Identification of the $J^{\pi}=1^{-}$ two-phonon state of ^{88}Sr

N. Pietralla
A.W. Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520
and Institut für Kernphysik, Universität zu Köln, D-50937 Köln, Germany

V. N. Litvinenko, S. Hartman, F. F. Mikhailov, I. V. Pinayev, and G. Swift
FEL Laboratory, Department of Physics, Duke University, Durham, North Carolina 27708

M. W. Ahmed, J. H. Kelley, S. O. Nelson, R. Prior, K. Sabourov, A. P. Tonchev, and H. R. Weller
Triangle Universities Nuclear Laboratory, Duke University, Durham, North Carolina 27708
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The linearly polarized γ-ray beam produced by the HIγS facility has been used to determine the parity of two previously known dipole excitations in ^{88}Sr. The azimuthal asymmetry of γ rays produced in the process of nuclear resonance fluorescence indicated that the dipole state at 4.742 MeV, recently discussed as a new form of $M1$ excitation, is in fact a 1^{-} $(E1)$ state. The 1^{-} state at 4.742 MeV must, therefore, be reconsidered as the $J^{\pi}=1^{-}$ member of the quadrupole-octupole coupled two-phonon multiplet. A second state at 7.535 MeV was also assigned $J^{\pi}=1^{-}$.

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Particularly interesting cases of multiphonon excitation in complex nuclei are those that involve different constituent phonon modes (inhomogenous phonon coupling) such as the $2^{+}\otimes 3^{-}$ quadrupole-octupole coupling (QOC) [1,2]. This multiplet is expected to consist of five states having spin and parity quantum numbers $J^{\pi}=1^{-},\ldots,5^{-}$, which should decay through collective $E2$ and $E3$ transitions to the 2^{+} and 3^{-} constituent one-phonon states.

The center of gravity of the two-phonon multiplet is expected in a harmonic phonon coupling scheme to lie at the sum energy $E_{2^{+}\otimes 3^{-}}\cong E(2^{+})+E(3^{-})$. Recent systematic photon scattering investigations have demonstrated that the 1^{-} member of the multiplet occurs in most nuclides at energies a few percent below the sum energy [3,4], i.e., showing moderate negative anharmonicity. It came as a surprise to find the only reasonable candidate for the $2^{+}\otimes 3^{-}$, $J^{\pi}=1^{-}$ state in the $N=50$ closed-shell nucleus ^{88}Sr to be at 4.742 MeV [5], an energy value larger than the two-phonon sum energy $E_{2^{+}\otimes 3^{-}}=4.570$ MeV. Consequently, since the parity of this $J=1$ state at 4.742 MeV was not measured [5], its two-phonon nature was questioned [6], despite the fact that the dipole decay transition strength is close to the measured $B(E1)$ value for the $3^{-}\rightarrow 2^{+}$ transition, a signature for quadrupole-octupole collectivity [6].

Following this, Käubler *et al*. [7] performed an experiment to measure the parity of this dipole state using Compton polarimetry in an on-axis bremsstrahlung-induced nuclear resonance fluorescence (NRF) experiment. The result was a small positive asymmetry, which pointed to an $M1$ character for the electromagnetic excitation mechanism leading to a 1^{+} assignment for the state at $E=4.742$ MeV in ^{88}Sr [7]. Although such a 1^{+} state could not be understood in the framework of the quasiparticle phonon model (QPM) [7], it was later suggested [8] that this state might constitute evidence for a new type of nuclear excitation: a "dynamic scissors mode" in a semimagic nucleus, having properties similar to those of the mixed-symmetry two-phonon 1^{+} states in the ^{94}Mo nucleus [9]. Obviously, the confirmation of the parity assignments of Käubler *et al.* is of significance.

