One-phonon $2^+_{1,\mathrm{ms}}$ mixed-symmetry state of ^{148}Sm observed in nuclear resonance fluorescence

T. C. Li,[1] N. Pietralla,[1] C. Fransen,[2] H. von Garrel,[3] U. Kneissl,[3] C. Kohstall,[3] A. Linnemann,[2] H. H. Pitz,[3] G. Rainovski,[1] A. Richter,[4] M. Scheck,[3] F. Stedile,[3] P. von Brentano,[2] P. von Neumann-Cosel,[4] and V. Werner[2,*]

[1]*Nuclear Structure Laboratory, SUNY at Stony Brook, Stony Brook, New York 11794, USA*

[2]*Institut für Kernphysik, Universität zu Köln, D-50937 Cologne, Germany*

[3]*Institut für Strahlenphysik, Universität Stuttgart, D-70569 Stuttgart, Germany*

[4]*Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany*

(Received 27 December 2004; published 28 April 2005)

To search for the $2^+_{1,\mathrm{ms}}$ state of ^{148}Sm, we studied the $^{148}\mathrm{Sm}(\gamma,\gamma')$ photon scattering reaction at the Stuttgart Dynamitron accelerator using bremsstrahlung with an endpoint energy of 3.2 MeV. Nuclear resonance fluorescence from eleven excited states, including three 2^+ states, between 1.4 and 3.1 MeV has been observed. The data allow the identification of the 2^+_5 state at 2146 keV as the $2^+_{1,\mathrm{ms}}$ state of ^{148}Sm.

DOI: 10.1103/PhysRevC.71.044318 PACS number(s): 21.60.Ev, 23.20.Js, 25.20.Dc, 27.60.+j

I. INTRODUCTION

Isovector nuclear excitations are sensitive to the proton-neutron restoring force. Experimental information on isovector modes is, therefore, important for quantifying the corresponding parts of the residual nuclear interaction. The $M1$ scissors mode in deformed nuclei [1,2] represents the most prominent example of an isovector excitation of the nuclear valence shell. Within the framework [3,4] of the interacting boson model (IBM-2), the scissors mode is just one example of a whole class [5] of collective nuclear valence shell excitations with isovector character, the class of mixed-symmetry (MS) states. They are characterized by a nonmaximum value of F spin [6] which represents the isospin for elementary proton and neutron bosons.

Because the *sd*-IBM-2 models the proton-neutron quadrupole collectivity in the valence shell, the building block of MS structures is the one-phonon $2^+_{1,\mathrm{ms}}$ MS state. This becomes particularly apparent in the Q-phonon scheme [7,8] for MS states [9]. The proton-neutron symmetric one-quadrupole phonon state takes the form

$$\left|2^+_s, F_{\max}\right\rangle = \mathcal{N}_s\,(Q_\pi + Q_\nu)\,\left|0^+_1\right\rangle \equiv \mathcal{N}_s\,Q_s\,\left|0^+_1\right\rangle, \quad (1)$$

where

$$Q_\rho = s^+_\rho \tilde{d}_\rho + d^+_\rho s_\rho + \chi\left(d^+_\rho \tilde{d}_\rho\right)^{(2)} \quad (2)$$

is the IBM-2 quadrupole operator for proton bosons ($\rho=\pi$) and for neutron bosons ($\rho=\nu$), respectively. It has typically a large overlap with the 2^+_1 state. In Eq. (1) we have used $\chi_\pi=\chi_\nu=\chi$, and $\mathcal{N}$ denotes a normalization factor. This state can be considered as the *isoscalar* quadrupole excitation in the valence shell. The *isovector* quadrupole excitation in the valence shell is generated by the orthogonal linear combination of Q_π and Q_ν acting on the ground state. In the limit of good F spin, the orthogonal configuration to Eq. (1) is given by [9,10]

$$\left|2^+_m, F_{\max}-1\right\rangle = \mathcal{N}_m\left(\frac{N}{2N_\pi}Q_\pi - \frac{N}{2N_\nu}Q_\nu\right)\left|0^+_1\right\rangle \equiv \mathcal{N}_m\,Q_m\,\left|0^+_1\right\rangle. \quad (3)$$

If the ground state is totally symmetric, so that $F(0^+_1) = F_{\max} = (N_\pi+N_\nu)/2$, then the wave vector Eq. (3) has no overlap with the space spanned by the symmetric states, because any one-body operator $\hat{O}_\rho$ has a matrix element between arbitrary $F_{\max}$ states proportional to N_ρ [11]; therefore, $\langle F_{\max}\alpha|2^+_m, F_{\max}-1\rangle \propto (N_\pi/N_\pi - N_\nu/N_\nu) = 0$.

In the F-spin dynamical symmetry limits of the IBM-2, Eq. (1) exactly gives the wave function of the 2^+_1 state with the F-spin quantum number $F_{\max}$, and Eq. (3) gives the lowest mixed-symmetry $2^+_{1,\mathrm{ms}}$ state with the F-spin quantum number $F_{\max}-1$. Consequently, the wave functions for other low-lying members of the class of MS states with $F = F_{\max}-1$ [including the 1^+ scissors mode in the SU(3) limit] can be obtained by the application of Q_s to the $2^+_{1,\mathrm{ms}}$ state's wave function along with appropriate angular momentum coupling. For example, in the Q-phonon scheme of the IBM-2, the 1^+_1 state has the form

$$\left|1^+_1\right\rangle = \mathcal{N}_1\,(Q_s Q_m)^{(1)}\,\left|0^+_1\right\rangle. \quad (4)$$

The Q-phonon scheme for MS states is well supported by microscopic calculations in random-phase-approximation (RPA)-based approaches [12,13] in nuclei not too far from closed shells.

