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High-spin μs isomer in ^{98}Zr

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A high-spin isomer in ^{98}Zr, of half-life 1.9 (2) μs, has been observed using the Lohengrin mass spectrometer of the high-flux reactor of the Institut Laue-Langevin, Grenoble. The isomer was produced by the thermal-neutron induced fission of ^{239}Pu. Measurements at the spectrometer focal point of γ-t and γ-γ-t, relative to the arrival of a fission fragment, allowed the isomer to be identified and the level scheme constructed. The isomeric state at 6603.3 keV of excitation energy is tentatively assigned a spin and parity of (17^-) and is proposed to have a $\pi(g^2_{9/2})\nu(g^1_{7/2}h^1_{11/2})$ configuration.

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I. INTRODUCTION

Neutron-rich nuclei around mass 100 are distinctive for the rapid spherical-to-deformed change in shape of their low-lying and ground states, which occurs when going from 58 to 60 neutrons [1]. On the boundary of this phenomenon are nuclei with 59 neutrons and deformed bands have recently been observed with $\beta_2 \sim 0.3$ at around 600 keV in ^{99}Zr [2] and ^{97}Sr [3] as well as the neighboring ^{98}Zr [4]. Furthermore, the maximum deformation for the region $\beta_2 \sim 0.4$ has also been recently observed in the $\nu 9/2[404]$ bands in ^{97}Sr [3] and in ^{99,101}Zr [2,3] at 830, 1039 and 942 keV, respectively. Hence, measurements of nuclear structure properties in this region can give insights into the interplay between collective and single particle modes of excitation and shape coexistence where the unique parity $\pi g_{9/2}$ and $\nu h_{11/2}$ orbitals appear to play an especially important role in these effects [2,3].

Shape-coexisting μs isomers with spin and parity of 10^- have recently been found in the $N = 59$ nuclei ^{96}Rb [5] and ^{98}Y [6]. These isomers are proposed to have spherical $\pi g_{9/2} \nu h_{11/2}$ configurations and hence single-particle states are in competition with collective excitations here. It is unusual to observe these spherical states at such high energies and spins, which exist due to the strongly attractive neutron-proton interaction, for orbits which have similar angular momenta.

To see if similar shape-coexisting μs isomers are present in neighboring nuclei a search was performed at the Lohengrin mass spectrometer of the ILL and a new high-spin μs isomer was observed in ^{98}Zr.

A description of the experimental method and results are presented in Sec. II. This is then followed in Sec. III by an interpretation of these results in terms of probable configurations of the states involved in this decay sequence.

II. EXPERIMENTAL METHOD AND RESULTS

The Lohengrin mass spectrometer was used to select nuclei, according to their mass-to-ionic charge ratios (A/q), recoiling from a thin 7×1 cm, 3.3 mg ^{239}Pu target which was undergoing thermal-neutron-induced fission. The flight time of the nuclei through the spectrometer was around 1.6 μs. The fission fragments were detected in an ionization chamber filled with isobutane gas at a pressure of 43 mb, allowing the identification of A/q. The chamber consists of two regions of gas, $\Delta E1 = 9$ cm and $\Delta E2 = 6$ cm, separated by a grid. The γ rays deexciting the isomeric states were detected by a Clover Ge detector [7] and three single Ge crystals of the Miniball array [8] assembled in the same cryostat. These detectors were placed perpendicular to the ion beam in a close geometry, possible as the ionization chamber was 6 cm thick. The total efficiency for γ-ray detection was 20% and 4% for photons of 100 keV and 1 MeV, respectively. Any γ rays detected in the germanium detectors up to 40 μs after the arrival of an ion were recorded on the disk of the data acquisition system. A time window of 250 ns was used for γ-γ coincidences in the data-analysis software.

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TABLE I. Energies and relative intensities of γ-ray transitions observed from the decay of the isomer in ^{98}Zr.

