ELSEVIER

1 September 1994

PHYSICS LETTERS B

Physics Letters B 335 (1994) 113–118

Observation of a 1^- two phonon $2^+ \otimes 3^-$ excitation in ^{116}Sn and ^{124}Sn

K. Govaert [a], L. Govor [b], E. Jacobs [a,1], D. De Frenne [a,1], W. Mondelaers [a], K. Persyn [a], M.L. Yoneama [a], U. Kneissl [c], J. Margraf [c], H.H. Pitz [c], K. Huber [d], S. Lindenstruth [d], R. Stock [d], K. Heyde [a], A. Vdovin [e], V. Yu Ponomarev [e]

[a] *Vakgroep Subatomaire en Stralingsfysica, Proeftuinstraat 86, B-9000 Gent, Belgium*
[b] *Russian Scientific Centre "Kurchatov Institute", Moscow, Russia*
[c] *Institut für Strahlenphysik, University Stuttgart, Stuttgart, Germany*
[d] *Institut für Kernphysik, University Giessen, Giessen, Germany*
[e] *Bogoliubov Laboratory of Theoretical Physics, Joint Institute of Nuclear Research, Dubna, Russia*

Received 5 April 1994; revised manuscript received 27 June 1994
Editor: R.H. Siemssen

Abstract

In nuclear resonance fluorescence experiments with unpolarized and linearly polarized bremsstrahlung we have observed for the first time very strong electric dipole transitions at about 3.5 MeV in the spherical, semi magic ^{116}Sn and ^{124}Sn nuclei. These transitions can be attributed to possible two phonon $2^+ \otimes 3^-$ excitations. The measured transition strengths are compared to the results of a QRPA calculation.

Collective excitations such as quadrupole and octupole vibrations are characteristic features in the low energy level scheme of spherical nuclei [1]. Much attention has been paid throughout the last years to multiphonon excitations in which two or more collective states couple with each other. In the case of quadrupole vibrations the coupling of two 2^+ phonons leads to a degenerate triplet of states with $J^\pi = 0^+, 2^+, 4^+$. Such multiplets have been found experimentally and described theoretically in many even–even nuclei near closed shells [1,2]. Data on multiphonon excitations involving octupole excitations are rare. The most compelling result is the observation of the coupling of two 3^- phonons in ^{147}Gd ($3^- \otimes 3^- \otimes$ particle multiplet) and ^{148}Gd [3,4]. Coupling between the quadrupole and octupole vibrational modes leads to another class of two-phonon states. A quintuplet of states with $J^\pi = 1^-, 2^-, 3^-, 4^-, 5^-$ is predicted at an energy close to the sum of the energies of the 2^+ and 3^- phonon [5]. The 1^- member of this multiplet generally displays a very strong E1 ground state transition. In photon scattering experiments such 1^- states have been found in various $N = 82$ nuclei [6–9] with large E1 decay strength to the ground state. Experimental efforts are under way to detect other members of this multiplet with different experimental techniques. Very recently dipole excitations to a $2^+ \otimes 3^- \otimes$ particle multiplet in the odd ^{143}Nd have also been identified [10]. As the semi magic Sn isotopes ($Z = 50$) have relatively low lying 3^- states varying in energy between 2.2 and 2.6 MeV with very strong (E3; $3^- \rightarrow 0^+$) transitions and 2^+ states at an

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[1] Research Director National Fund for Scientific Research.

SSDI 0370-2693(94)00867-1

almost stable energy of about 1.2 MeV, the 1^- member of the $2^+ \otimes 3^-$ multiplet should be found at about 3.5 MeV. This paper reports on the first observation of such 1^- states in ^{116}Sn and ^{124}Sn in nuclear resonance fluorescence (NRF) experiments performed at the bremsstrahlung facilities of the Nuclear Physics Laboratory in Gent and the Institut für Strahlenphysik in Stuttgart.

