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Short note

Is the 4.742 MeV state in ^{88}Sr the 1^- two-phonon state?

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Abstract. A nuclear resonance fluorescence experiment on ^{88}Sr has been performed with bremsstrahlung of 6.7 MeV endpoint energy. The γ-ray linear polarisation has been measured with a EUROBALL CLUSTER detector used as a Compton polarimeter. The results indicate positive parity for the $J=1$ state at 4.742 MeV in ^{88}Sr, in contrast to the previous interpretation as a 1^- two-phonon $(2_1^+ \otimes 3_1^-)$ state and in conflict with the predictions of the quasiparticle-phonon model. On the basis of such calculations the 1^+ state at 3.486 MeV may be considered as the 1_1^+ one-phonon state and the very strong $1_1^+ \to 0_1^+$ deexcitation as proton spin-flip $2p_{1/2} \to 2p_{3/2}$ transition.

PACS. 21.10.Hw Spin, parity, and isobaric spin – 21.10.Tg Lifetimes – 21.60.-n Nuclear-structure models and methods – 27.50.+e $59 \leq A \leq 89$

The existence of low-lying two-phonon 1^- states formed by the coupling of the first quadrupole and octupole phonons $(2_1^+ \otimes 3_1^-)$ seems to be a general feature of vibrational nuclei near closed shells [1,2]. Such states have been identified in even-mass semi-magic nuclei with N=82 [3–5], with Z=50 [6,7] as well as in the N=28 nucleus ^{52}Cr [8]. The experimental excitation energy of these two-phonon states lies in all known cases slightly below the sum of the energies of the quadrupole vibrational 2_1^+ and octupole vibrational 3_1^- states [9]. Calculations within the quasiparticle-phonon model (QPM) are capable of reproducing the observed excitation energies and transition strengths connected with the two-phonon 1^- states in $N = 82$ and $Z = 50$ nuclei [7,10,11]. It is an interesting question whether such states can be found also in the semi-magic N=50 nuclei. The assumption of the existence of 1^- two-phonon states in N=50 nuclei plays an important role for the explanation of the structure of highly collective core-plus-particle states in odd-mass N=50 nuclei [12].

In ^{88}Sr a state at 4.742 MeV with angular momentum J=1 has been observed in a previous nuclear resonance fluorescence experiment [13]. In that work the parity of this level was not measured. Nevertheless, on the basis of the rough correspondence of its excitation energy with the energy sum $E(2_1^+) + E(3_1^-) = 4.570$ MeV, it has been considered to be the 1^- two-phonon state [13]. However, this state would be the only known 1^- two-phonon state lying clearly above the mentioned energy sum. Therefore, we have performed a (γ,γ') experiment on ^{88}Sr at the superconducting electron accelerator S-DALINAC [14] of the Technische Universität Darmstadt to determine the parity of the 4.742 MeV state.

Bremsstrahlung with an endpoint energy of 6.7 MeV has been collimated onto a $^{88}SrCO_3$ target with an enrichment of 99.9 % for ^{88}Sr, a diameter of 18 mm and a mass of 2.7318 g. For the calibration of the photon flux, the target has been covered on the front- and backsides with disks of natural boron of masses of 0.2710 g and 0.3125 g, respectively. Two EUROBALL CLUSTER detectors [15] placed at angles of Θ=94° and Θ=132° with respect to the incident photon beam have been used to detect the scattered γ-rays. Details of the experimental arrangement for a one-CLUSTER configuration are given in [16].