Despite the outstanding importance of the $2^+_{1,\mathrm{ms}}$ state for our understanding of MS structures, we have only limited knowledge of its properties, because it has been firmly identified only for a handful of nuclides with vibrational character. Recently, it became possible to study the $2^+_{1,\mathrm{ms}}$ state in more detail due to a novel combination of γ-ray spectroscopic techniques [16,17] for the investigation of multiphonon MS structures. New MS states with spin and parity quantum numbers $J^\pi = 3^+$ and 2^+ were discovered [17–20], and a new isovector $E1$ decay channel of the $2^+_{1,\mathrm{ms}}$ to the 3^-_1 octupole vibration was identified [21], which can serve as an additional signature for the identification of the $2^+_{1,\mathrm{ms}}$ MS state. The observation

*Present address: WNSL, Physics Department, Yale University, New Haven, CT 06520-8124.

 ©2005 The American Physical Society

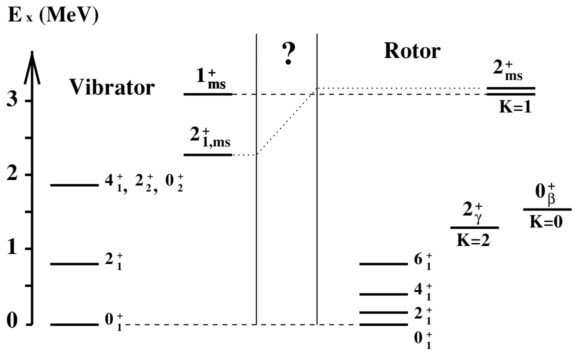

FIG. 1. Schematic of the evolution of $J^\pi = 1^+$ and 2^+ MS states in a vibrator-to-rotor shape transition. The energy of the $1^+_{\rm ms}$ state is known to stay constant (at about 3 MeV in rare earth nuclei [14,15]) as a function of deformation. The $2^+_{1,\rm ms}$ state is expected to evolve from the one-phonon state at about 2.1 MeV in vibrators to a member of the $K = 1$ rotational band of the scissors mode in rotors.

of γ-ray transitions between MS states [22] proved that they form a class of nuclear states with similar structure. However, because of the lack of experimental information on $2^+_{1,\rm ms}$ states in deformed nuclei (see, however, [23]), the evolution of the properties of this state with nuclear deformation is still largely unknown. Figure 1 depicts schematically the expected evolution of the $2^+_{1,\rm ms}$ state from the one-phonon state in vibrational nuclei to the 2^+ member of the $K = 1$ rotational band on top of the 1^+ scissors mode in deformed rotors. Data on the details of that evolution would help quantify the parameters of the Majorana operator of the IBM-2 [4,11].

The classical testing ground for studying the evolution of structure with nuclear quadrupole deformation are the Nd and Sm isotopic chains with stable nuclides spanning the transition path from spherical nuclei at the $N = 82$ neutron shell closure to deformed nuclei closer to midshell. For example, the onset of the splitting of the $E1$ giant dipole resonance (GDR) has been observed in these isotopic chains [24,25], as well as the δ^2 law for the $M1$ strength of the scissors mode [26,27]. While the chain of stable Nd isotopes terminates in the nucleus ^{150}Nd right at the critical point of the spherical-to-deformed shape phase transition [28], the stable isotopes of the Sm chain extend beyond that point [29,30]. Unfortunately, the $2^+_{1,\rm ms}$ state has not yet been identified for any Sm nuclide. It has been the goal of the present work to firmly identify the $2^+_{1,\rm ms}$ state of the nuclide ^{148}Sm on the solid basis of absolute electromagnetic matrix elements.

The properties of the $2^+_{1,\rm ms}$ state in the dynamical symmetry limits of the IBM-2 have been discussed in the literature [4,5,11,31]. The $2^+_{1,\rm ms}$ state always decays by a strong magnetic dipole transition to the symmetric 2^+_1 state. Mixed-symmetry states and F-spin changing $M1$ and $E2$ transitions outside of the dynamical symmetries in near-vibrational nuclei are discussed, e.g., in Refs. [32,33]. Let us point out the signatures for the $2^+_{1,\rm ms}$ state that are evident in the Q-phonon scheme:

- The $E2$ decay from the $2^+_{1,\rm ms}$ one-quadrupole phonon state to the ground state should be weakly collective, say ~0.2–5.0 W.u., because its matrix element involves the same proton and neutron parts of the collective $E2$ transition from the 2^+_1 state to the ground state, with opposite signs, however. An accidental exact cancellation of the large proton and neutron matrix elements cannot be excluded, although it is very unlikely.
- The $2^+_{1,\rm ms} \to 2^+_1$ $M1$ transition should be the strongest of all $2^+ \to 2^+_1$ transitions with an $M1$ matrix element of the order of 1 μ_N.
- The $2^+_{1,\rm ms} \to 3^-_1$ $E1$ transition should be enhanced because of its isovector nature [21].

To identify the $2^+_{1,\rm ms}$ state on the solid basis of the preceding criteria, we must measure the electromagnetic transition strengths for off-yrast 2^+ states. The fragmentation of the $2^+_{1,\rm ms}$ state can be studied by the observation of all fragments in a complete reaction. It has been shown [10,22] that recent improvements in the technique of nuclear resonance fluorescence (NRF) [34,35] have sufficiently increased the sensitivity of that method for detecting the $2^+_{1,\rm ms}$ state and measuring its short lifetime. Therefore, we have chosen to study the nucleus ^{148}Sm using resonant photon scattering to search for the $2^+_{1,\rm ms}$ state of this nuclide.