Photon scattering (NRF) experiments represent an outstanding tool to investigate such 1^- states. The fundamental advantage of this technique is the well understood mechanism of excitation and deexcitation via the electromagnetic interaction. Therefore completely model independent information can be extracted from such experiments. The small momentum transfer of real photons makes photon scattering extremely selective in exciting states, mainly by dipole and to a much lesser extent by electric quadrupole transitions. Transition width ratios Γ_0^2/Γ (Γ_0 and Γ: ground state and total decay width) and reduced transition probabilities $B(\pi L)$ can be determined from the measured scattering cross sections while the spins of the excited states J can be extracted from the measured angular distributions for even–even nuclei [11]. Parity assignments can be achieved by using linearly polarized photons and measuring the azimuthal asymmetry of the scattered photons. The measured asymmetry ϵ is the product of the degree of polarization of the beam P_γ and the analyzing power $\Sigma(\theta)$ of the reaction:

$$\epsilon = \frac{N_\perp - N_\parallel}{N_\perp + N_\parallel} = P_\gamma \Sigma(\theta) , \tag{1}$$

with $N_\perp$ and $N_\parallel$ the measured counting rates perpendicular and parallel to the polarization plane of the polarized bremsstrahlung beam. The analyzing power $\Sigma(\theta)$ is maximal at a scattering angle of 90° for spin cascades 0–1–0 and 0–2–0 and amounts to +1 for E1 and −1 for M1 and E2 transitions. This technique has been applied successfully for several years at the Giessen 65 MeV linac using partially linearly polarized off-axis bremsstrahlung [11]. Since 1992 a new polarized bremsstrahlung facility is operational at the Gent 15 MeV linac [12].

Our interest in the Sn isotopes is also due to the expectation of considerable spin-flip M1 strength in the energy region between 6 and 9 MeV. Searching for dipole transitions in ^{116}Sn and ^{124}Sn NRF experiments have been performed at the 15 MeV linac in Gent [12]. Both angular correlations and cross sections measurements using unpolarized bremsstrahlung [(γ, γ') experiments] and polarization measurements using linearly polarized off-axis bremsstrahlung [$(\vec{\gamma}, \gamma')$ experiments] were carried out. The complete results will be published in a forthcoming paper. In addition, for the low energy region, (γ, γ') measurements were performed at the bremsstrahlung facility of the Dynamitron in Stuttgart [13]. The results for excitation below 4 MeV will be presented in this paper. The targets consisted of 2 cm diameter disks of isotopically enriched (>96%) metallic Sn sandwiched between H_3BO_3 (Gent) or Al (Stuttgart) disks. The well-known transitions in ^{11}B, ^{16}O or ^{27}Al served as a standard for energy and photon flux calibration. The amount of target material used in the different experiments varied between 1 and 5 g.

In Gent we have performed (γ, γ') experiments with 10 MeV bremsstrahlung, followed by $(\vec{\gamma}, \gamma')$ experiments with 12 MeV linearly polarized bremsstrahlung. In the energy region of interest between 3 and 4 MeV unfortunately no conclusions about multipolarity and parity were possible at first sight due to a strong feeding of the levels from higher lying excited states. This is illustrated by Fig. 1 which shows the measured asymmetry in the $(\vec{\gamma}, \gamma')$ experiment on ^{116}Sn as a function of the energy. The dashed bands in this figure represent the expected asymmetry values for electric and magnetic dipole transitions. These values are equivalent to the degree of polarization of the bremsstrahlung beam. Above about 5 MeV all transitions clearly turned out to be E1 transitions except for one tentative M1 assignment. At lower energy the asymmetries are strongly reduced due to the feeding of these levels from higher lying excited states. For almost all of these levels we will show later that feeding is the dominating phenomenon resulting in almost isotropic angular distributions and hence vanishing asymmetries.