It was recently demonstrated [10–12] that the high flux of quasimonochromatic, polarized γ rays available at the HIγS facility opens up a new generation of nuclear structure studies using the NRF technique. In particular, the high degree of polarization of the intense γ-ray beam at the HIγS facility [13] leads to a new degree of efficiency and accuracy in the assignment of parity quantum numbers in nuclear dipole excitations. In the case of resonant, elastic scattering of fully polarized γ rays off a $J=1$ level in an even-even nucleus, the asymmetry can be written in terms of the angular correlation function $W(\theta,\phi)$, where ϕ represents the azimuthal angle between the direction of the scattered γ ray and the polarization plane of the incident beam. At a polar angle $\theta=90°$ one obtains

$$\Sigma(90°)=\frac{W(90°,0°)-W(90°,90°)}{W(90°,0°)+W(90°,90°)}. \tag{1}$$

The value of $\Sigma(90°)$ is $+1$ for a $J^{\pi}=1^{+}$ state and -1 for a $J^{\pi}=1^{-}$ state [14,12]. In the present experiment, the HIγS facility was used to produce nearly monoenergetic, 100% linearly polarized γ-ray beams at energies of 4.74, 5.02, and 7.54 MeV. The typical energy resolution [full width at half maximum of $N_{\gamma}(E)$] was about 3%, and was obtained by collimating the beam using a 2.54-cm-diameter collimator. The typical intensity of the beam on target was measured to be $\sim 10^{6}$ γ rays/sec, with a maximum observed intensity on target of 10^{7} γ rays/sec.

The target consisted of 3.24 g/cm^{2} of ^{nat}SrF$_{2}$ powder contained in a thin-walled plastic cylinder, 5.37 cm long with a 38 mm inner diameter, having its axis oriented along the beam direction. The target was surrounded by four 60% efficient HPGe detectors at $\phi=0°$, 90°, 180°, and 270°, all at

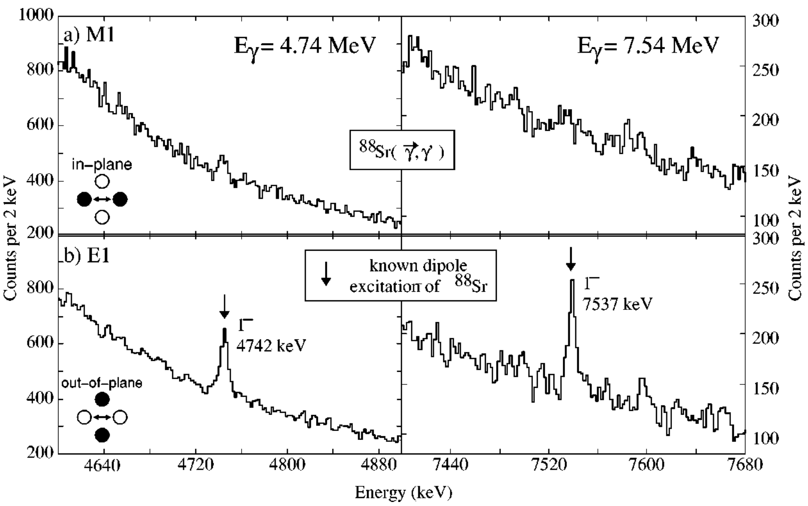

FIG. 1. γ-ray spectra obtained with Ge detectors for the initial γ-ray energies 4.74 MeV (left) and 7.54 MeV (right). (a) and (b) show the elastic resonance γ-scattering lines observed in the polarization plane (i.e., $\phi=0°$ and 180°) and perpendicular to it (i.e., $\phi=90°$ and 270°), respectively.

$\theta=90°$. The detectors were located 10 cm from the axis of the beam. Further details of this setup were presented in Refs. [12,15].

The energy calibrations of the γ-ray spectra were performed using "natural" background lines observed during the actual measurements (1.4608 and 2.6145 MeV) and γ-ray lines from the decay of ^{11}B, which was photoexcited to its $3/2^-$ state at 5.020 MeV. The instrumental symmetry of the detector setup was measured by means of a ^{226}Ra source mounted at the target position and by the 5.020-MeV line from ^{11}B. A fifth HPGe detector was located 2.5 m downstream of the target and behind a lead attenuator and pinhole collimator for the purpose of monitoring the beam intensity and tuning the beam energy.

The total spectra obtained from the detectors in the polarization plane of the incident beam (a) and from the detectors perpendicular to this plane (b) are shown in Fig. 1 for incident γ-ray energies $\overline{E}_\gamma=4.74$ MeV (left) and 7.54 MeV (right). By inspection it is obvious that the dominant yield for the γ rays corresponding to levels at 4.742 and 7.537 MeV is in the detector mounted perpendicular to the polarization plane of the beam—indicating negative parity for both states. These results were verified by rotating the detector assembly by an azimuthal angle of $\Delta\phi=90°$ around the beam axis in the case of the 4.742-MeV level.

