μs isomers of ^{158,160}Nd

E. Ideguchi,[1] G. S. Simpson,[2,3,4,*] R. Yokoyama,[5] Mn. Tanaka,[1] S. Nishimura,[6] P. Doornenbal,[6] G. Lorusso,[6] P.-A. Söderström,[6] T. Sumikama,[7] J. Wu,[8,6] Z. Y. Xu,[9] N. Aoi,[1] H. Baba,[6] F. L. Bello Garrote,[10] G. Benzoni,[11] F. Browne,[12,6] R. Daido,[13] Y. Fang,[13] N. Fukuda,[6] A. Gottardo,[14,15] G. Gey,[2,16] S. Go,[5] N. Inabe,[6] T. Isobe,[6] D. Kameda,[6] K. Kobayashi,[17] M. Kobayashi,[5] I. Kojouharov,[18] T. Komatsubara,[19,20] T. Kubo,[6] N. Kurz,[18] I. Kuti,[21] Z. Li,[8] M. Matsushita,[5] S. Michimasa,[5] C.-B. Moon,[22] H. Nishibata,[13] I. Nishizuka,[7] A. Odahara,[13] Z. Patel,[23,6] S. Rice,[23,6] E. Sahin,[10] H. Sakurai,[6,9] H. Schaffner,[18] L. Sinclair,[24,6] H. Suzuki,[6] H. Takeda,[6] J. Taprogge,[25,26] Zs. Vajta,[21] H. Watanabe,[6,27,28] and A. Yagi[13]

[1]*Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki, Osaka 567-0047, Japan*
[2]*LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, F-38026 Grenoble Cedex, France*
[3]*School of Engineering, University of the West of Scotland, Paisley PA1 2BE, United Kingdom*
[4]*Scottish Universities Physics Alliance, University of Glasgow, Glasgow G12 8QQ, United Kingdom*
[5]*Center for Nuclear Study (CNS), University of Tokyo, Wako-shi, Saitama 351-0198, Japan*
[6]*RIKEN Nishina Center, RIKEN, 2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan*
[7]*Department of Physics, Tohoku University, Aoba, Sendai, Miyagi 980-8578, Japan*
[8]*School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*
[9]*Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[10]*Department of Physics, University of Oslo, Oslo, Norway*
[11]*INFN, Sezione di Milano, I-20133 Milano, Italy*
[12]*School of Computing, Engineering and Mathematics, University of Brighton, Brighton BN2 4JG, United Kingdom*
[13]*Department of Physics, Osaka University, Machikaneyama-machi 1-1, Osaka 560-0043 Toyonaka, Japan*
[14]*Dipartimento di Fisica dellUniversità degli Studi di Padova, I-35131 Padova, Italy*
[15]*INFN, Laboratori Nazionali di Legnaro, Legnaro I-35020, Italy*
[16]*Institut Laue-Langevin, B.P. 156, F-38042 Grenoble Cedex 9, France*
[17]*Department of Physics, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima-ku, Tokyo 171-8501, Japan*
[18]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*
[19]*Research Facility Center for Pure and Applied Science, University of Tsukuba, Ibaraki 305-8577, Japan*
[20]*Rare Isotope Science Project, Institute for Basic Science, Daejeon 305-811, Korea*
[21]*MTA Atomki, P. O. Box 51, Debrecen H-4001, Hungary*
[22]*Hoseo University, Asan, Chungnam 336-795, Korea*
[23]*Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom*
[24]*Department of Physics, University of York, Heslington, York YO10 5DD, United Kingdom*
[25]*Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain*
[26]*Departamento de Física Teórica, Universidad Autónoma de Madrid, E-28049 Madrid, Spain*
[27]*International Research Center for Nuclei and Particles in the Cosmos, Beihang University, Beijing 100191, China*
[28]*School of Physics and Nuclear Energy Engineering, Beihang University, Beijing 100191, China*
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The neutron-rich nuclei ^{158,160}Nd have been studied via delayed γ-ray spectroscopy of μs isomeric states at the RIBF facility, RIKEN. These nuclei were produced following the projectile fission of a 345 A MeV ^{238}U beam and delayed γ rays were detected by the EURICA cluster Ge array. The isomeric states have measured half-lives of 339(20) ns and 1.63(21) μs for ^{158}Nd and ^{160}Nd, respectively. From the observed γ decays and the systematics of levels in the neighboring Nd isotopes first level schemes were constructed for these nuclei. The isomeric states of ^{158,160}Nd have been assigned spins of (6^-) and (4^-), with proposed $\nu 5/2[523] \otimes \nu 7/2[633]$ and $\nu 1/2[521] \otimes \nu 7/2[633]$ configurations, respectively.