E_γ (keV)	I_γ	E_γ (keV)	I_γ
63.0 (1)[a]	17(4)	770.0(1)	44(9)
240.1 (1)	10(10)	776.0(1)	28(6)
511.9 (1)	31(7)	804.3(1)[a]	72(14)
583.2 (1)	39(8)	820.4(1)[a]	68(13)
620.4 (1)	67(13)	834.6(1)	37(7)
622.6 (1)	56(11)	952.1(1)[a]	40(8)
647.0 (1)	55(11)	994.2(2)	8(3)
717.7 (1)[a]	59(11)	1221.0(5)	13(8)
725.4 (1)	53(10)	1222.7(2)	100(18)
752.6 (1)	16(3)	1258.2(2)	21(5)
768.4 (1)	40(8)		

[a]Denotes transitions observed for the first time.

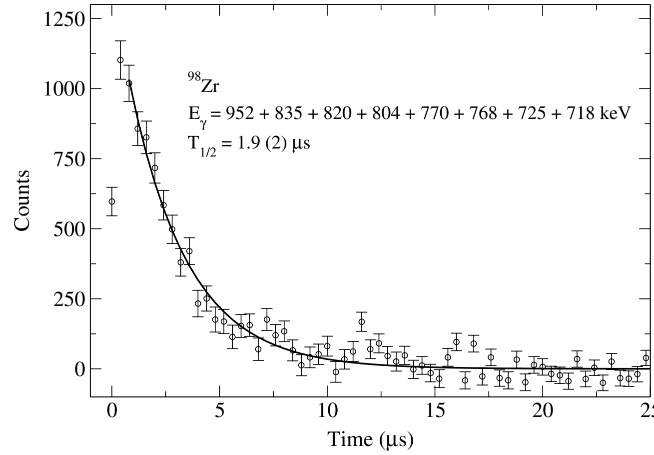

FIG. 2. Sum of the time spectra observed when gating on the 952.1, 834.6, 820.4, 804.3, 768.4, 770.0, 725.4, and 717.7 keV transitions.

A new (17$^-$) μs isomeric state at 6603.3 keV has been observed for the first time in ^{98}Zr. Mass and isotopic identification of the isomer were performed by examining coincidences between the mass-separated ions, detected in the ionization chamber, and the isomer-delayed γ rays. Much of the decay scheme below the isomer has already been assigned to ^{98}Zr. This nucleus has previously been studied by prompt γ-ray spectroscopy of secondary fission fragments populated by light-ion-induced [9] and spontaneous fission [4,10]. Observed γ rays emitted from states below the new isomer in ^{98}Zr are reported in Table I. By gating on the different γ rays depopulating the isomer, and examining the coincident γ rays, a level scheme was constructed. Good agreement is found with the level schemes previously reported in [9,10] and the majority of the level scheme reported in Ref. [4]. The 204.3 keV transition reported in previous works was not reported here, as a transition of the same energy was also present in the time-delayed spectra from the decay of the strongly produced μs isomer in ^{98}Y [6,11] which was present as an isobaric contaminant. In addition to the positive-parity band previously reported, a new negative-parity collective band has been observed for the first time. Sums of fragment-γ-γ coincidence spectra gated on transitions in the the two bands, or transitions which feed the two bands, are shown in Fig. 1.

Background-subtracted time spectra were produced by gating on the strongest and cleanest transitions in the decay sequence. These spectra were then added together and a fit gave a half-life of 1.9 (2) μs, as shown in Fig. 2. Strong transitions in the lower portion of the level scheme (583.2, 620.4, 622.6, 647.0, 1222.7 keV) were not included in the determination of the lifetime as they were also present as background emanating from the β-decay of ^{98}Y [12].