In Stuttgart (γ, γ') experiments were performed with 4.1 MeV bremsstrahlung. Fig. 2 displays the spectra obtained for both isotopes. One immediately observes the dominating peaks at 3334 keV in ^{116}Sn and at 3490 keV in ^{124}Sn. In both cases five transitions could be observed between 2 and 4 MeV. In Fig. 3 the intensity ratio $W_{90°}/W_{127°}$ is plotted for both isotopes. The full lines at 0.75 and 2.03 represent the expected values for pure dipole and quadrupole scattering. The dotted line represents the situation for an isotropic dis-

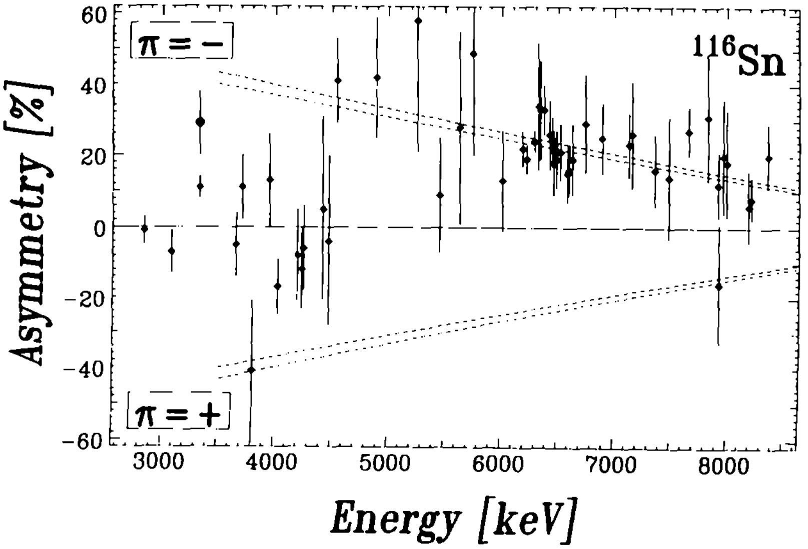

Fig. 1. Measured asymmetry as a function of the energy in the ($\vec{\gamma}$, γ') experiment on ^{116}Sn, measured with 12 MeV polarized bremsstrahlung. For the 1^- state at 3334 keV both the measured value (◆) and the value obtained after correcting for feeding are displayed (●).

tribution. The crosses in the figure correspond to transitions in ^{27}Al which have an (almost) isotropic angular distribution.

The results are summarized in Table 1. In the last column the ratio of the obtained transition width in the experiment with 10 MeV bremsstrahlung to the transition width with 4.1 MeV bremsstrahlung is given: $R=(\Gamma_0^2/\Gamma)^{10\ \mathrm{MeV}}/(\Gamma_0^2/\Gamma)^{4.1\ \mathrm{MeV}}$. The conclusion is clear: the levels are strongly fed from higher lying excited states in the experiment with 10 MeV bremsstrahlung. Typical values for this ratio at 3.5 MeV are of the order of 20 for ^{116}Sn and of the order of 5 for ^{124}Sn. This corresponds to respectively 95% and 80% feeding. By feeding we mean here the ratio $(R-1)/R$, i.e. the ratio of the observed transition strength with 10 MeV bremsstrahlung that is caused by population

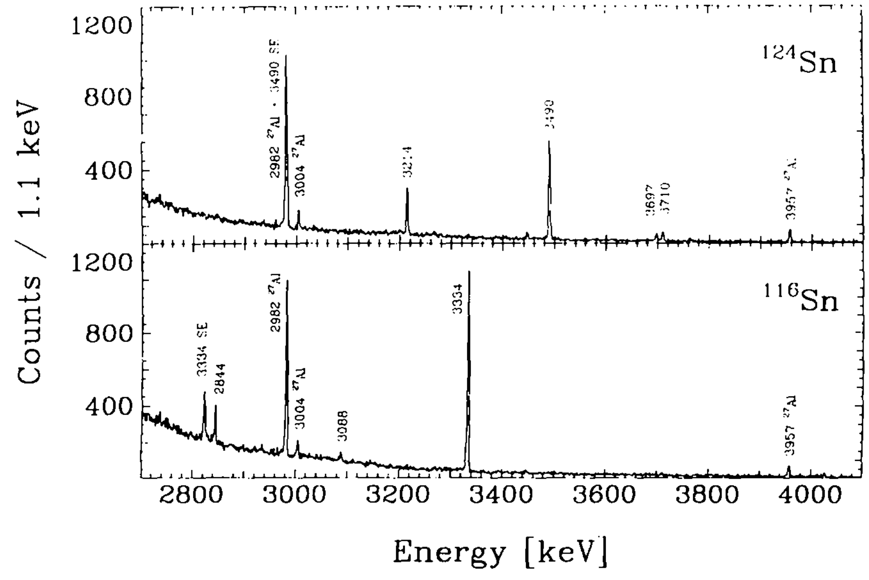

Fig. 2. (γ, γ') spectra for ^{116}Sn and ^{124}Sn measured with 4.1 MeV bremsstrahlung.