The finite geometry of the target and detectors leads to a deviation of the observed analyzing powers from their ideal values of ±1.0. Although it is not necessary to correct the observed values (typically ~0.7) in order to make parity assignments (which require only that we distinguish between $+0.7$ and -0.7), corrected values were generated by performing a Monte Carlo simulation for the sake of completeness. The measured and the corrected values of the analyzing powers are presented in Table I (note that the "corrected values" do not include a correction for any instrumental asymmetry and that they are consistent, within error, with the value of -1.0 expected for a 100% polarized beam).

The results indicated that both states have an electric dipole ($E1$) excitation character. An $M1$ character can be excluded by 14 standard deviations for the $1^-\rightarrow0^+$ transition at 4.742 MeV and by more than seven standard deviations for the 7.54-MeV $1^-\rightarrow0^+$ transition in ^{88}Sr.

Previous speculation about a positive parity structure near 4.7 MeV in ^{88}Sr is clearly invalid. The $J=1$ state of ^{88}Sr at 4.742 MeV has negative parity and must be considered to be the best candidate for the $2^+\otimes3^-$, $J^\pi=1^-$ two-phonon state. A confirming 2008-keV collective $E2$ transition to the 3^- octupole state at 2.734 MeV, expected if the 4.742-MeV state is indeed the two-phonon state, was not observed above background. Assuming $B(E2;1^-\rightarrow3^-)\equiv B(E2;2^+\rightarrow0^+)=167(5)\ e^2\ \mathrm{fm}^4$ ([16] adopted value) for the strength of the $1^-\rightarrow3^-$ $E2$ transition, however, indicates that we should expect in this case a branching ratio

$$BR=\Gamma(1^-\rightarrow3^-)/\Gamma(1^-\rightarrow0^+)=0.046(10).$$

TABLE I. Measured and corrected asymmetries and parity quantum number assignments along with previous results.

E_x (MeV)	Previous asymmetry measurements Σ	J^π	This work $\Sigma_{measured}$	$\Sigma_{corrected}$	J^π
4.742	0.11(5) [a]	1^+ [a]	$-0.63(9)$	$-0.89(13)$	1^-
7.54	b	1 [c]	$-0.75(18)$	$-1.06(25)$	1^-

[a]Reference [7].
[b]Reference [20].
[c]Reference [19].

Based on the background count rate at the transition energy of 2008 keV in our spectra, we can infer an upper limit of $R<0.25$, not in contradiction with the expected value for a two-phonon structure.

The $E1$ transition strength $B(E1;1^-\rightarrow 0_1^+)=0.9(2)\times 10^{-3}$ e^2 fm^2 [4,5,7] is close to the value $B(E1;3_1^-\rightarrow 2_1^+)=0.764(4)\times 10^{-3}$ e^2 fm^2 ([16] and references therein). This fact represents another argument in favor of the two-phonon character for the 1^- state since it follows the empirical correlation [6] of quadrupole-octupole collective $E1$ transition strengths. A parameter-free understanding of the positive energy anharmonicity

$$e\equiv\frac{E(1^-)-[E(2_1^+)+E(3_1^-)]}{E(2_1^+)+E(3_1^-)}=+0.038$$

in ^{88}Sr is a challenge for nuclear structure theory. The detailed QPM calculations reported in Ref. [7] predicted a negative anharmonicity. Considerable theoretical effort has recently been directed at trying to understand positive anharmonicities of so-called double-γ two-phonon states in deformed nuclei, e.g., [17]. An understanding of the anharmonicity of QOC states has not yet been obtained.