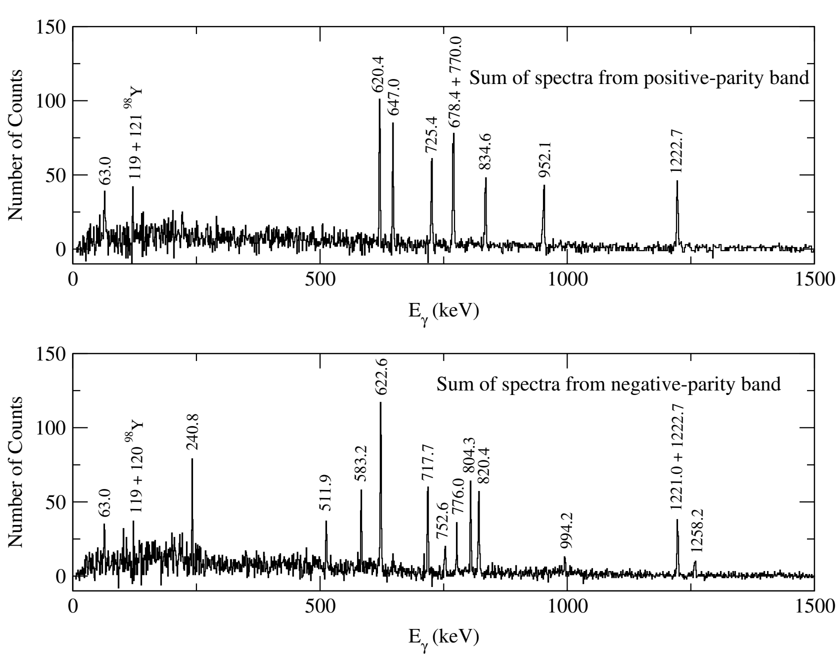

FIG. 1. γ-γ coincidence spectra made by summing the cleanest gated transitions in the positive and negative parity bands. The gating transitions were the 952.1, 834.6, 770.0, 768.4, 725.4, and 647.0 keV transitions for the positive-parity band and the 820.4, 804.3, 717.7, and 583.2 keV transitions for the negative-parity band.

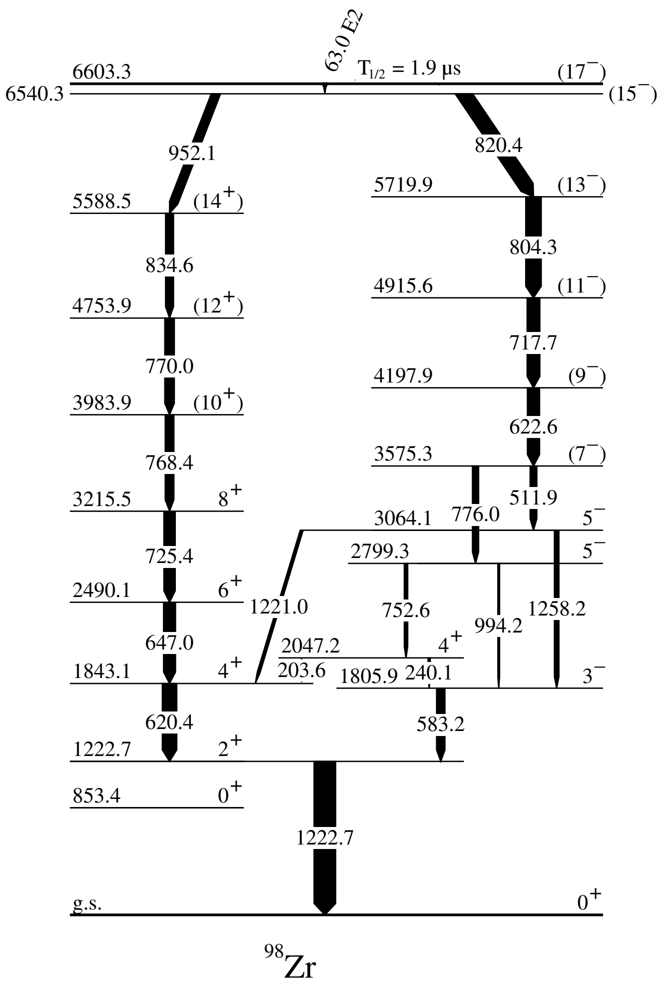

FIG. 3. Decay scheme of the 1.9 (2) μs isomer observed in the present work. The 853.4 keV 0^+ bandhead [4] is also included.