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I. INTRODUCTION

The doubly midshell nuclei of the $A \sim 160$ region are well known for undergoing a rapid increase in the deformation of their ground states when going from $N = 88$ to 90 [1]. From $N = 92$ onwards their quadrupole deformation is close to saturation and these nuclei possess well-deformed prolate ground-state rotational bands, as evidenced by their $E(4^+)/E(2^+)$ ratios of $\sim$3.3 [2]. The isotopes $^{152\text{–}156}$Nd have exactly these properties [3–5] and the latter is the most neutron-rich Nd isotope with known excited states [4,6,7]. This nucleus was studied using spontaneous fission sources placed at the center of large arrays of Ge detectors. Low fission yields, along with near-identical γ-ray transition energies in neighboring nuclei, limit the possibilities of studying excited states of the more neutron-rich isotopes of this chain with this technique. All known deformed, neutron-rich, even-even Nd

*simpson@lpsc.in2p3.fr

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nuclei with $N > 90$ possess K-isomeric states [6–8], which result from decays invoking large changes of the projection of the angular momentum vector on the symmetry axis. Several of the nearby $N = 98$ and 100 isotopes are also known to possess two-quasiparticle (2-qp) isomeric states, [7,9,10], one may therefore expect similar long-lived states to exist in ^{158,160}Nd. The presence of isomeric states offers the opportunity to study the structure of these nuclei via the use of delayed γ-ray spectroscopy of in-flight, mass-separated beams of fission fragments. The observation of K isomers can allow the position of single-particle Nilsson states to be mapped in regions dominated by collective structures. In the present work we have studied excited states in the nuclei ^{158,160}Nd via delayed γ-ray spectroscopy.

II. EXPERIMENT

The experiment was performed at the RIBF facility, of the RIKEN Nishina Center. Neutron-rich Nd isotopes were produced via the projectile fission of a 345 MeV/u ^{238}U beam, impinging on a 4-mm thick Be target. The average primary beam intensity was about 7 pnA during 2 d of measurement time. The ions of interest were separated from other reaction products and identified on an ion-by-ion basis by the BigRIPS in-flight separator [11]. Particle identification was performed using the ΔE-ToF-$B\rho$ method in which the energy loss (ΔE), time of flight (ToF), and magnetic rigidity ($B\rho$) were measured and used to determine the atomic number, Z, and the mass-to-charge ratio (A/q) of the fragments. Details about this procedure can be found in Ref. [12]. The selected fragments were transported through the ZeroDegree spectrometer (ZDS) and finally implanted into the WAS3ABi (wide-range active silicon strip stopper array for β and ion detection) Si array positioned at the focal plane of the ZDS. The WAS3ABi detector [13] consisted of five double-sided silicon-strip detectors (DSSSDs) each with an area of 40×60 mm^2, and a thickness of 1 mm. The DSSSDs had segmentations of 40×60 strips each. The flight time of the ions was around 680 ns. In total 1.27×10^5 and 10^4 ions of ^{158,160}Nd, respectively, were identified and implanted in WAS3ABi. A second short run, with a higher secondary beam intensity, was also performed where a 1-mm thick Cu plate replaced the WAS3ABi detector at the ZDS focal plane. This measurement lasted ~8 h and in this time 1.43×10^5 and 3400 ions of ^{158,160}Nd, respectively, were implanted in the Cu passive stopper.

