Strong Fragmentation of Low-Energy Electromagnetic Excitation Strength in ^{117}Sn

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(Received 4 June 1999)

Results of nuclear resonance fluorescence experiments on ^{117}Sn are reported. More than 50 γ transitions with $E_\gamma < 4$ MeV were detected. For the first time microscopic calculations making use of a complete configuration space for low-lying states are performed for a heavy odd-mass spherical nucleus. The theoretical predictions are in good agreement with the data. It is concluded that although the $E1$ transitions are the strongest ones also $M1$ and $E2$ decays contribute substantially to the observed spectra. In contrast to the neighboring even $^{116-124}$Sn nuclei, in ^{117}Sn the 1^- component of the two-phonon $[2_1^+ \otimes 3_1^-]$ multiplet built on top of the $1/2^+$ ground state is proved to be fragmented.

PACS numbers: 21.10.Re, 21.60.–n, 23.20.–g, 25.20.Dc

During the past years the study of the properties of multiphonon excitations in atomic nuclei has been one of the key topics in nuclear structure research. The concept of phonons is widely used in nuclear physics to describe collective vibrations. Coupled to each other they form a set of multiphonon states, multiplets, with different spin, J, and same parity, π, which should be energy degenerated in an harmonic picture. The main motivation for the above-mentioned studies is to gain insight into the applicability of the harmonic vibrational or, in other words, the phonon picture to a finite strongly interacting fermion system, like an atomic nucleus. In addition to the well-known two-phonon states constructed of the two identical lowest quadrupole vibrations, other multiphonon states have been under attention recently: two-phonon states built up of a collective quadrupole and octupole phonons (notated as $[2_1^+ \otimes 3_1^-]_{J^\pi}$) [1–3], of two octupole phonons [4–6], and of two giant resonances [7,8].

Different nuclear reactions are used in these investigations. Nuclear resonance fluorescence (NRF) is one of them. It is very selective to dipole excitations. For this reason it is applied to examine the 1_1^- state which is known to be a practically pure two-phonon $[2_1^+ \otimes 3_1^-]_{1^-}$ state. This state decays predominately directly to the ground state. The main conclusion from systematic studies [2,3,9–11] of this 1^- state in even spherical nuclei in different mass regions is that anharmonicity effects are rather weak, supporting a harmonic treatment of these nuclear excitations.

The next logical step in these studies should be their extension to spherical odd-mass nuclei, where the experimental information is sparse. NRF experiments on ^{113}Cd [12], ^{133}Cs [13], and ^{143}Nd [14] have been already reported. From very general arguments one expects rather weak changes in the properties of collective vibrations when they are coupled to an odd quasiparticle. However, even the first NRF experiments indicated a rather strong fragmentation of the excitation strength. To minimize the number of possible excited levels it is imperative to consider this coupling of collective vibrations to an odd quasiparticle in a nucleus with ground state spin $1/2$.

In the present Letter we report on NRF experiments on ^{117}Sn ($J^\pi_{\mathrm{g.s.}} = 1/2^+$) in which more than 50 transitions with $E_\gamma < 4.05$ MeV have been observed. It is clear that a detailed theoretical analysis which provides information on the structure of the excited states is necessary to explain the results of this experiment. For this reason a full microscopic calculation of the properties of multiphonon states in heavy odd-mass spherical nuclei has been performed for the first time.

Experimental results have been obtained with the bremsstrahlung NRF facility at the 4.3 MV Dynamitron accelerator of Stuttgart University [1]. The NRF technique has already been extensively described in review articles (see, e.g., Ref. [1]). The electron beam energy was 4.1 MeV. For this experiment, three HPGe detectors with 100% efficiency [relative to a $3'' \times 3''$ NaI(Tl) crystal] were used at scattering angles of 90°, 127°, and 150°. The NRF target consisted of two tin disks. The total amount of tin was 1.649 g and the enrichment in ^{117}Sn was 92.10%. Two ^{27}Al disks with a total weight of 780 mg were sandwiched between the tin disks. Well-known photon scattering cross sections [15] of the aluminum nuclei enabled the photon flux calibration and thereby the absolute measurement of the photon scattering cross sections of excited states in the ^{117}Sn nuclei.

