$ state to the ground-state but also (this transition is not allowed in the harmonic model) to the first $2^+$ state (cf. Fig. 4).

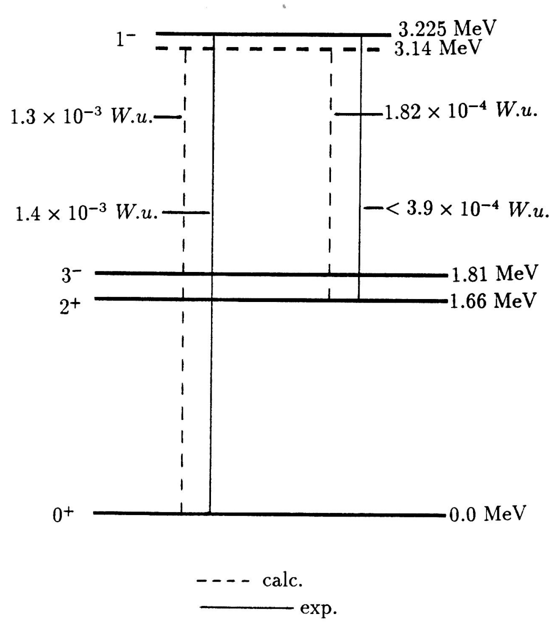


*Fig. 4. Partial level scheme showing the proposed $1^-$ state in $^{144}$Sm. Measured (—-) and calculated (- - -) E1 transition rates are in Weisskopf units.*

## 4. Conclusions

An overall account of the experimental findings concerning the energy and gamma-decay rates of the $(2^+ \otimes 3^-)$ two-phonon multiplet is obtained within the framework of the nuclear field theory.

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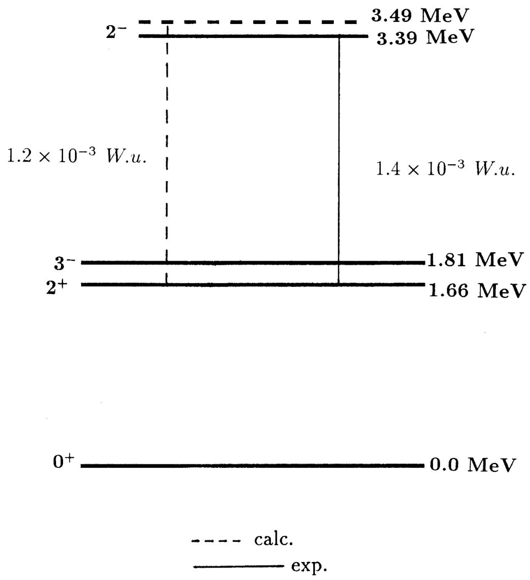


*Fig. 5. Partial level scheme showing the proposed 3⁻ state in $^{144}$Sm. Measured (—-) and calculated (- - -) E1 transition rates are in Weisskopf units.*

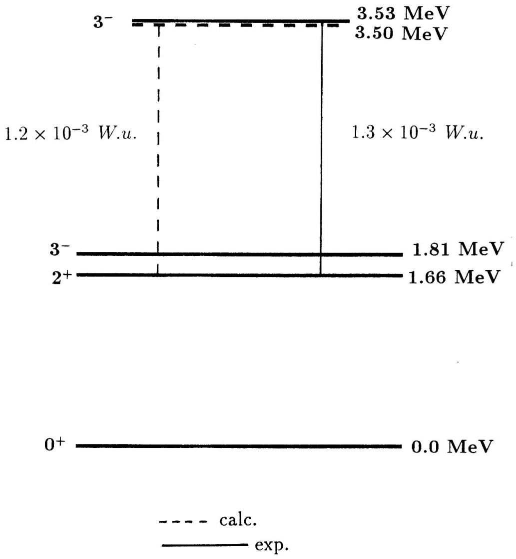


*Fig. 6. Partial level scheme showing the proposed 3⁻ state in $^{144}$Sm. Measured (—-) and calculated (- - -) E1 transition rates are in Weisskopf units.*

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## $(2^+ \bigotimes 3^-)$ DVO-FONONSKA STANJA I BRZI PRIJELAZI U $^{144}$Sm

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Primjenom nuklearne teorije polja na problem dvo-fononskih pobuđenja razmatrana su $(2^+ \bigotimes 3^-)$ dvo-fononska multipletna stanja u jezgri $^{144}$Sm. Dobivena je kvalitativna ocjena energija i prijelaznih vjerojatnosti gama raspada.