II. EXPERIMENT

The experiment was performed at the photon scattering site of the Stuttgart Dynamitron accelerator [35]. The accelerator was tuned to provide a monochromatic 3.2 MeV electron beam which hit a water-cooled gold target to produce continuous-energy bremsstrahlung with photon energies of $E_\gamma \leqslant 3.2$ MeV for increased sensitivity at energies below 3 MeV with respect to previous nuclear resonance fluorescence experiments on that nuclide [36]. The forward-peaked bremsstrahlung cone was defined by a lead collimator with a bore diameter of 1 cm. The beam hit the photon scattering target in an evacuated beam pipe. Three large-volume Ge detectors positioned at angles of 90°, 127°, and 150° relative to the incident beam axis detected the photons scattered from the target. The detector at 127° was equipped with a BGO anti-Compton shield for background suppression. Data were taken for about 120 h. The relative efficiencies of the detectors were measured before the experimental runs with a ^{56}Co source. The target, $^{148}Sm_2O_3$ (total mass 1.721 g), was isotopically enriched to 96.52(8)%. It was sandwiched between ^{27}Al (total mass 0.506 g) to use the well-known cross sections [37] of some low-lying states of ^{27}Al for a photon flux calibration, which in turn allowed measurements of the absolute cross sections of the NRF reactions on ^{148}Sm. Figure 2 shows the photon scattering spectra for the ^{148}Sm sample at two scattering angles, $\theta = 90^\circ$ and 127°, between 2.3 and 3.4 MeV, where most of the excited states were observed.

Spin quantum numbers were assigned according to the angular distribution ratios involving all three observation angles, $W(90^\circ)/W(127^\circ)$, and $W(150^\circ)/W(127^\circ)$. The intensity ratio $W(90^\circ)/W(127^\circ)$ takes values of 0.75 and 2.2 for pure dipole and quadrupole cascades with spin sequences 0-1-0 and 0-2-0, respectively. Absolute photon scattering cross sections are measured relative to known cross sections in ^{27}Al [37]. From the measured branching ratios Γ_0/Γ and from the absolute

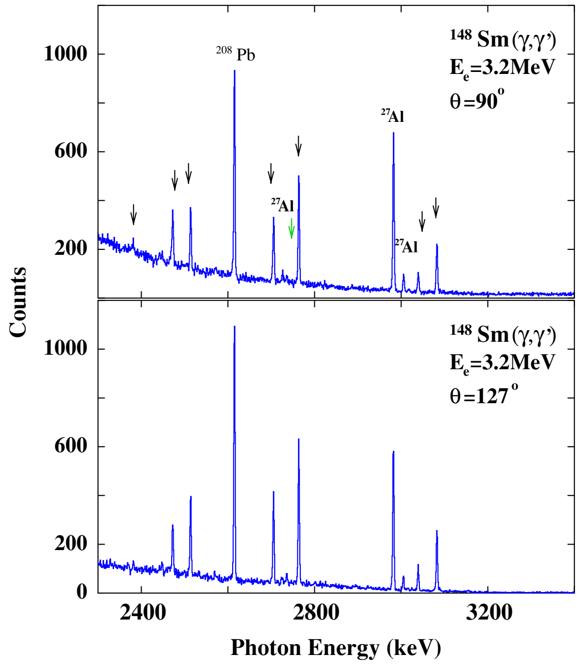

FIG. 2. (Color online) Sum of NRF γ-ray spectra of ^{148}Sm in the energy range between 2.3 and 3.4 MeV detected at scattering angles of 90° (top) and 127° (bottom) with respect to the incident beam. Arrows mark peaks from Sm decays. γ-ray lines from the ^{27}Al photon flux calibration standard and a line from the natural background are also labeled.

cross sections

$$I_{s,f} = g\pi^2 ƛ^2 \frac{\Gamma_0 \Gamma_f}{\Gamma} \tag{5}$$

of the resonance scattering cascades for excitations from the ground state and decays to some final state f, Γ_0 and Γ can be deduced. Here, $g = (2J+1)/(2J_0+1)$ is a statistical factor, where J and J_0 are the spin of the excited state and the ground state spin, respectively. $ƛ = \hbar c/E_x$ is the reduced wavelength for excitation. Γ_0 denotes the partial decay width to the ground state, and $\Gamma = \sum_f \Gamma_f = \hbar/\tau$ is the total level width. The partial level widths can be converted to the reduced electromagnetic transition strengths

$$B(\pi\lambda : J \to J_f) = c_{\pi\lambda} \frac{\Gamma_{f,\pi\lambda}}{E_\gamma^{2\lambda+1}} \tag{6}$$

if information on the radiation character (electric or magnetic) or on multipole mixing ratios is available. $\Gamma_{f,\pi\lambda}$ is the single-multipole partial decay width to the final level, and $c_{\pi\lambda}$ is a constant ($c_{E1} = 0.9554 \cdot 10^{-3}\, e^2\,\mathrm{fm}^2\,\mathrm{MeV}^3/\mathrm{meV}$, $c_{M1} = 0.0864\mu_N^2\,\mathrm{MeV}^3/\mathrm{meV}$, $c_{E2} = 0.1240\, e^2\,\mathrm{b}^2\,\mathrm{MeV}^5/\mathrm{meV}$).

III. RESULTS

Table I summarizes the data. A total of sixteen γ-ray lines from eleven excited states of ^{148}Sm between 1.4 and 3.1 MeV were observed, two of them for the first time. The quoted uncertainties of the γ-ray energies are from this work unless otherwise noted. More information on some of the observed states is available in the literature [38], which has also been included in Table I for completeness. All photon scattering cross sections are from this work. Those for the dipole transitions above 2.5 MeV (except for the 2705 keV level, which will be discussed in detail) all agree within error bars with the earlier measurement [36].

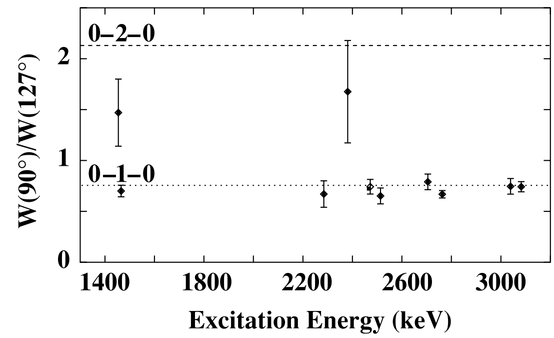

FIG. 3. Angular distribution for $J^\pi \to 0^+_1$ ground state transitions in ^{148}Sm. From the ratio $W(90°)/W(127°)$ we can make eight $J = 1$ and two $J = 2$ spin quantum number assignments to the ten states for which we could observe ground state transitions. The deviation of the data point for the known two-phonon 2^+_2 state at 1454 keV from the $J = 2$ line toward more isotropic distribution is most likely due to unobserved feeding from higher-lying levels.