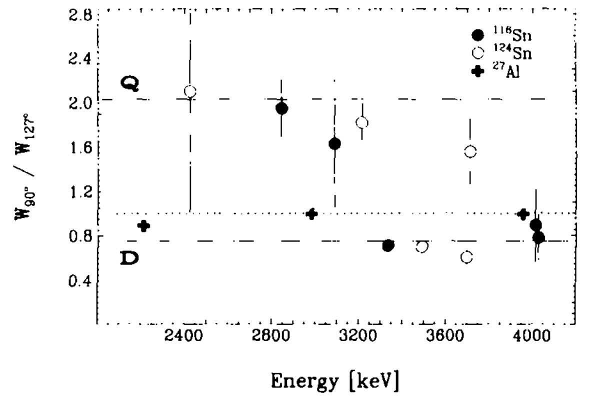

Fig. 3. Measured intensity ratio $W_{90°}/W_{127°}$ as a function of the energy.

from higher lying excited states to the total observed transition strength. The difference between ^{116}Sn and ^{124}Sn is probably mainly due to the difference in neutron separation energy for the two nuclei: 9.6 MeV for ^{116}Sn and 8.5 MeV for ^{124}Sn. Our results for the transition widths of the first 2^+ levels in ^{116}Sn and ^{124}Sn agree very well with the known values from literature [14,16]. For the other levels we have compared our results with the transition widths obtained in (n, n′, γ) measurements and found a reasonable (^{116}Sn) to good (^{124}Sn) agreement [15].

Very strong electric dipole transitions are observed at 3334 keV in ^{116}Sn with $\Gamma_0 = 85(8)$ meV and at 3490 keV in ^{124}Sn with $\Gamma_0 = 90(10)$ meV. The multipolarities and transition widths of these transitions were determined in the (γ, γ′) experiments performed in Stuttgart. The parities of these levels which are only weakly fed, could be extracted from the ($\vec{\gamma}$, γ′) experiments performed in Gent. Asymmetry values of respectively 10.7(34)% for ^{116}Sn and 21.8(66)% for ^{124}Sn were measured. Correcting for the amount of feeding of respectively 60.2(72)% and 38.8(77)% deduced from comparing the measurements at high and low energy results in asymmetry values of respectively 28.6(90)% and 36(11)%. These values should be compared with the degree of polarization of the bremsstrahlung beam: 42.0(20)% at 3.33 MeV and 40.8(20)% at 3.49 MeV. They allow the conclusion that the electric dipole character of these transitions has been determined unequivocally. Both the measured asymmetry value (♦) and the asymmetry value obtained after correcting for feeding (●) for the 1^- state at 3334 keV in ^{116}Sn are displayed in Fig. 1.

The strong E1 transitions observed for both isotopes can be attributed to two-phonon $2^+ \otimes 3^-$ excitations. Already the extremely low feeding (see Table 1) of the two 1^- states at 3334 keV in ^{116}Sn and at 3490 keV