In summary, we have measured NRF intensity asymmetries scattered off a $^{\rm nat}$SrF$_2$ sample around a 100% linearly polarized γ-ray beam produced by the HIγS facility. The electromagnetic characters of previously known dipole excitations of ^{88}Sr at 4.742 MeV and 7.54 MeV are both found to be $E1$ leading to negative parity quantum number assignments, $J^\pi=1^-$, in both cases. The recently claimed 1^+ assignment for the 4.742-MeV level must be considered an artifact probably generated by an underestimate of the uncertainties for the (small) Compton scattering asymmetry, being a few percent in size, due to some ambiguities in the background subtraction procedure applied in that analysis [18]. The 1^- state at 4.742 MeV must again be considered as the best candidate for the $J=1$ member of the $2^+\otimes 3^-$ two-phonon multiplet in ^{88}Sr on the basis of the empirical correlation of the $E1$ strengths for the $1^-\rightarrow 0_1^+$ and $3_1^-\rightarrow 2_1^+$ transitions. The anharmonicity of this two-phonon 1^- state is positive. This fact is not yet understood. The negative parity of the 1^- state at 7.84 MeV leaves no known levels above 3.5 MeV that are candidates for the previously debated [19] $M1$ resonance of ^{88}Sr.

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[1] P.O. Lipas, Nucl. Phys. **82**, 91 (1966).
[2] W. Donner and W. Greiner, Z. Phys. **197**, 440 (1966).
[3] M. Wilhelm, S. Kasemann, G. Pascovici, E. Radermacher, P. von Brentano, and A. Zilges, Phys. Rev. C **57**, 577 (1998), and references therein.
[4] W. Andrejtscheff, C. Kohstall, P. von Brentano, C. Fransen, U. Kneissl, N. Pietralla, and H.H. Pitz, Phys. Lett. B **506**, 239 (2001), and references therein.
[5] F.R. Metzger, Phys. Rev. C **11**, 2085 (1975).
[6] L. Käubler, H. Schnare, R. Schwengner, P. von Brentano, F. Dönau, J. Eberth, J. Enders, A. Fitzler, C. Fransen, M. Grinberg, E. Grosse, R.-D. Herzberg, H. Kaiser, P. von Neumann-Cosel, N. Pietralla, H. Prade, A. Richter, S. Skoda, Ch. Stoyanov, H.-G. Thomas, H. Tiesler, D. Weisshaar, and I. Wiedenhöver, Eur. Phys. J. A **7**, 15 (2000).
[7] N. Pietralla, Phys. Rev. C **59**, 2941 (1999).
[8] L. Käubler *et al.*, in *Nuclear Structure Physics*, edited by R.F. Casten, J. Jolie, U. Kneissl, and K.P. Lieb (World Scientific, Singapore, 2001), p. 363.
[9] N. Pietralla, C. Fransen, D. Belic, P. von Brentano, C. Friessner, U. Kneissl, A. Linnemann, A. Nord, H.H. Pitz, T. Otsuka, I. Schneider, V. Werner, and I. Wiedenhöver, Phys. Rev. Lett. **83**, 1303 (1999).
[10] V.N. Litvinenko and J.M.J. Madey, Nucl. Instrum. Methods Phys. Res. A **375**, 580 (1996).
[11] V.N. Litvinenko *et al.*, Nucl. Instrum. Methods Phys. Res. A **407**, 8 (1998).
[12] N. Pietralla, Z. Berant, V.N. Litvinenko, S. Hartmann, F.F. Mikhaillov, I.V. Pinayev, G. Swift, M.W. Ahmed, J.H. Kelley, S.O. Nelson, R. Prior, K. Sabourov, A.P. Tonchev, and H.R. Weller, Phys. Rev. Lett. **88**, 012502 (2002).
[13] S.H. Park *et al.*, Nucl. Instrum. Methods Phys. Res. A **475,** 425 (2001).
[14] L.W. Fagg and S.S. Hanna, Rev. Mod. Phys. **31**, 711 (1959).
[15] N. Pietralla, H.R. Weller, V.N. Litvinenko, M.W. Ahmed, and A.P. Tonchev, Nucl. Instrum. Methods Phys. Res. A (to be published).
[16] H.-W. Müller, Nucl. Data Sheets **54**, 1 (1988).
[17] J.E. Garcia-Ramos, J.M. Arias, and P. Van Isacker, Phys. Rev. C **61**, 064309 (2000).
[18] L. Käubler (private communication).
[19] G. Isoyama, T. Ishimatsu, E. Tanaka, K. Kageyama, and N. Kumagai, Nucl. Phys. **A342**, 124 (1980).
[20] K. Wienhard, C. Bläsing, K. Ackermann, K. Bangert, U.E.P. Berg, K. Kobras, W. Naatz, D. Rück, R.K.M. Schneider, and R. Stock, Z. Phys. A **302**, 185 (1981).