As described in [17,18] the EUROBALL CLUSTER detector consisting of seven HPGe crystals can be used as a nonorthogonal Compton polarimeter for the measurement of the γ-ray linear polarisation [19]. In Fig. 1 a schematic picture of a CLUSTER detector is shown. A

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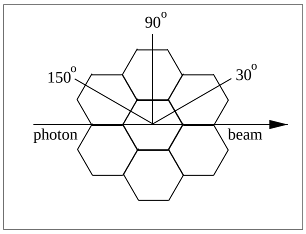

Fig. 1. View from the target to the seven crystals of the CLUSTER detector positioned perpendicular to the photon beam direction. The scattering from one crystal into three neighboured ones is shown schematically

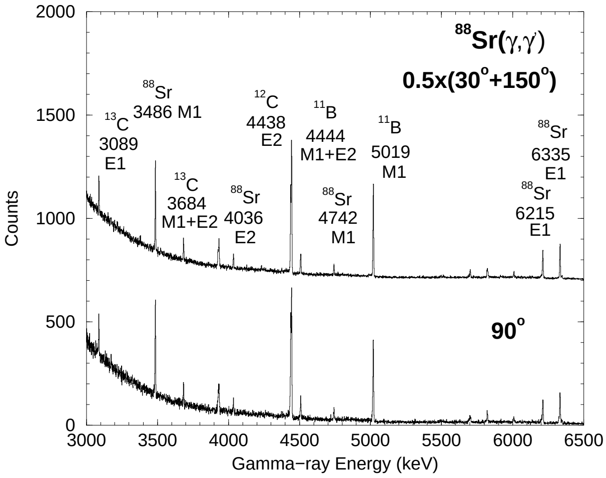

Fig. 2. Sections of coincidence spectra obtained with the Compton polarimeter for scattering to 30° or 150° (upper spectrum) and 90° (lower spectrum) for an energy threshold of 300 keV. The upper spectrum has been multiplied by a factor of 0.5 and shifted up by 700 counts (cf. the text)

γ-ray emitted from the target can be Compton scattered by one of the crystals of the CLUSTER, the so-called scatterer, into a neighbouring detector crystal, the analyser, and can be fully absorbed there. For one CLUSTER, there exist 4 scatterer - analyser combinations for a scattering into 90° and altogether 8 combinations for a scattering into 30° and 150° with respect to the reaction plane (Fig. 1). Thereby, the reaction plane is defined by the direction of the incident photon beam and the direction of a γ-ray resonantly scattered from the target into one crystal of the CLUSTER detector.

In our experiment, the CLUSTER detector at Θ=94° has been used as Compton polarimeter. Gamma-rays, which were Compton scattered into a direction of 90° have been sorted offline into a " 90° " spectrum, those scattered by 30° or 150° into a " 30°+150° " spectrum. The energy of an event in these coincidence spectra results from the sum of the energies absorbed in the scatterer and the analyser. During the sorting process events with γ-ray energies of $E_\gamma < 0.3$ MeV have been suppressed in the scatterer as well as in the analyser. Partial spectra are shown in Fig. 2. The polarisation sensitive asymmetry A=$(I_{90^\circ} - aI_{(30^\circ+150^\circ)})/(I_{90^\circ} + aI_{(30^\circ+150^\circ)})$ has been calculated using the intensities I of full-energy peaks of γ-rays in the " 90° " or " 30°+150° " spectra, respectively, where the intensities have been obtained by summing up the channel contents after background subtraction. For the normalisation factor the geometrical value a=0.5 resulting from the number of scatterer - analyser combinations has been used. The obtained A values for known γ-rays in ^{88}Sr [20], ^{11}B [21] and ^{12,13}C [21] are shown in Fig. 3. With the exception of the 4.742 MeV transition, their multipolarities and angular correlations are known from the literature cited above.