Table 1
Experimental results for ^{116}Sn and ^{124}Sn

Nucleus	E_x (keV)	J^π	$W_{90°}/W_{127°}$	Γ_0^2/Γ (meV)		R [a]
				this work	other works	
^{116}Sn	1294	2+	1.76(19)	1.10(10)	1.157(31) [c]	210(26)
	2844	2+	1.95(26)	2.37(26)	$3.1^{+0.5}_{-0.6}$ [d]	24.9(37)
	3088	(2+)	1.63(58)	1.11(21)	$0.9^{+0.5}_{0.5}$ [d]	34.5(65)
	3334	1− [b]	0.71(3)	84.7(84)	51^{+15}_{-12} [d]	2.49(28)
	4013	1	0.89(33)	8.5(36)	23^{+16}_{-8} [d]	17.4(74)
	4027	1	0.78(21)	14.6(56)	>4 [d]	7.4(29)
^{124}Sn	1132	2+	1.69(38)	0.488(67)	0.470(10) [e]	179(19)
	2426	(2+)	2.1(11)	0.41(10)	$0.56^{+0.20}_{-0.20}$ [d]	140(36)
	3214	2+	1.82(17)	8.87(97)	$13.4^{+3.9}_{-2.7}$ [d]	3.64(43)
	3490	1− [b]	0.70(3)	90.2(98)	73^{+92}_{-29} [d]	1.63(19)
	3697	1	0.61(10)	11.3(17)	$11.7^{+5.1}_{4.3}$ [d]	5.04(83)
	3710	(2+)	1.56(30)	6.6(10)	$8.9^{+4.1}_{-2.1}$ [d]	6.4(12)

[a] $R = (\Gamma_0^2/\Gamma)^{10\,\mathrm{MeV}}/(\Gamma_0^2/\Gamma)^{4.1\,\mathrm{MeV}}$.
[b] Parity determined in ($\vec{\gamma}$, γ′) experiment.
[c] From Ref. [14].
[d] From Ref. [15].
[e] From Ref. [16].

in ^{124}Sn in comparison to the neighbouring states can be regarded as a hint for a special configuration of these states. Their energies are close to the sum of the energies of the 2^+ (1294 keV and 1132 keV) and the 3 phonon (2266 keV and 2602 keV). Their E1 transition strengths $B(\mathrm{E1}, 1^- \to 0^+)$ of $2.18(22) \times 10^{-3} e^2\,\mathrm{fm}^2$ corresponding to $1.42(14) \times 10^{-3}$ W.u. and $2.03(22) \times 10^{-3} e^2\mathrm{fm}^2$ corresponding to $1.27(14) \times 10^{-3}$ W.u. are about two orders of magnitude larger than the usual E1 strengths in this mass region [17]. These E1 strengths are also of the same order of the values for the corresponding E1 strengths $B(\mathrm{E1}, 3^- \to 2^+)$ of respectively $1.1(4) \times 10^{-3}$ and $1.26(10) \times 10^{-3}$ W.u. [15]. Similar large $B(\mathrm{E1}, 1^- \to 0^+)$ transition strengths have been observed in the $N = 82$ isotones [6–9] and a successful theoretical interpretation of these 1^- states as two-phonon excitations was given in the framework of the quasi-particle phonon model (QPM) [18,19].

The decay of the particular 1^- two-phonon $|2^+ \otimes 3^-; 1^-\rangle$ configuration occurring through the one-body E1 operator will vanish unless ground state correlations and 1p–1h 1^- (one-phonon) admixtures of the giant electric dipole resonance into the two-phonon $|2^+ \otimes 3^-; 1^-\rangle$ state are considered. In a schematic model one can derive the latter (polarization) charge considering only the lowest lying proton 1p–1h $|1g_{9/2}^{-1}\, 1h_{11/2}(\pi); 1^-\rangle$ admixture. In more realistic calculations all unperturbed proton and neutron 1p–1h states need to be considered, also including the residual interaction within this complete 1p–1h space in order to address the question of fragmentation of the two-phonon state $|2^+ \otimes 3^-; 1^-\rangle$. The diagonalization in the 1p–1h 1^- space results into the formation of the E1 giant dipole resonance (GDR) at 15.5 MeV in the Sn nuclei pulling the unperturbed 1p–1h E1 strength into that resonant state. As an outcome the unperturbed two-phonon $|2^+ \otimes 3^-; 1^-\rangle$ excitation retains its major structure (see Table 2). Similar results show up in the experimental data for the $N = 82$ nuclei. In the detailed calculation in which the wave functions describing the first 2^+ and 3^- states are derived within the QRPA, a non-vanishing direct E1 component is present in the ground state decay of the two-phonon $|2^+ \otimes 3^-; 1^-\rangle$ state. The precise reason for the appearance of such a contribution is the fact that specific 2 qp, 4 qp, ... components are contained in the construction of the QRPA correlated ground state [18]. In the schematic model only the large polarization contribution shows up. In the realistic studies, where we call the one-phonon states $|i; 1^-\rangle$ (i: rank number), the 1^- wave function reads