A fraction of the fragments produced by the fission reaction are populated in isomeric states which live for long enough to survive the flight through the BigRIPS spectrometer. The aim of the present experiment was to observe delayed γ rays emitted following the decay of isomeric states, after implantation in the WAS3ABi array or the Cu plate. These delayed γ rays were detected by the EURICA array [13] of 12 large-volume Ge cluster detectors [14], from the former EUROBALL spectrometer [15], arranged in a close geometry around the WAS3ABi detector [13]. The use of ion-γ coincidences, within a window of a few μs after the arrival of an ion, meant that any delayed γ rays detected could be unambiguously assigned to an implanted isotope.

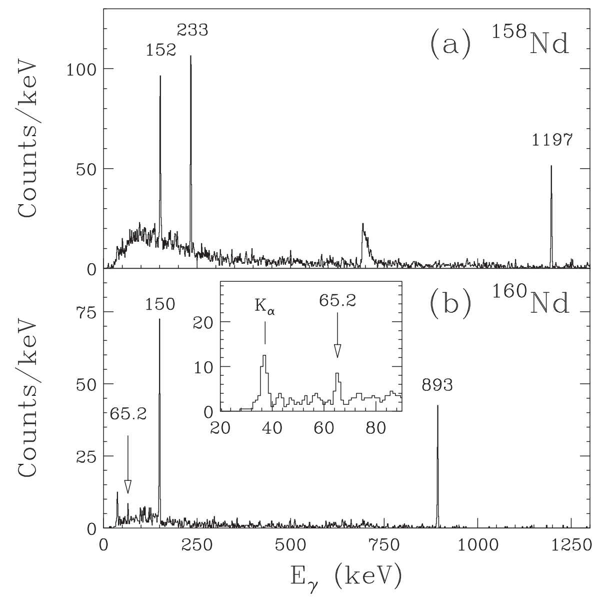

FIG. 1. Delayed γ and x rays detected in coincidence with ions of (a) ^{158}Nd and (b) ^{160}Nd.

III. RESULTS

Spectra of delayed γ and x rays detected in coincidence with ions of ^{158,160}Nd are shown in Fig. 1. The energies and intensities of these transitions are summarized in Table I. Figures 2 and 3 show that all delayed transitions in both ^{158,160}Nd are observed in mutual coincidence, with the exception of the weak 65.2-keV γ ray, and form a single cascade in each nucleus. The $(4_1^+) \rightarrow (2_1^+)$ decays of the ground-state rotational bands of ^{152,154,156}Nd have energies of 164.2, 162.4, and 155.0 keV, respectively [3,7]. The observed 151.7- and 149.9-keV delayed γ rays are close to these energies and are therefore assigned as transitions between the (4_1^+) and (2_1^+) levels of ^{158,160}Nd, respectively. Analogous comparisons with the energies of transitions in ^{152,154,156}Nd allowed the 233.4-keV γ ray to be assigned to the $(6_1^+) \rightarrow (4_1^+)$ decay of ^{158}Nd and the weak 65.2-keV transition to the $2_1^+ \rightarrow 0_1^+$ γ ray of ^{160}Nd. A delayed γ-ray transition with an energy of ~65 keV was not observed in coincidence with ^{158}Nd ions in the present experiment and its energy is estimated below.

TABLE I. Level energies, γ-ray energies, relative γ-ray intensities, proposed multipolarity, and total decay intensities of delayed cascades in ^{158,160}Nd. The energy labeled by an asterisk * was estimated from the moment of inertia, see text.

Nucleus	Level energy (keV)	E_γ (keV)	I_γ (rel.)	Mult.	I_{tot} (rel.)
^{158}Nd	(65.9*)	65.9(10)*		($E2$)	
	(217.6)	151.7(5)	66(9)	($E2$)	100(10)
	(451.0)	233.4(5)	102(9)	($E2$)	114(9)
	(1648.1)	1197.1(5)	99(12)	($E1$)	99(12)
^{160}Nd	65.2	65.2(5)	7(2)	($E2$)	83(28)
	215.1	149.9(5)	66(5)	($E2$)	100(7)
	1107.9	892.8(5)	97(8)	($E1$)	97(8)