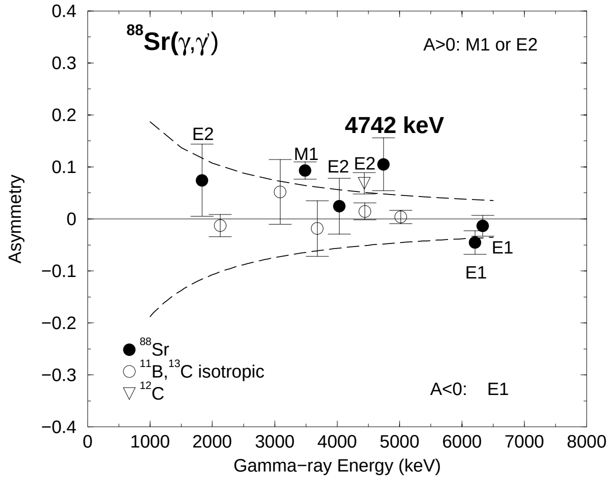

Fig. 3. Asymmetry A resulting from a measurement of the γ-ray linear polarisation in a (γ,γ') experiment on ^{88}Sr. Transitions with known multipolarities are denoted by σL. The dashed lines are explained in the text

For the used detector geometry γ-rays with multipolarity $M1$ and $E2$ should have positive asymmetry values and $E1$ transitions negative ones. The value A=0 is expected for isotropic transitions. The dashed lines represent asymmetry values $A = Q \cdot P/(1 + Q \cdot P/3)$ obtained by means of experimentally calibrated polarisation sensitivity values Q for an energy threshold of 0.35 MeV [17], assuming maximum polarisation of $P = 1$. This relation for the asymmetry A holds for the CLUSTER detector, which is a nonorthogonal polarimeter. The experimental determination of Q was performed for transition energies up to 4.5 MeV [17]. The Q values for $E_\gamma > 4.5$ MeV were obtained by extrapolation of the fitted curve for Q.

The 2.124, 4.444 and 5.019 MeV transitions in ^{11}B and the 3.089 and 3.684 MeV transitions in ^{13}C have isotropic or nearly isotropic angular correlations. Therefore, they should have asymmetry values of $A \approx 0$. This is obtained in the experiment (Fig. 3) within the error bars. The 4.438 MeV $2^+ \rightarrow 0^+$ $E2$ transition in ^{12}C shows the expected positive asymmetry value. Discussing the transitions with known multipolarity in ^{88}Sr, the $E2$ transition from the first 2_1^+ to the ground state with 1.836 MeV shows the expected reduced A value within the error limit, where the attenuation is caused by indirect feeding of the 1.836

MeV level. The asymmetry value of the strong 3.486 MeV transition, which deexcites the known 1_1^+ state [22], lies close to the curve of expectation. The statistically poor 4.036 MeV $2^+ \rightarrow 0^+$ $E2$ transition gives a positive A value as well. The asymmetry values of the shown $E1$ $1^- \rightarrow 0^+$ transitions above 6 MeV are negative, but have small absolute values because the polarisation sensitivity at these energies is small. Summarising, the above discussion proves the used CLUSTER detector to be a properly working polarimeter. This is also confirmed by a polarisation measurement on ^{138}Ba using the same experimental arrangement [19].

As also seen in Fig. 3, the A value for the 4.742 MeV transition in ^{88}Sr is clearly positive. Considering even a 2σ confidence limit, the asymmetry value remains positive and the measured value is more than 3σ distant to the expected value for an $E1$ transition at this energy. Together with J=1, determined in [13] and confirmed by our angular correlation measurement, multipolarity $M1$ is obtained, i.e. positive parity for the 4.742 MeV state in ^{88}Sr.

As a further result of our nuclear resonance fluorescence experiment we obtained the total widths Γ=168(39) and 105(28) meV for the 3.486 and 4.742 MeV states, respectively, which are in agreement with Γ=150(24) and 95(20) meV, respectively, reported by Metzger [22,13]. For the determination of the widths total spectra have been employed, that contain single events detected in each crystal of the CLUSTER detector as well as so-called add-back events reconstructing full-energy signals from γ-rays scattered from one crystal into a neighboured one. Additionally to [13] we found for the 4.742 MeV state also a γ branch of 2.906 MeV to the 2_1^+ state. The branching ratio of Γ_0/Γ=0.94(2) is obtained for the transition to the ground state.