In this experiment 56 γ transitions have been detected in the energy range from 1440 to 4050 keV. From the consideration of γ energy differences we have found that only five of the observed γ transitions may be due to inelastic photon scattering. The energy integrated cross sections for elastic scattering, I_s, are plotted in Fig. 1a. Spin quantum numbers could be assigned to some excited states from angular distribution measurements: for five levels the spin value $3/2$ is suggested and for another six levels an assignment $1/2(3/2)$ is made, meaning that $1/2$ is more likely. The applied NRF setup did not allow us to deduce parities for levels in ^{117}Sn. In the energy region under consideration only a few levels are known from other experiments [16]. More details on the experimental analysis and the complete information on observed transitions will be published in a forthcoming article.

Comparing our results with those for ^{113}Cd [12], ^{133}Cs [13], and ^{143}Nd [14] we conclude that strong fragmentation of low-energy electromagnetic excitation strength is a general feature in heavy odd-mass nuclei. With the present state-of-the-art NRF technique alone it is not possible to study in detail the properties of the many levels involved and thus, a theoretical support is needed.

To accomplish this task a theoretical analysis of the properties of low-lying states in ^{117}Sn has been performed within the quasiparticle-phonon model (QPM) [17]. The QPM has been successfully applied to describe the position and the $E1$ excitation probability of the lowest 1^- state in the even-even $^{116-124}$Sn isotopes [3]. This state has a 96%–99% $[2_1^+ \otimes 3_1^-]_{1^-}$ two-phonon configuration. A general QPM formalism to treat odd-mass spherical nuclei is presented in review articles [18,19]. A Woods-Saxon potential is used in QPM as an average field for protons and neutrons. Phonons of different multipolarities and parities are obtained by solving RPA equations with a separable form of the residual interaction. The single-particle spectrum and phonon basis are fixed from

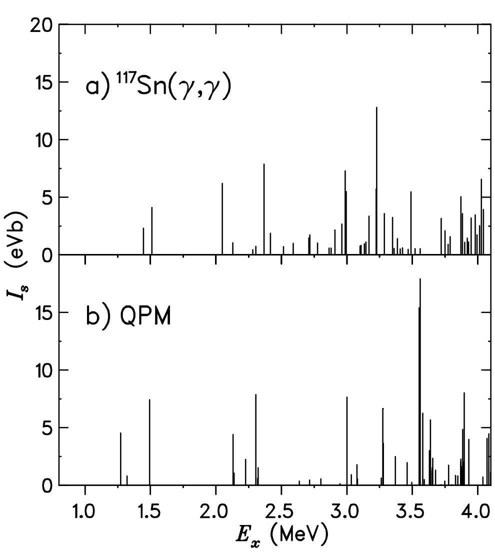

FIG. 1. (a) Experimental and (b) calculated integrated elastic γ cross sections in ^{117}Sn.

calculations in the neighboring even-even nuclear core, i.e., in ^{116}Sn [3] when the ^{117}Sn nucleus is considered.

In our present calculations the wave functions of the ground state and excited states with spin and parity J^π are mixtures of different "quasiparticle $\otimes N$-phonon" ($[\mathrm{qp} \otimes N\mathrm{ph}]_{J^\pi}$) configurations, where $N = 0, 1, 2,$ and 3. All interaction matrix elements between them are calculated on a microscopic footing, making use of the internal fermion structure of the phonons and the model Hamiltonian. When $N \geq 1$, phonon excitations of the core couple to a quasiparticle for any level of the average field, not only for the ones with the quantum numbers J^π as for a pure quasiparticle configuration. To achieve a correct position of the $[\mathrm{qp} \otimes 2\mathrm{ph}]$ configurations, in which we are especially interested in these studies, $[\mathrm{qp} \otimes 3\mathrm{ph}]$ configurations are important. The excitation energies and the contribution of different components from the configuration space to the structure of each excited state are obtained by a diagonalization of the model Hamiltonian on a set of employed wave functions. Interaction matrix elements are calculated to first order perturbation theory. This means that any $[\mathrm{qp} \otimes N\mathrm{ph}]$ configuration interacts with the $[\mathrm{qp} \otimes (N \pm 1)\mathrm{ph}]$ ones, but its coupling to $[\mathrm{qp} \otimes (N \pm 2)\mathrm{ph}]$ configurations is not included in this theoretical treatment. The omitted couplings have nonvanishing interaction matrix elements only in second order perturbation theory. They are much smaller than the ones accounted for and excluded from consideration for technical reasons. Pauli principle corrections which result in an energy shift of complex configurations from the energy sum of their constituents have been treated in a diagonal approximation (see Ref. [18] for details). Configurations which violate the Pauli principle have been excluded from the configuration space.