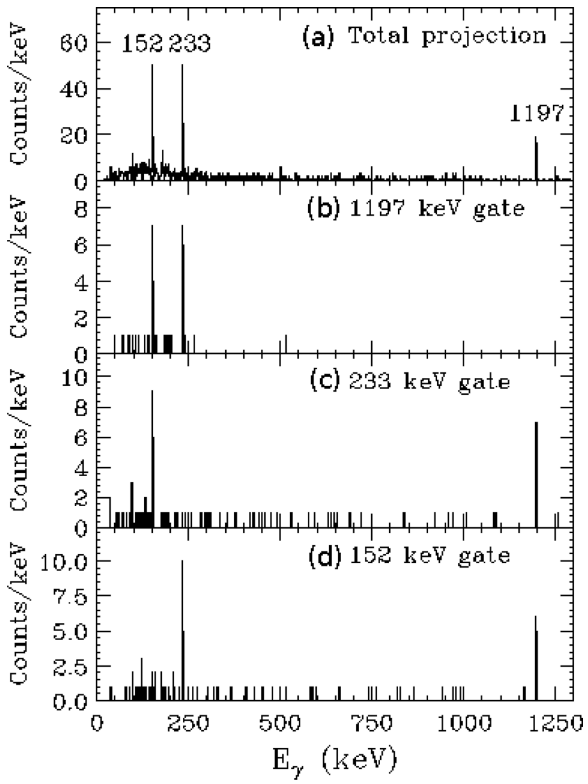

FIG. 2. Delayed γ singles and γ-γ spectra for ^{158}Nd. (a) Total projection, coincidences with (b) 1197-, (c) 233-, and (d) 152-keV γ rays.

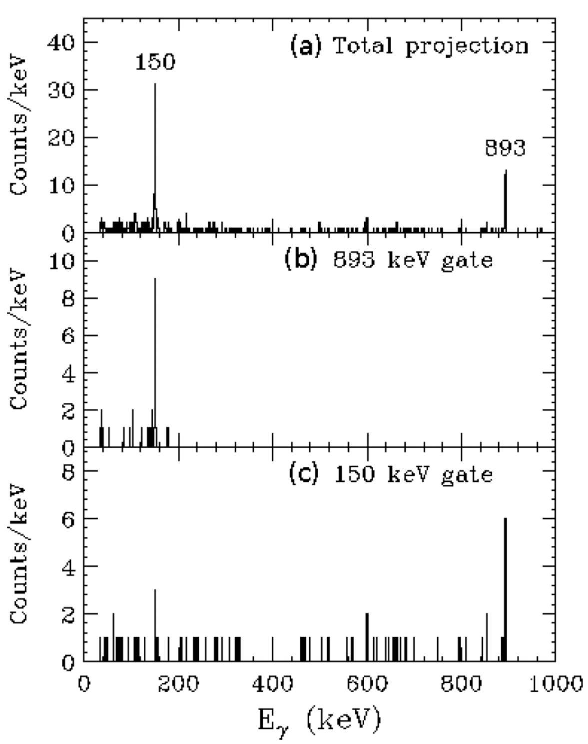

FIG. 3. Delayed γ singles and γ-γ spectra for ^{160}Nd. (a) Total projection, coincidences with (b) 893-, and (c) 150-keV γ rays.

Even though the observed number of counts for the $4_1^+ \rightarrow 2_1^+$ decays are similar for delayed cascades emanating from ^{158,160}Nd the higher background present in coincidence with ^{158}Nd ions, prevents the observation of the $2_1^+ \rightarrow 0_1^+$ transition. The increased background is due to the shorter half-life of the isomer which is on a similar timescale to the prompt flash associated with the arrival of the beam particles.