Angular distribution ratios of ground state transition intensities observed at $\theta = 90°$ and 127° are shown in Fig. 3. We observed eight dipole and three quadrupole excitations. The data from 150° is consistent with these assignments. Among the quadrupole excitations, the known 2^+_5 state at 2146.35 keV [38] decays strongly to the 2^+_1 state such that the competing ground state decay branch is too weak and could not be observed in this experiment. Therefore, only two data points that correspond to 0-2-0 cascades are shown in Fig. 3. However, the observed decay of the 2^+_5 state at 2146.35 keV to the 2^+_1 state with $E_\gamma = 1596$ keV proves that we have populated this level in our experiment. This state will be discussed below in more detail. Fig. 4 displays the 1596 keV

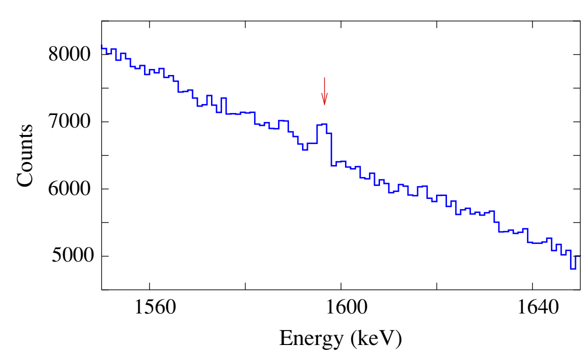

FIG. 4. (Color online) Sum of photon scattering spectra at $\theta = 127°$ and 150°. The peak at $E_\gamma = 1596.1(4)$ keV, marked with the arrow (online red), corresponds to the previously reported [38] decay of the 2^+_5 state at 2146.35 keV to the 2^+_1 state at 550.26 keV. It proves that the 2^+_5 state was populated in our experiment. This signal corresponds to a cross section of $I_{s,1} = 4.2$ eV b for the $0^+_1 \to 2^+_5 \to 2^+_1$ photon scattering cascade (see Table I and text).

TABLE I. Results of the ^{148}Sm(γ, γ') reaction. Given are the excitation energies E_x, spin and parity quantum numbers J^π of the levels, the level lifetimes τ, γ-ray energies E_γ, angular distribution ratios $W(90^\circ)/W(127^\circ)$ for decay transitions to the ground state, relative intensities I_γ, observed absolute photon scattering cross sections $I_{s,f}$ for the corresponding decay channel, ground state decay widths Γ_0, and reduced dipole and quadrupole transition strengths $B(\pi\lambda)\downarrow$.

E_x (keV)	J^π ($\hbar$)	τ (fs)	E_γ (keV)	$\frac{W(90^\circ)}{W(127^\circ)}$	I_γ (%)	$I_{s,f}$ (eV b)	Γ_0 (meV)	$B(M1)\downarrow$[a] (μ_N^2)	$B(E2)\downarrow$ (e^2 fm^4)	$B(E1)\downarrow$[a] (10^{-3} e^2 fm^2)
1454.2(5)	2^+	411(40)	903.83(15)[b]		100(2)[b]			0.0147(19)[c]	1388(150)	
			1454.2(5)	1.47(33)	99.6(2)[b]	3.61(37)	0.796(82)		152(15)	
1465.3(6)	1^-	133(11)	303.59(3)[b]		0.17(2)[b]				2648(380)	
			914.916(15)[b]		51.6(4)[b]					2.09(24)
			1465.3(6)	0.700(57)	100(3)[b]	11.49(81)	3.25(25)			0.98(8)
2146.35(3)[b]	2^+	⩽92.5	985.16(20)[b]		10.4(12)[b]					⩾0.607
			1596.1(4)		100(11)	4.16(54)		⩾0.116		
			2146.3		⩽17		0.96–1.43		26–39	
2284.5(3)	1	66.2(71)	362.8(2)[b]		⩽5[b]					
			819.27(3)[b]		30(5)[b]			0.205(41)		2.26(46)
			1734.2(4)		99(6)	4.28(48)		0.0712(80)		0.768(89)
			2284.5(3)	0.67(13)	100(6)	4.18(35)	4.34(42)	0.0315(30)		0.347(34)
2381.1(6)	2^+	125(24)	1830.9(5)		100(10)	4.13(49)		0.042(10)[c]	38(14)	
			2381.1(6)	1.68(50)	43(7)	1.62(20)	1.59(26)		25.8(42)	
2472.2(2)	1	52.9(41)	1922.0(5)		91.3(78)	5.99(45)		0.0722(78)		0.799(86)
			2472.2(2)	0.73(11)	100(3)	6.41(33)	6.50(43)	0.0372(25)		0.411(27)
2513.5(2)	1	99.3(51)	2513.5(2)	0.652(78)	100(3)	12.11(64)	6.63(35)	0.0361(19)		0.400(21)
2704.9(2)	1	29.0(17)	2154.6(3)		33.5(22)	6.77(49)		0.0492(43)		0.544(48)
			2704.9(2)	0.790(77)	100(3)	20.1(11)	17.01(97)	0.0742(42)		0.821(47)
2763.2(9)	1^+	10.84(61)	2213.0(10)		68(4)[d]			0.196(16)[c]		
			2763.2(9)	0.668(36)	100(2)	32.5(15)	36.1(19)	0.1480(79)[c]		
3039.0(4)	1	59.8(32)	2489		⩽10	⩽1.3				
			3039.0(4)	0.746(77)	100(4)	13.72(75)	10.99(60)	0.0339(19)		0.374(21)
3082.2(2)	1	14.6(10)	2531.9(9)		8.8(15)	4.06(77)		0.0194(36)		0.215(40)
			3082.2(2)	0.742(50)	100(3)	46.1(32)	41.3(29)	0.1219(86)		1.348(95)

[a]For $J = 1$ states with unknown parity, dipole transition strengths are given for both radiation characters.
[b]From Ref. [38].
[c]$B(M1)$ value for states with known parity.
[d]From Ref. [36].

transition in the sum of the spectra at $\theta = 127^\circ$ and 150°. Some aspects of the experimental results require more detailed discussion, as given in the following sections.