III. DISCUSSION

A. Positive-parity band

The γ rays present in the positive-parity band, shown in Fig. 3, are the same as those presented in Refs. [9,10], with the exception of the 952.1 keV transition. This band has a slightly different structure to that reported in Ref. [4], where the stopping time of the fission fragments in the thick target was approximately the same as the lifetimes of these states. This induced large Doppler broadening which degraded the quality of the γ-ray spectra. The Doppler broadened gamma rays however, allowed lifetimes to be measured for these states, and hence deformations. Urban *et al.* [4], extracted a deformation of Q_0 of 2.0 (1) eb for this band. This band has been extended to higher spins by Wu *et al.* [9] where it was shown to be mostly vibrationlike, up to spin $14\hbar$ and then rotational above this. The band crossing, a transition from vibrationlike to rotational motion, occurs due the alignment of two $h_{11/2}$ neutron orbitals with the axis of rotation, which make rotational motion more energetically favorable [13].

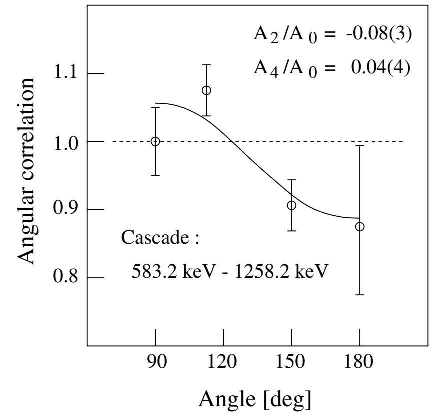

FIG. 4. Angular correlation function for the 1258.2 keV–583.2 keV cascade measured using data from Ref. [4].

B. Negative-parity band

The negative-parity band shown in Fig. 3, is reported for the first time in this work. Little is known about the properties of the negative-parity states in ^{98}Zr. Most of what is known comes from the reaction ^{96}Zr$(t, p)^{98}$Zr [14], where these data, combined with systematic trends in other Zr isotopes, allowed a spin of 3^- to be assigned to the level at 1805.9 keV and 5^- to the state at 2799.3 keV. These states were proposed to be mainly $1h_{11/2}1g_{7/2}$ and $2d_{3/2}1h_{11/2}$ configurations, respectively. An angular-correlation function for the 1258.2 keV –583.2 keV cascade, measured using the data from Ref. [4] is shown in Fig. 4. This indicates that one of the transitions in the cascade is a $\Delta I = 1$ while the is other is $\Delta I = 2$ in character. It is known from previous studies that the 583.2 keV transition is a stretched electric dipole with $\Delta I = 1$ [4]. Consequently, the $\Delta I = 2$ spin change is assigned to the 1258.2 keV transition. This allows the spin of the level at 3064.1 keV to be determined as $I = 5$. The parity of this level can be deduced from its observed decay properties. This level decays also by the 1221.0 keV branch to the 4^+ level at 1843.1 keV. Thus one of the transitions should be electric, while the other magnetic in character. The branching ratio for the level at 3064.1 keV, $I_\gamma(1221.0\text{keV})/I_\gamma(1258.2\text{keV}) = 0.6(4)$, obtained in this work is only consistent with the assumption that the 1258.2 keV transition is a stretched $E2$ and the 1221.0 keV transition has $\Delta I = 1$, $E1$ multipolarity. In this case an estimate, based on single-particle rates and taking into account a typical hindrance factor of 10 for an $E2$ transition and a slight acceleration by a factor of 10 for an $E2$ transition gives a branching ratio of $\sim$1. For the opposite case, assuming an $M1 + E2$ character for the 1221.0 keV transition and an $M2$ multipolarity for the 1258.2 keV transition an analogous estimate, taking into account a hindrance of 10 for an $M2$ transition, gives a branching ratio of approximately 10^{-6}, clearly below the observed value. This therefore allows the spin and parity of the state at 3064.1 keV to be tentatively assigned as 5^-.