In principle, 1^+ states should be found also in inelastic electron scattering experiments on ^{88}Sr. In fact, the first 1^+ state at 3.486 MeV was observed by van der Bijl et al. [23,24]. The statistics obtained in this experiment did not allow the much weaker 4.742 MeV state to be observed. In the earlier inelastic electron scattering experiment of Peterson et al. [25] the kinematic conditions prevented to identify 1^+ states.

In Table 1, the reduced downward transition probabilities $B(\sigma, L)\!\downarrow$ of the considered dipole transitions in ^{88}Sr are given. The value of $B(M1)\!\downarrow$=0.19 W.u. for the 3.486 MeV transition in ^{88}Sr is relatively large compared with the systematics of $M1$ transitions [26] for the massnumbers $45 \le A \le 90$. It is comparable to the total $M1$ strength $B(M1)\!\downarrow$=0.11(1) W.u. obtained for the scissors mode state at about 3.2 MeV in ^{94}Mo [27], i.e. for a nucleus having only two neutrons more than the $N = 50$ nucleus ^{88}Sr. On the other hand, such $B(M1)\!\downarrow$ values are obtained also for proton spin-flip transitions in nuclei around $A = 90$ (see the discussion below). The $B(M1)\!\downarrow$ value for the 4.742 MeV transition is rather small compared to the systematics [26].

In Table 1, we compare the experimental excitation energies and the corresponding reduced downward transition probabilities also with the results of QPM calculations. The model is explained in detail in [10]. The model wave functions are constructed out of quasiparticle RPA-phonons and the wave function of an excited state is taken as a superposition of one-, two- and three-phonon components. The model parameters have been fixed to reproduce the experimentally measured 2_1^+ and 3_1^- states and the corresponding transition probabilities to the ground state predicting the first 2^+ state at 1.852 MeV (E_{exp}=1.836 MeV) and the first 3^- state at 2.640 MeV (E_{exp}=2.734 MeV). The $M1$ transition strengths have been calculated with the effective g_s-factors $g_s^{eff} = 0.7 g_s^{free}$.

Table 1. Experimental excitation energies E_x, reduced downward transition probabilities $B(\sigma L)\!\downarrow$ obtained in this work and the results of QPM calculations for the first and second 1^+ states in ^{88}Sr. For comparison, also the first calculated 1^- state and the corresponding $B(E1)\!\downarrow$ values are given, assuming the 4.742 MeV state to be a 1^- state

E_x(MeV)				$B(\sigma L)\!\downarrow$(W.u.) [a]	
exp	QPM	$J_i^\pi \rightarrow J_f^\pi$	σL	exp	QPM
3.486	3.121	$1_1^+ \rightarrow 0_1^+$	$M1$	$0.19^{+0.06}_{-0.04}$	0.14
4.742	5.283	$1_2^+ \rightarrow 0_1^+$	$M1$	$(4.4^{+1.6}_{-0.9})\times10^{-2}$	0.2×10^{-2}
		$1_2^+ \rightarrow 2_1^+$	$M1$	$(1.3^{+0.5}_{-0.3})\times10^{-2}$	4.4×10^{-2}
	4.522 [b]	$1_1^- \rightarrow 0_1^+$	$E1$	$(0.69^{+0.25}_{-0.14})\times10^{-3}$	1.3×10^{-3}
		$1_1^- \rightarrow 2_1^+$	$E1$	$(2.0^{+0.7}_{-0.4})\times10^{-4}$	6.0×10^{-7}

[a] 1 W.u.($M1$)=1.79 μ_N^2; 1 W.u.($E1$)=1.28 e^2fm^2
[b] first calculated 1^- state

As seen in Table 1, the first 1^+ state is predicted at 3.121 MeV in fairly good accordance with the first observed 1^+ state. The experimental and calculated $B(M1)\!\downarrow$ values for the corresponding transition to the ground state agree well. The wave function for the 1_1^+ state consists of 95 % of the 1_1^+ RPA one-phonon component. The 1_1^+ RPA phonon itself has the two-quasiparticle proton structure $\pi(2p_{3/2}2p_{1/2})$. Because the ground state of ^{88}Sr is dominantly characterised by four paired protons in the $2p_{3/2}$ shell model orbit, the $1_1^+ \rightarrow 0_1^+$ transition comes out to be from the QPM calculations a spin-flip proton $2p_{1/2} \rightarrow 2p_{3/2}$ transition. This interpretation is supported by form factor measurements in electron scattering experiments [23].