A. 2_5^+ state at 2146.35 keV

The 2_5^+ state is known [38] from earlier γ-ray spectroscopy following (n,γ) and $(n,n'\gamma)$ neutron-induced reactions by Govor *et al.* [39] and from deuteron scattering by Veje *et al.* [40]. Decay transitions to the 2_1^+ and 3_1^- states with transition energies of 1596.08(3) and 985.16(20) keV have been reported with an intensity branching ratio of 100(3):10.4(12) [38,39]. Govor *et al.* measured the $E2/M1$ multipole mixing ratio of the $2_5^+ \to 2_1^+$ transition to $\delta = -0.11(5)$. This corresponds to 99% of $M1$ radiation. Neither a decay transition to the ground state with an energy of 2146.35 keV nor an upper limit for its intensity have been reported [38]. Apparently, there existed a doublet of γ-ray lines with the strong 2147.5 keV line from the $3^+, 4^+$ level at 2697.8 keV to the 2_1^+ state in the (n,γ) and $(n,n'\gamma)$ data [38,39].

The spectrum displayed in Fig. 4 shows that we observe a 1596.1(4) keV γ-ray line in our data. This transition energy coincides with the known $2_5^+ \to 2_1^+$ transition in ^{148}Sm. We can rule out that this line stems from the $9/2 \to 5/2^-$ transition in the 1.3% target contaminant of ^{147}Sm because otherwise we would have observed the corresponding $9/2 \to 7/2^-$ ground state decay, which is absent in our data, at 1717 keV with an intensity of 80(2)% [38] of the intensity at 1596 keV. Also, the possible transition of the 5/2 level of ^{149}Sm (present in the target as a 1.4% impurity) at 1617(2) keV [38] could result in a

1594.5(20) keV decay transition. However, no γ-ray from that level is known. Moreover, again a similarly strong decay to the ground state should have been seen at 1617 keV, because an excitation in a target impurity of the order of 1% had to be two orders of magnitude stronger than comparable transitions in the main part of the target. This would only be reasonably possible if the ground state excitation width Γ_0 in the contaminant could not be much smaller than the decay width to the first excited state. Consequently, we would have observed the ground state transition at 1617 keV, which, however, is absent from the spectra. Thus, we can safely interpret the γ-ray line at 1596.1(4) keV as the known $2^+_5 \to 2^+_1$ transition in ^{148}Sm.

A corresponding $2^+_5 \to 0^+_1$ ground state transition at 2146.35 keV is, however, too weak for observation. From the analysis of our sensitivity limit at that energy, we can determine an upper limit for the ground state decay branching ratio of $\Gamma_0/\Gamma_1 \leqslant 0.17$. From the peak area at 1596 keV, we deduced a cross section for the $0^+_1 \to 2^+_5 \to 2^+_1$ NRF cascade of $I_{s,1}(2146.35) = 4.16(54)$ eV b. This integrated cross section is proportional to the quantity $\Gamma_0\Gamma_1/\Gamma$, for which we obtain a value of 0.99(13) meV. Using $\Gamma = \Gamma_1(1 + \Gamma_0/\Gamma_1 + \Gamma_{3^-}/\Gamma_1) = (0.99 \text{ to } 1.25)\Gamma_1$ from our upper limit for Γ_0/Γ_1 along with the known decay intensity ratio to the 3^-_1 state, we can deduce the ground state decay width $\Gamma_0 = 1.0$ to 1.4 meV. This partial decay width corresponds to a reduced $E2$ transition strength to the ground state of $B(E2; 2^+_5 \to 0^+_1) = 27\text{–}40\, e^2\,\mathrm{fm}^4 = 0.56 - 0.84$ W.u.

From the upper limit for the ground state decay branching ratio Γ_0/Γ_1, we then deduce a lower limit for the partial decay width to the 2^+_1 state, $\Gamma_1 = \Gamma_1/\Gamma_0 \times \Gamma_0 > 5.6$ meV. This $2^+_5 \to 2^+_1$ γ transition has almost pure magnetic dipole character with only a 1% $E2$ admixture [38,39]. The $M1$ decay strength, thus, exceeds $B(M1; 2^+_5 \to 2^+_1) = 0.12\,\mu_N^2$. Analogously, one obtains $B(E1; 2^+_5 \to 3^-_1) \geqslant 0.61 \cdot 10^{-3} e^2$ fm^2 for the decay to the octupole vibrational state.

The preceding analysis is based on the interpretation of the 1596 keV peak as stemming completely from the inelastic $0^+_1 \to 2^+_5 \to 2^+_1$ photon scattering reaction. Feeding from higher-lying states may represent an alternate population path for the 2^+_5 level, in which case the quoted value for the cross section $I_{s,1}(2146.35)$ would have been incorrectly determined. However, this scenario would require unreasonably strong, comparatively low-energy transitions from the four levels above 2.7 MeV to the 2^+_5 state at 2146.35 keV. For example, the highest population luminosity, proportional to the excitation cross section times the photon flux, was obtained for the 1^+ state at 2763 keV (see Fig. 2). If the 1596 keV peak resulted from the population of the 2^+_5 state by an unobserved 617 keV feeding transition from the photoexcited state at 2763 keV, then that feeding transition would have to have a strength of 4.2 μ_N^2 in the case of $M1$ or 3000 W.u. for the $E2$ character in order to account for the observed peak area at 1596 keV. Such strengths are incompatible with our current knowledge on dipole excitations in that mass region, and we thus discard such a feeding scenario. Using reasonable values [e.g., $B(M1; 1^+_{2763} \to 2^+_5) = 0.1\ \ \mu_N^2$ and $B(E2; 1^+_{2763} \to 2^+_5) = 50$ W.u.] for the strengths of possible feeding transitions to the 2^+_5 state, we find that at most about 16% of the population of the 2^+_5 state might possibly be due to feeding, predominantly from the 1^+ states at 2763 and 3082 keV. All values discussed above are based on the assumption that the total population of the 2^+_5 state is due to direct $E2$ photoexcitation of that level with a $B(E2)$ value of about 0.7 W.u. from the ground state.