The nature of the states in the band built on this 3064.1 keV level can be described as vibrationlike from slope the so-called E-Gamma Over Spin (E-GOS) [13] plot shown in Fig. 5, which also includes the data from Wu *et al.* [9] for the high-spin positive-parity states.

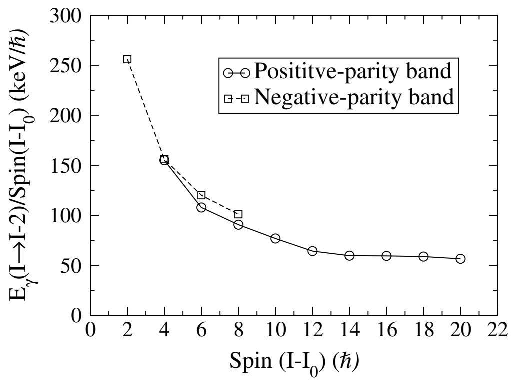

FIG. 5. E-GOS plot for the positive and negative parity bands. The bandhead spin of 5 has been subtracted from the E-GOS values for the negative parity band. The 820.4 keV transition emitted from the 15^- state has been included in the plot, though it is uncertain if this transition is a member of the negative-parity band.

The bandhead spin of 5 (I_0) has been subtracted from all the spins in this band in the E-GOS plot. For a pure vibrator the E-GOS ratio decreases hyperbolically to zero with increasing spin, whereas for an axially symmetric rotor it approaches a constant $4(\hbar^2/2J)$ [13]. The E-GOS plot would appear to show that this band has a mostly vibrational character. The question as to whether the 820.4 keV transition is a member of this band remains open. If the 820.4 keV transition is included in the E-GOS plot in Fig. 5 then it correlates reasonably well with the other existing points. If the (15^-) state at 6540.3 keV is single-particle in origin it is most likely a member of the same multiplet as the isomer. The absence of the observation of any interband transitions would appear to show that this negative-parity band is not octupole in nature. This is because the electric-dipole moment of an octupole mode would most likely be expressed through interband $E1$ transitions. Experimental observational limits for hypothetical interband transitions can be estimated from $E2 - E1$ branching ratios. The reduced transition rate for a collective $E2$ transition can be estimated to be $B(E2) = \frac{5}{16\pi} Q_0^2 \langle I_i K_i 20 | I_f K_f \rangle^2$. The value of Q_0 for the negative-parity band is estimated to be that of the positive-parity band, 2.0(1) eb from Ref. [4]. The weakest transition observed in the data set (994.2 keV) has a relative intensity of 8 (3), which can be taken as a lower observable limit for a hypothetical interband $E1$ tranistion. Measured intensities for the intraband $E2$ transitions in the negative-parity band were then used to calculate lower observable limits for $B(E1)$ reduced transition rates, shown in Table II.

$B(E1)$ rates for nuclei exhibiting octupole deformation are typically in the range 10^{-3} to 10^{-2} W.u. [15]. The sensitivity of the experiment is below this value, which therefore strengthens the assumption that the negative-parity band is not octupole in nature. In fact a band built on an octupole mode was tentatively assigned in Ref. [14].

C. Decays from the isomeric state into the collective bands

Only one γ ray, of energy 63.0 keV, was observed from the decay of the (17^-) isomeric state, as shown in Fig. 3. Comparisons between the γ-ray intensity of the 63.0 keV

TABLE II. Lower observational limits for hypothetical interband $B(E1)$ transitions in this experiment.