Let us discuss in the following the possible structure of the 1_2^+ state at 4.742 MeV. The interpretation as $(2_1^+ \otimes 3_1^-)$ two-phonon state is ruled out by the experimentally obtained positive parity. In addition, the excitation energy of this state, which is clearly above the experimental sum $E(2_1^+)+E(3_1^-)$=4.570 MeV, is in contradiction to the position of 1^- two-phonon states observed up to now, lying in all cases below the harmonic limit. Our QPM calculations to ^{88}Sr predict the first 1^- state, which is the $(2_1^+ \otimes 3_1^-)$ two-phonon state, at 4.522 MeV (Table 1). If the 4.742 MeV level were this 1^- state, the calculated excitation energy and the theoretical $B(E1,1_1^- \rightarrow 0_1^+)$ value would roughly agree with the observed 4.742 MeV state but the $E1$ strength of the observed γ branch to the 2_1^+ state deviates by a factor of about 300 from the theoretical prediction. Moreover, our observed γ branch of about 6 % from the 4.742 MeV state to the first 2^+ state is by a factor of three larger than the $1_1^- \rightarrow 2_1^+$ γ branches experimentally obtained for the semi-magic $N = 82$ nuclei ^{142}Nd and ^{144}Sm [5], which gives an additional argument against a 1^- assignment to the 4.742 MeV state in ^{88}Sr.

The QPM predicts the second 1^+ state at 5.283 MeV (Table 1) which is to 81 % a two-phonon $(1_1^+ \otimes 2_1^+)$ state where the first 1^+ and 2^+ phonons are coupled to each other. The energy of this calculated level is by 0.541 MeV larger than that of the observed state at 4.742 MeV, the calculated $B(M1)\downarrow$ value for the transition to the ground state is smaller than the experimental value by a factor of about 20, and one finds only a rough agreement for the $B(M1,1_2^+ \rightarrow 2_1^+)\downarrow$ values. Therefore, the structure of the 1_1^+ state at 4.742 MeV cannot be explained by the second 1^+ state predicted in the QPM calculation.

In conclusion, as a result of a nuclear resonance fluorescence experiment positive parity was found for the 4.742 MeV state in ^{88}Sr. This is in contradiction to the previous assumption that this level is the quadrupole-octupole coupled 1^- two-phonon state and is in contrast to the predictions of the well accepted quasiparticle-phonon model. The structure of the second 1^+ state at 4.742 MeV in ^{88}Sr cannot be explained up to now. Comparing the experimental results with the predictions of the QPM, the 1^+ state at 3.486 MeV in ^{88}Sr may be considered as the 1_1^+ one-phonon state. The $1_1^+ \rightarrow 0_1^+$ transition is a very strong spin-flip proton $2p_{1/2} \rightarrow 2p_{3/2}$ transition.

The existence of 1^- two-phonon states in N=50 nuclei remains an open question. In our nuclear resonance fluorescence experiment on ^{88}Sr six further, but very weakly excited states are observed between 4 and 4.5 MeV [28], which are in comparison to the predictions of the QPM too weak as candidates for the theoretically expected but hitherto experimentally missing $E1$ strength in this region of excitation energy. It is also a challenge for the nuclear structure theory to explain the structure of such low-lying $M1$ excitations as the 1_2^+ state at 4.742 MeV in ^{88}Sr.

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