B. $J = 1$ state at 2704.9 keV

Our data contain a large peak at a γ-ray energy of 2704.9 keV. This γ-ray line was observed already in the previous photon scattering experiment on ^{148}Sm by Ziegler *et al.* [36] using a bremsstrahlung beam with an end-point energy of about 4.5 MeV. However, in that experiment, another strong ground state transition was observed at 3255 keV = 2705 keV + $E(2^+_1)$ and, consequently, the γ-ray line at 2705 keV was interpreted as being due to the $1_{3255} \to 2^+_1$ transition. In our experiment, the dipole excitation at 3255 keV has not been populated because it lies above the end-point energy of our bremsstrahlung beam. The existence of the 2705 keV line in our spectra proves unambiguously that it stems from the elastic photon scattering reaction on the $J = 1$ state at this excitation energy with a considerable cross section of 20 eV b. Consequently, an appreciable fraction of the 2705 keV line in Ziegler's data must be attributed to the ground state decay of the level at 2705 keV rather than to the decay of the dipole excitation at 3255 keV to the 2^+_1 state. Our observation implies that the decay branching ratio for the level at 3255 keV to the 2^+_1 state is smaller than previously reported. The dipole excitation strength for the level at 3255 keV reported by Ziegler *et al.* must, therefore, be considered to be overestimated by a factor of up to about 2. Note that the summed dipole excitation strength is less affected because the dipole strength of the 2705 keV level also contributes to the total strength.

IV. DISCUSSION

A. New transitions and corrected level scheme

Our results are compared with the known data on ^{148}Sm from the nuclear data sheets [38] and particularly to Ref. [36]. Two new transitions were observed. One is the decay from the $J = 1$ state at 2705 keV to the 2^+_1 state with a γ-ray energy $E_\gamma = 2154.6$ keV. The other one is the ground state transition of the level at 2381.1 keV. A new spin quantum number $J = 2$ was assigned to this level, which suggests that either the previous spin assignment $J^\pi = 3^+, 4^+$ done on the basis of primary γ-ray intensities following neutron capture [39] was in error or there exists a close-lying doublet of levels at this excitation energy. There are two more new spin assignments to two previously known levels at 2284.5 and 2705 keV. Both were unambiguously assigned $J = 1$ in our experiment and reported as (1, 2^+) before [38]. Additionally, the dipole level scheme as proposed by Ziegler *et al.* has to be slightly corrected as discussed above. Most importantly, we have measured ten level lifetimes of short-lived low-spin states, five of them (for the levels at 2146, 2284.5, 2381, 2472, and 2705 keV) for the first time. In the other cases, our values, typically with smaller errors, coincide with the literature values, particularly those found previously by Ziegler *et al.* [36].

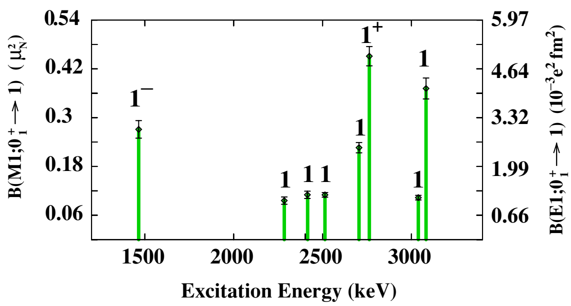

FIG. 5. (Color online) Experimental $B(\pi 1; 0_1^+ \rightarrow 1)$ dipole excitation strength distribution for ^{148}Sm up to 3.2 MeV. The error bars together with spin and parity quantum numbers are displayed at the top of the data bars (online green). Magnetic (electric) dipole excitation strength refers to the scale on the left (right).

B. Dipole strengths of $J = 1$ states

Figure 5 shows the dipole excitation strength distribution in the energy range under investigation in the present experiment. Parity assignments were taken from [38] whenever possible. The left and right scales refer to $B(M1)\uparrow$ and $B(E1)\uparrow$ values, respectively. The corresponding $B(\pi 1; 1 \rightarrow 0_1^+)$ values are given in Table I. Except for two states, the 1^- state at 1465 keV and the 1^+ state at 2763 keV, the parities of all the other $J = 1$ states are unknown.

C. Identification of the one-phonon $2^+_{1,\mathrm{ms}}$ state

Figure 6 displays absolute $M1$ and $E2$ transition strengths for 2^+ states of ^{148}Sm. Except for the lifetime values for the 2_1^+ and 2_3^+ states and multipole mixing ratios from the nuclear data sheets [38], all other data are from this work. The top part shows the $M1$ transition strength distribution to the 2_1^+ state from those excited 2^+ states for which lifetime information is available. Obviously, the 2_5^+ state at 2146.35 keV shows the strongest $M1$ transition to the 2_1^+ state. Note that the plotted $B(M1)$ value represents a *lower limit* (see discussion above). This strong $M1$ transition with a matrix element of $|\langle 2_1^+ \| M1 \| 2_5^+ \rangle| \geqslant 0.76\,\mu_N$ is the main signature for the $2^+_{1,\mathrm{ms}}$ state. Lifetimes are unknown for the 2_4^+ and 2_6^+ states at 1972.480(21) and 2313.57(8) keV [38]. They could be considered to contribute to the $2^+_{1,\mathrm{ms}}$ structure, too. However, their known decay pattern [38], in particular, the intense low-energy γ decays; the large $E2/M1$ mixing ratios of their decay transitions to the 2_1^+ state; and their too small photon excitation cross sections rule out their potential to substantially contribute to the $2^+_{1,\mathrm{ms}}$ structure.