The phonon basis includes the phonons with multipolarity and parity $\lambda^\pi = 1^\pm, 2^+, 3^-,$ and 4^+. Several low-energy phonons of each multipolarity are included in the model space. The most important ones are the first collective $2^+, 3^-,$ and 4^+ phonons and the ones which form the giant dipole resonance (GDR). Noncollective low-lying phonons of an unnatural parity and natural parity phonons of higher multipolarities are of marginal importance. To make realistic calculations possible one has to truncate the configuration space. We have done this on the basis of excitation energy arguments. All $[\mathrm{qp} \otimes 1\mathrm{ph}]$ and $[\mathrm{qp} \otimes 2\mathrm{ph}]$ with $E_x \leq 6$ MeV, and $[\mathrm{qp} \otimes 3\mathrm{ph}]$ with $E_x \leq 8$ MeV configurations which do not violate the Pauli principle are included in the model space. The only exceptions are $[\mathrm{qp} \otimes 1\mathrm{ph}]$ configurations of the type $[J_{\mathrm{g.s.}} \otimes 1^-]$. They have not been truncated at all to treat a core polarization effect due to the coupling of low-energy dipole transitions to the GDR on a microscopic level. Thus, for electric dipole transitions we have not renormalized effective charges and used $e^{\mathrm{eff}}(p) = (N/A)e$ and $e^{\mathrm{eff}}(n) = -(Z/A)e$ values to separate the center of mass motion. For $M1$ transitions we use $g_s^{\mathrm{eff}} = 0.64 g_s^{\mathrm{free}}$ as recommended in Ref. [20]. By doing this, all the important configurations for the description of low-lying states up to 4 MeV are included in the model space. The dimension of this space depends on the total spin of the excited states and it varies between 500 and 700.

Since only $E1$, $M1$, and $E2$ transitions could be observed in the present experiment, the properties of excited states with $J^\pi = 1/2^\pm$, $3/2^\pm$, and $5/2^+$ will be presented. As the parities of the decaying levels are unknown and spin only for a few levels could be assigned, the best choice is the integrated cross sections, I_s, for the comparison between theoretical predictions and experimental data. The calculated I_s values

$$I_s(\lambda) \propto E_x^{2\lambda-1} B(\pi\lambda) \cdot \frac{\Gamma_0}{\Gamma_{\rm tot}}, \tag{1}$$

where E_x is an excitation energy, $B(\pi\lambda)$ is a reduced transition probability of a multipolarity λ and parity π, and Γ_0 denotes the partial ground state decay width, for elastic transitions are plotted in Fig. 1b. The inelastic decays are accounted for in the total decay width $\Gamma_{\rm tot}$. Details concerning the calculations and branching ratios will be presented elsewhere. Supporting the experimental findings our calculations also provide a strong fragmentation of electromagnetic strength. The strongest transitions have $E1$ character, but also $E2$ and $M1$ excitations yield comparable cross sections. They are presented separately in Figs. 2b–2d, respectively, in comparison to calculated I_s values of the core nucleus, ^{116}Sn (Fig. 2a). The calculated total cross sections, I_s, of the plotted E1, $M1$, and $E2$ transitions in Figs. 2b–2d equal 73, 37, and 42 eV b. The summed experimental elastic cross sections, presented in Fig. 1a, equal 133 eV b and agree within 15% with the theoretically predicted 152 eV b.