$$|1^-\rangle = R(2\mathrm{ph}\,|2^+ \otimes 3^-; 1^-\rangle + \sum_i R(i)\,|i; 1^-\rangle\,. \tag{2}$$

Here we include all 1^- one phonon states up to 20 MeV and only one two-phonon state. The coupling strengths between the pure two-phonon component and all the pure one-phonon states are calculated in a fully microscopic way using the QRPA description of these one-phonon states (see Refs. [20,21]). Both the direct two-phonon to ground state and one-phonon to ground state contributions as well as the two-phonon amplitude, the final $B(\mathrm{E1})\uparrow$ value and the theoretical energy for the lowest 1^- state are given in Table 2. For comparison the results from the NRF experiments have also been included. The polarization contributions are rather large giving rise to (taken separately) $B(\mathrm{E1})\uparrow$ values of the order of $(5\text{–}10) \times 10^{-3}\, e^2\,\mathrm{fm}^2$. In the studies carried out here, the major contribution to the polarization charge is coming from the GDR E1 state at 15.5

Table 2
Results from QRPA calculations for ^{116}Sn and ^{124}Sn and comparison with experimental results

		^{116}Sn	^{124}Sn
theory	$\langle 2^+ \otimes 3^-; 1^- \| M(\mathrm{E1}) \| 0^+\rangle$ ($e$fm)	0.0318	0.0495
	$\sum_i R(i)\langle i; 1^- \| M(\mathrm{E1}) \| 0^+\rangle$ ($e$fm)	0.0688	0.114
	Amplitude $(2^+ \otimes 3^-)$	−0.949	−0.964
	$B(\mathrm{E1})\uparrow$ ($e^2\,\mathrm{fm}^2$)	1.49×10^{-3}	4.39×10^{-3}
	E_x (MeV)	3.15	3.57
Experiment	$B(\mathrm{E1})\uparrow$ ($e^2\,\mathrm{fm}^2$)	$6.55(65) \times 10^{-3}$	$6.08(66) \times 10^{-3}$
	E_x (MeV)	3.334	3.490

MeV with a 0.1% amplitude admixture in the original two-phonon state. There is however a direct two-phonon to ground state component (even though the ground state correlations are rather small) going through 90% of the 1^- wave function. Both contributions interfere destructively giving rise to final $B(\mathrm{E1})\uparrow$ values that are of the correct magnitude in the investigated Sn nuclei.

We can conclude that we have shown in our NRF experiments the presence of 1^- states in ^{116}Sn and ^{124}Sn at about 3.5 MeV decaying via strong E1 transitions. These 1^- states are very near to the unperturbed energy of the two-phonon $|2^+\otimes 3^-; 1^-\rangle$ configuration. The observed large E1 strength seems to be a general feature near closed shells since in the $N=82$ closed shell nuclei, similar strongly excited 1^- states have been observed and interpreted as two-phonon $|2^+\otimes 3^-; 1^-\rangle$ states. The E1 strength is resulting from (i) a component originating through small admixtures (0.1% amplitude admixture) of the 1^- GDR at 15.5 MeV, called polarization charge, and (ii) a direct two-phonon to ground state component originating in the QRPA correlations present in the 0^+ ground state.

Thanks are due to the technical staffs of the Nuclear Physics Laboratory in Gent and the Institut für Strahlenphysik in Stuttgart for the reliable operation of the accelerators. We also thank R.-D. Herzberg, N. Pietralla and A. Zilges from the Institut für Kernphysik in Köln for their support during the experiments in Stuttgart. This research is supported by the Belgian Inter University Institute for Nuclear Sciences–National Fund for Scientific Research and by the Deutsche Forschungsgemeinschaft.

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