Another expected property of the $2^+_{1,\mathrm{ms}}$ state is its weakly collective $E2$ excitation from the ground state. The $E2$ excitation strength distribution of the lowest-five 2^+ states is shown at the bottom of Fig. 6 on logarithmic scale. The excitation strength $B(E2; 0_1^+ \rightarrow 2_5^+) = 150(50)\, e^2\,\mathrm{fm}^4$ amounts to about 2% of the dominant excitation strength to the 2_1^+ state and corresponds to a decay strength of 0.7 W.u., which may still be considered as weakly collective. This observation is consistent with the $2^+_{1,\mathrm{ms}}$ assignment to the 2_5^+ state of ^{148}Sm.

The existence of an enhanced $E1$ transition to the 3_1^- octupole vibrational state has recently been identified as

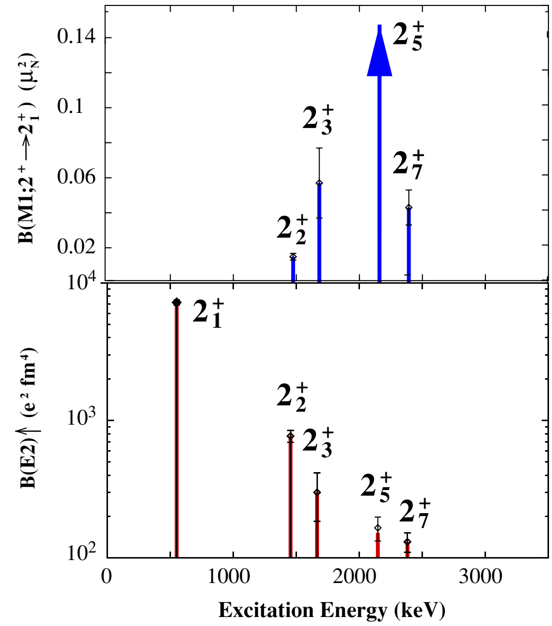

FIG. 6. (Color online) $M1$ and $E2$ strength distribution relevant for the identification of the $2^+_{1,\mathrm{ms}}$ state of ^{148}Sm. The top shows the $B(M1; 2^+ \rightarrow 2_1^+)$ distribution for four low-lying 2^+ states above the 2_1^+ state. The arrow represents the lower limit measured for the 2_5^+ state. The bottom shows the $B(E2)\uparrow$ values for these five low-lying 2^+ states on a logarithmic scale.

another signature for the $2^+_{1,\mathrm{ms}}$ state in near-vibrational nuclei [21]. Among the four 2^+ states considered at the top of Fig. 6, only the 2_5^+ state was observed to decay to the 3_1^- state. This is the only enhanced $E1$ transition from a 2^+ state in the low-energy spectrum. From our lifetime information, we can infer an $E1$ transition strength of $B(E1; 2_5^+ \rightarrow 3_1^-) > 0.61 \cdot 10^{-3} e^2\,\mathrm{fm}^2$. This lower limit agrees already in its order of magnitude with that of typical allowed quadrupole-octupole $E1$ transition rates in this mass region [21,41]. This again supports the identification of the 2_5^+ state of ^{148}Sm as its $2^+_{1,\mathrm{ms}}$ state. Based on this evidence from absolute transition rates, we assign the MS character to the 2_5^+ state at 2146.35 keV. Figure 7 summarizes the observations for this state.

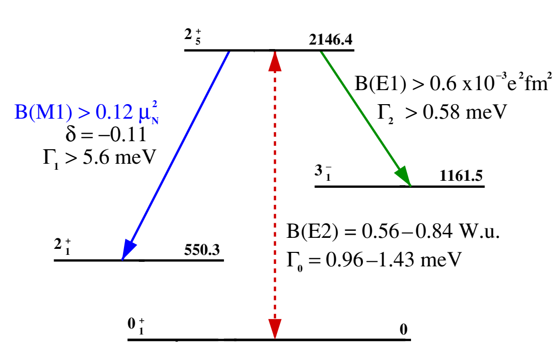

FIG. 7. (Color online) Measured decay properties for the 2_5^+ state of ^{148}Sm at 2146.35 keV. The observations match the criteria for the $2^+_{1,\mathrm{ms}}$ state.

V. SUMMARY

A ^{148}Sm(γ, γ') photon scattering experiment has been performed at the Stuttgart Dynamitron accelerator using on-axis unpolarized bremsstrahlung with an end-point energy of 3.2 MeV for the sensitive observation of nuclear resonance fluorescence of ^{148}Sm below 3 MeV. NRF transitions from eleven excited states were observed. Three of them stem from $J^\pi = 2^+$ states. The photon scattering cross sections in combination with literature data enable us to identify the 2^+_5 state at 2146.35 keV as the $2^+_{1,ms}$ state of ^{148}Sm. The decay transition of this state to the ground state was not observed. However, from the observation of the population of this level, we can determine its photon scattering cross section, its partial width Γ_0, and its $E2$ excitation strength. Its photoexcitation cross section and the lower limit for its decay branching ratio to the 2^+_1 state yield a lower limit for the $M1$ transition matrix element to the 2^+_1 state of $|\langle 2^+_1 \| M1 \| 2^+_{1,ms}\rangle| > 0.76\,\mu_N$. This large $M1$ strength, together with the decay strengths of this state to the ground state and to the 3^-_1 octupole vibration, matches the signatures for the $2^+_{1,ms}$ state. This is the first assignment of the $2^+_{1,ms}$ state in a nuclide of the Sm isotopic chain, as well as in a nuclide of the $N = 86$ isotonic chain, that is firmly based on information on absolute electromagnetic transition strengths.

ACKNOWLEDGMENTS

C.F., A.L., V.W., and N.P. thank the people at the IfS of the Universität Stuttgart for their hospitality. This work was supported by the DFG under support Nos. Kn 154/30, Pi 393/1-2, Br 799/12-1, and SFB 634; by the NSF under Grant No. PHY-0245018; and by the OJI program of the DOE under Grant No. DE-FG02-04ER41334.