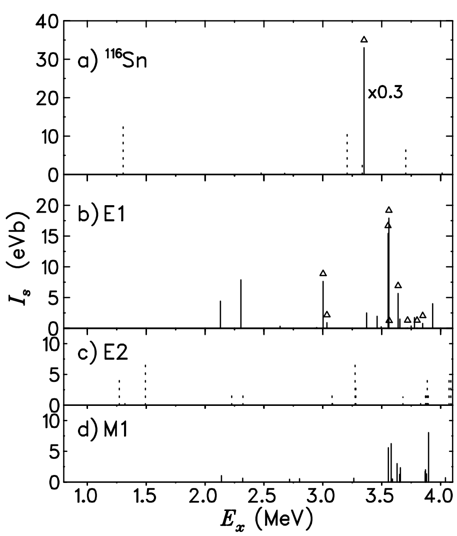

FIG. 2. Calculated integrated elastic γ cross sections in (a) ^{116}Sn and (b)–(d) ^{117}Sn. I_s for $E2$ decays are plotted by dashed lines in (a) and (c). $E1$ decays in (b) which are predominantly due to $[3s_{1/2} \otimes [2_1^+ \otimes 3_1^-]_{1^-}]_{1/2^-,3/2^-} \rightarrow 3s_{1/2}$ transitions are marked by triangles.

The good correspondence between experimental and theoretical results concerning strength fragmentation, position of main groups of levels, and the total electromagnetic strength makes us confident in the theoretical predictions. Thus, the theory can be confidently used for explaining the main features of the experimentally observed transitions.

Let us first ask whether the unpaired quasiparticle in odd-mass nuclei plays the role of a spectator. To answer this question we compare the structure of the excited states in ^{117}Sn with the structure of the corresponding states in the neighboring even-even core, ^{116}Sn. The most essential differences are in the electric dipole strength distribution over low-lying states in even- and odd-mass nuclei. The reason becomes clear by considering which states can be excited from the ground state by $E1$ transitions. In the even-even core there is only one 1^- configuration with an excitation energy below 4 MeV (line with triangle in Fig. 2a). It has a $[2_1^+ \otimes 3_1^-]_{1^-}$ two-phonon nature [3]. This is a general feature in heavy semimagic even-even nuclei [21]. All other 1^- configurations have excitation energies more than 1 MeV higher, therefore, the 1_1^- state has practically pure two-phonon character in semimagic nuclei. In contrast, there are many [qp $\otimes$ 1ph] and [qp $\otimes$ 2ph] configurations with the same spin and parity close to the two corresponding configurations $[3s_{1/2} \otimes [2_1^+ \otimes 3_1^-]_{1^-}]_{1/2^-,3/2^-}$ in ^{117}Sn. Interactions with them lead to strong fragmentations of these two main configurations (see Fig. 3). The resulting states are carrying a fraction of the $E1$ excitation strength from the ground state. A large part of the $[3s_{1/2} \otimes [2_1^+ \otimes 3_1^-]_{1^-}]_{1/2^-,3/2^-}$ configurations is concentrated in $3/2^-$ states with an excitation energy of 3.04 (11%), 3.55 (48%), and 3.56 MeV (32%) and in $1/2^-$ states at 3.00 (22%) and 3.63 MeV (63%) (see lines with triangles in Fig. 2b). The $E1$ strength distribution among low-lying levels is even more complex because $3/2^-$ states at 2.13, 2.33, and 3.93 MeV have a noticeable contribution from the $3p_{3/2}$ one-quasiparticle configuration with a large reduced excitation matrix element $\langle 3p_{3/2} \| E1 \| 3s_{1/2} \rangle$ for which there is no analog in the even-even core ^{116}Sn. Also the coupling to $[3s_{1/2} \otimes 1^-_{\rm GDR}]$, which treats the core polarization effect, is somewhat different than in the core nucleus, because the blocking effect plays an important role in the interaction with

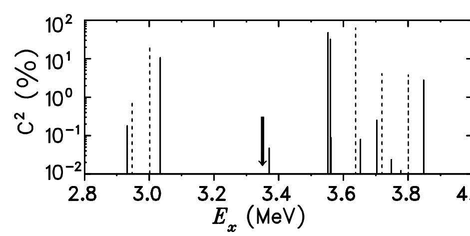

FIG. 3. Contribution C^2 of the $[3s_{1/2} \otimes [2_1^+ \otimes 3_1^-]_{1^-}]_{J^\pi}$ configuration to wave functions of $J^\pi = 3/2^-$ (solid lines) and $J^\pi = 1/2^-$ (dashed lines) states in ^{117}Sn. The position of the $[2_1^+ \otimes 3_1^-]_{1^-}$ state in ^{116}Sn is indicated by the arrow.