Hypothetical transition	Observable limit for interband $B(E1)$ in W.u.
$13^- \rightarrow 12^+$	3.2×10^{-5}
$11^- \rightarrow 10^+$	2.5×10^{-5}
$9^- \rightarrow 8^+$	1.1×10^{-5}
$7^- \rightarrow 6^+$	5.1×10^{-6}

line and the intensity of the 952.1 and 820.4 keV transitions allow an internal-conversion coefficient of $\alpha_{\rm exp} = 5.5(16)$ to be obtained. This value, when compared to the theoretical value for an $E2$ transition of $\alpha_{E2} = 5.95$, shows that this transition is a pure, or almost pure, $E2$. A comparison with Weisskopf lifetime estimates give a hindrance factor of $H_w \sim 0.4(1)$ showing that it is slightly accelerated.

The (15^-) state at 6540.3 keV, decaying by 952.1 and 820.4 keV transitions, is most likely a different state to the 6539.6 keV, 16^+ rotational state measured by Wu *et al.* [9] which decays by a 949.6 keV transition. This can be shown most clearly by comparing the intensities of the transitions emitted by this state. In the prompt γ-ray spectroscopy works performed by Wu *et al.* [9] and by Hamilton *et al.* [10], all the observed intensity passes to the (14^+) state at 5590.2 keV in the positive-parity yrast band. In this work the intensity from the decay of the isomer passes to both the positive- and negative-parity bands, with more intensity going to the negative-parity band. If the (16^+) state, reported in both Refs. [9] and [10], and the (15^-) state observed here were the same then the negative-parity band should have also been observed previously. Furthermore the nonobservation of strong inter-band transitions also shows that these two bands are quite different in nature.

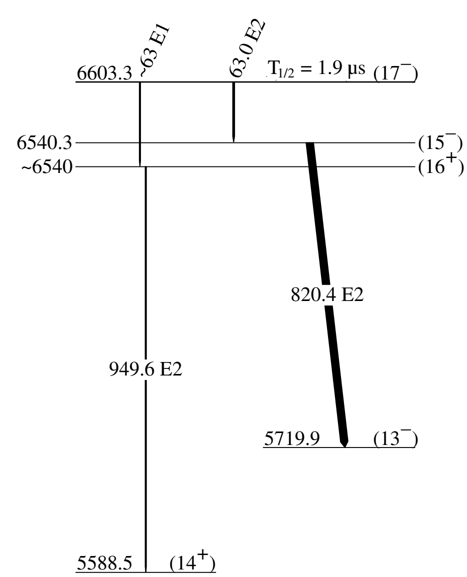

FIG. 6. A second possible scenario for the decay out of the isomer. This scenario is less likely than that shown in Fig. 3.

Another possible scenario could be that the (17$^-$) isomer decays to two different states at ∼6540 keV, both so close in energy that the two ∼63.0 keV transitions cannot be resolved in the present data. These decays would be an $E1$ transition to the (16$^+$) state and an $E2$ transition to a (15$^-$) state. This possible decay scheme is shown in Fig. 6, where the value of the (16$^+$) to (14$^+$) transition is taken from Ref. [9]. This is, however, unlikely for the following reasons: No interband transitions have been observed below the isomer so the total intensity of an $E1$ decay branch from the (17$^-$) isomer would have the same intensity as that of the 952.1 keV transition below it (40 (8)). This would give a partial γ-ray intensity of 28(6). An $E2$ decay out of the isomer to the (15$^-$) state would have the same total intensity as the 820.4 keV transition and would have a partial γ-ray intensity of 10(2). Therefore, the total γ-ray intensity would be 38 (6) for two unresolved lines. This is inconsistent with the observed γ-ray intensity of 17(4). Comparisons of the partial γ-ray decay lifetimes to Weisskopf estimates for the two decays in this scenario give hindrance factors of $H_w \sim 5.1(12) \times 10^6$ for an $E1$ decay and $H_w \sim 0.9(2)$ for an $E2$ decay. A (17$^-$) state in ^{92}Zr with a 60(20) ps lifetime, decaying by an $E1$ transition to a (16$^+$) state, has been reported in Ref. [16], which has a hindrance factor of 2.5×10^4. It is likely that this state has the same configuration as the (17$^-$) state in ^{98}Zr, as few orbitals are available in this region capable of giving such a spin and parity. The hindrance factors for these $E1$ decays from a 17$^-$ to a 16$^+$ state in these two Zr nuclei are thus inconsistent, lending further weight to the assumption that the isomer decays by a single $E2$ transition to a (15$^-$) state. The consequence of this result reinforces the idea that the 952.1 keV transition observed in the present work is a different transition to the 949.6 keV intraband transition feeding the 16$^+$ state reported by Wu *et al*. [9].