[1] D. Bohle, A. Richter, W. Steffen, A. E. L. Dieperink, N. Lo Iudice, F. Palumbo, and O. Scholten, Phys. Lett. **B137**, 27 (1984).
[2] A. Richter, Prog. Part. Nucl. Phys. **34**, 261 (1995).
[3] A. Arima, T. Otsuka, F. Iachello, and I. Talmi, Phys. Lett. **B66**, 205 (1977).
[4] F. Iachello and A. Arima, *The Interacting Boson Model* (Cambridge University Press, Cambridge, 1987).
[5] F. Iachello, Phys. Rev. Lett. **53**, 1427 (1984).
[6] T. Otsuka, A. Arima, and F. Iachello, Nucl. Phys. **A309**, 1 (1978).
[7] T. Otsuka, K.-H. Kim, Phys. Rev. C **50**, 1768(R) (1994).
[8] N. Pietralla, P. von Brentano, R. F. Casten, T. Otsuka, and N. V. Zamfir, Phys. Rev. Lett. **73**, 2962 (1994).
[9] K.-H. Kim, T. Otsuka, P. von Brentano, A. Gelberg, P. Van Isacker, and R. F. Casten, in *Proceedings of the 9th International Symposium on Capture Gamma Ray Spectroscopy and Related Topics*, Budapest 1996, edited by G. Molnár (Springer, Budapest, 1998), p. 195.
[10] N. Pietralla *et al.*, Phys. Rev. C **58**, 796 (1998).
[11] P. Van Isacker, K. Heyde, J. Jolie, and A. Sevrin, Ann. Phys. (NY) **171**, 253 (1986).
[12] R. Schwengner *et al.*, Nucl. Phys. **A620**, 277 (1997).
[13] N. Lo Iudice and Ch. Stoyanov, Phys. Rev. C **62**, 047302 (2000); **65**, 064304 (2002).
[14] N. Pietralla, P. von Brentano, R.-D. Herzberg, U. Kneissl, N. Lo Iudice, H. Maser, H. H. Pitz, and A. Zilges, Phys. Rev. C **58**, 184 (1998).
[15] J. Enders, H. Kaiser, P. von Neumann-Cosel, C. Rangacharyulu, and A. Richter, Phys. Rev. C **59**, 1851(R) (1999).
[16] N. Pietralla, Czech. J. Phys. **52**, C607 (2002).
[17] C. Fransen *et al.*, Phys. Rev. C **67**, 024307 (2003).
[18] C. Fransen, N. Pietralla, P. von Brentano, A. Dewald, J. Gableske, A. Gade, A. Lisetskiy, and V. Werner, Phys. Lett. **B508**, 219 (2001).
[19] H. Klein, A. F. Lisetskiy, N. Pietralla, C. Fransen, A. Gade, and P. von Brentano, Phys. Rev. C **65**, 044315 (2002).
[20] N. Pietralla, C. Fransen, P. von Brentano, A. Dewald, A. Fitzler, C. Frießner, and J. Gableske, Phys. Rev. Lett. **84**, 3775 (2000).
[21] N. Pietralla, C. Fransen, A. Gade, N. A. Smirnova, P. von Brentano, V. Werner, and S. W. Yates, Phys. Rev. C **68**, 031305(R) (2003).
[22] N. Pietralla *et al.*, Phys. Rev. Lett. **83**, 1303 (1999).
[23] D. Bohle, A. Richter, K. Heyde, P. Van Isacker, J. Moreau, and A. Sevrin, Phys. Rev. Lett. **55**, 1661 (1985).
[24] P. Carlos, H. Beil, R. Bergère, A. Leprêtre, A. de Miniac, and A. Veyssière, Nucl. Phys. **A225**, 171 (1974).
[25] P. Carlos, H. Beil, R. Bergère, A. Leprêtre, and A. Veyssière, Nucl. Phys. **A172**, 437 (1971).
[26] W. Ziegler, C. Rangacharyulu, A. Richter, and C. Spieler, Phys. Rev. Lett. **65**, 2515 (1990).
[27] J. Margraf *et al.*, Phys. Rev. C **47**, 1474 (1993).
[28] R. Krücken *et al.*, Phys. Rev. Lett. **88**, 232501 (2002).
[29] R. F. Casten and N. V. Zamfir, Phys. Rev. Lett. **87**, 052503 (2001).
[30] N. Pietralla and O. M. Gorbachenko, Phys. Rev. C **70**, 011304(R) (2004).
[31] T. Otsuka, in *Algebraic Approaches to Nuclear Structure: Interacting Boson and Fermion Models*, Contemporary Concepts in Physics, Vol. 6 edited by R. F. Casten (Harwood Academic, Chur, Switzerland, 1993).
[32] K.-H. Kim, A. Gelberg, T. Mizusaki, T. Otsuka, and P. von Brentano, Nucl. Phys. **A604**, 163 (1996).
[33] N. Pietralla, P. von Brentano, A. Gelberg, T. Otsuka, A. Richter, N. Smirnova, and I. Wiedenhöver, Phys. Rev. C **58**, 191 (1998).
[34] F. R. Metzger, Prog. Nucl. Phys. **7**, 53 (1959).
[35] U. Kneissl, H. H. Pitz, and A. Zilges, Prog. Part. Nucl. Phys. **37**, 349 (1996).
[36] W. Ziegler, N. Huxel, P. von Neumann-Cosel, C. Rangacharyulu, A. Richter, and C. Spieler, Nucl. Phys. **A564**, 366 (1993).
[37] N. Pietralla *et al.*, Phys. Rev. C **51**, 1021 (1995).
[38] M. R. Bhat, Nucl. Data Sheets **89**, 797 (2000).
[39] L. I. Govor, A. M. Demidov, and Yu. K. Cherepantsev, Yad. Fiz. **60**, No. 10, 1733 (1997); Phys. At. Nucl. **60**, 1579 (1997).
[40] E. Veje, B. Elbek, B. Herskind, and M. C. Olesen, Nucl. Phys. **A109**, 489 (1968).
[41] N. Pietralla, Phys. Rev. C **59**, 2941 (1999).