other configurations (see also Ref. [22], where only the last type of transitions has been accounted for). The calculated total $B(E1)\uparrow$ strength in the energy region from 2.0 to 4.0 MeV is $7.2 \times 10^{-3} e^2\,\mathrm{fm}^2$. It agrees well with the calculated $B(E1, 0^+_{\mathrm{g.s.}} \to [2^+ \otimes 3^-]_{1^-}) = 8.2 \cdot 10^{-3} e^2\,\mathrm{fm}^2$ in the neighboring ^{116}Sn nucleus [23].

Positive parity states in ^{117}Sn are deexciting to the $1/2^+$ ground state by $E2$ or $M1$ or mixed $M1/E2$ transitions. The $B(E2)\uparrow$ strength distribution is dominated by the excitation of the $3/2^+$ state at 1.27 MeV and the $5/2^+$ state at 1.49 MeV. The wave functions of these states carry 85% and 60% of the $[3s_{1/2} \otimes 2^+_1]$ configuration, respectively. A smaller fraction of this configuration can be found in the $3/2^+$ state at 2.32 MeV (5%) and the $5/2^+$ state at 2.23 MeV (6%). The rather fragmented $E2$ strength at higher energies (Fig. 2c) is mainly due to $[3s_{1/2} \otimes 2^+_{4,5}]$ configurations which are much less collective than the first one. Fragmented $E2$ strength between 2.0 and 4.0 MeV originated from excitation of $2^+_{4,5}$ phonons has also been observed in NRF experiments on the even ^{116}Sn nucleus [23]. It could be well reproduced by theoretical calculations (see the dashed lines in Fig. 2a). In the odd-mass ^{117}Sn nucleus the corresponding strength is even more fragmented because of the higher density of configurations. Nevertheless, these $E2$ excitations at high energies contribute appreciably to the reaction cross section, because the $E2$ photon scattering cross section is a cubic function of the excitation energy [see Eq. (1)].

The $B(M1)\uparrow$ strength in these calculations is concentrated mainly above 3.5 MeV as can be seen in Fig. 2d. The wave functions of the $1/2^+$ and $3/2^+$ states at these energies are very complex. The main configurations, responsible for the $M1$ strength, are the $[2d_{5/2,3/2} \otimes 2^+_i]$ ones which are excited because of the internal fermion structure of the phonons (similar to $E1$ $0^+_{\mathrm{g.s.}} \to [2^+_1 \otimes 3^-_1]_{1^-}$ excitations). They have no analogous transitions in even-even nuclei. The configuration $[3s_{1/2} \otimes 1^+_1]$ has an excitation energy of about 4.2 MeV but its contribution to the structure of states below 4 MeV is rather weak. Most of the states with the largest $B(M1)\uparrow$ values have $J^\pi = 1/2^+$.

To conclude, a strong fragmentation of low-energy electromagnetic excitation strength in ^{117}Sn has been observed in NRF experiments. This observation could be understood by microscopic calculations using a complete configurational space for low-lying states. The calculations show that several $E1$, $M1$, and $E2$ excitations lead to comparably large electromagnetic cross sections, which are expected to be observed in this highly sensitive NRF experiment. The structure of decaying states has been analyzed. We have shown that the $[1/2^+_{\mathrm{g.s.}} \otimes [2^+ \otimes 3^-]_{1^-}]$ configuration is strongly fragmented. The responsible configuration mixing is calculated to be considerably more complex than was suggested previously [14] in order to explain the similar fragmentation of electromagnetic excitation strength in the semimagic nucleus ^{143}Nd.

We thank Professor K. Heyde for fruitful suggestions to this manuscript. This work is part of the Research program of the Fund for Scientific Research-Flanders. The support by the Deutsche Forschungsgemeinschaft (DFG) under Contracts No. Kn 154/30 and No. Br 799/9-1 is gratefully acknowledged. V. Yu. P. acknowledges support from the Research Council of the University of Gent and a NATO fellowship.

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