D. Isomeric state

As mentioned previously the isomeric state decays by a pure, or almost pure, slightly accelerated $E2$ transition. The isomer spin and parity assignment of (17$^-$), resulting from the discussions in the previous sections, put severe constraints on the available orbitals capable of producing such a state. Two configurations which can generate a spin of 17$\hbar$ are the maximally aligned $\pi(g^2_{9/2})\nu(g^1_{7/2}h^1_{11/2})$ and $\pi(g_{9/2}f^{-1}_{5/2})\nu h^2_{11/2}$). No other combinations of four, or fewer, orbitals in this region can generate such a spin and parity. Of these two configurations the $\pi(g^2_{9/2})\nu(g^1_{7/2}h^1_{11/2})$ is the most likely to be responsible for this isomeric state because the $\pi g_{9/2}\nu g_{7/2}$ and $\pi g_{9/2}\nu h_{11/2}$ fully aligned configurations are expected to be strongly attractive, as the proton and neutron orbits have similar orbital angular momentum, substantially lowering the energy of this level.

The $\pi(g^2_{9/2})\nu(h^2_{11/2})_{18^+}$ configuration is the only other remaining set of orbitals able to produce such a high spin in this region, and would also be expected to have a strongly attractive neutron-proton interaction, due to their similar angular momenta. However, if the isomer deexcites by an $E2$ transition to a 16$^+$ then this would mean that the state at 6540.3 keV would decay by an $E3$ of 820.4 keV and a 952.1 keV $E2$ transition. Using the quadrupole moment of 2.0 eb measured by Urban *et al*. a lifetime estimate of 0.75 ps is obtained. As similar intensities are observed for both transitions the 820.4 keV transition would have to be accelerated by a factor of 3×10^5, which would seem unlikely.

Recently μs isomers with spin 10$^-$ have been found in ^{96}Rb [5] and ^{98}Y [6], both of which are proposed to consist of $\pi g_{9/2}\nu h_{11/2}$ orbitals, which are thought to be components of this isomer. These isomers all demonstrate the presence of a strong, attractive neutron-proton interaction for maximally aligned states in this region, allowing single particle states to compete with collective modes of excitation at high energies and spin.

IV. CONCLUSION

A new 1.9(2) μs isomer at 6603.3 keV has been observed in ^{98}Zr, with a proposed configuration of $\pi(g^2_{9/2})\nu(g^1_{7/2}h^1_{11/2})$ and a single particle nature. The isomer decays by a pure, or almost pure, $E2$ transition into a 15$^-$ state, which then decays into two collective bands, one of positive parity, the other negative, the later of which is observed for the first time. The existence of a spherical, single-particle state at such a high energy (6603.3 keV) and spin (17$^-$) is quite unusual, in fact both these values are the highest known for a μs isomer in this region. These high-spin shape coexisting states again demonstrate the richness of nuclear structure phenomena in this region.

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