The energy of the 2_1^+ state of ^{158}Nd can be estimated from an examination of the kinematic moments of inertia, $\mathcal{J}^{(1)} = \hbar^2(2I-1)/E_\gamma$, derived from the energies of the $6^+ \rightarrow 4^+$ and $4^+ \rightarrow 2^+$ transitions. These then allow the ground-state rotational band to be quantified in terms of the Harris parameters [16]

$$\mathcal{J}^{(1)} = \mathcal{J}_0 + \mathcal{J}_1\omega^2, \tag{1}$$

where the rotational frequency $\omega = E_\gamma/2$. Values of $\mathcal{J}_0 = 45.4\,\hbar^2\text{MeV}^{-1}$ and $\mathcal{J}_1 = 125.3\,\hbar^2\text{MeV}^{-3}$ are obtained, which can then be used to estimate the energy of the $E(2^+)_1$ state using

$$I = \mathcal{J}_0\omega + \mathcal{J}_1\omega^3 + 1/2. \tag{2}$$

A value of $E(2^+)_1 = 65.9(10)$ keV was derived for ^{158}Nd. The error on this value was estimated using only those of the measured γ-ray energies.

The 1197.1- and 892.8-keV transitions are assigned as decays directly out of 2-qp isomeric states of ^{158,160}Nd, respectively, giving energies for the isomeric states of (1648.1) and 1107.9 keV. These isomer level energies are close to the ones of known 2-qp isomeric states in the neighboring Nd and Sm nuclei [5–7].

The ion-γ time spectra for delayed decays of ^{158,160}Nd, shown in Fig. 4, were obtained by gating on the individual γ transitions listed in Table I of each nucleus. These time spectra were then summed and the results fitted with an exponential-plus-background function. Half-lives of 339(20) ns and 1.63(21) μs were determined for the isomeric states of ^{158,160}Nd, respectively.

IV. DISCUSSION

The data of the present work have allowed the level schemes of ^{158,160}Nd shown in Fig. 5 to be constructed. The 2-qp isomeric states are proposed to decay by hindered $E1$ transitions. Strongly retarded $E1$ γ decays out of low-lying, 2-qp states with $\sim\mu$s lifetimes have been observed in nearly all of the neighboring even-even Sm and Nd nuclei [6–8,17]. The measured ion-γ half-lives, presented in Fig. 4, allow $B(E1)$ values of $4.0(2)\times10^{-10}$ and $2.0(3)\times10^{-10}$ W.u. (Weisskopf units) to be determined for the $E1$ decays out of the isomeric states of ^{158,160}Nd, respectively. These extracted $B(E1)$ values are consistent with the ones of retarded $E1$ transitions decaying out of 2-qp isomers in the neighboring Sm and Nd isotopes, which span the range $9\times10^{-9} \geqslant B(E1) \geqslant 3\times10^{-12}$ W.u. [6–8,17]. The spins of the isomers have been determined to be the same as the states they feed, but with a negative parity assignment, namely (6^-) and (4^-) for ^{158,160}Nd, respectively. The energies of the (8^+) and (6^+) members of the ground-state bands of ^{158,160}Nd can be estimated to be 761 and 445 keV, respectively, using Eq. (2). If hypothetical

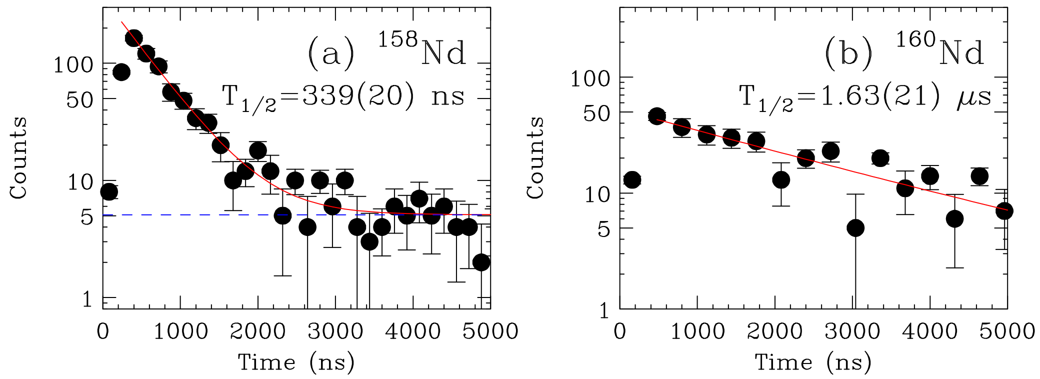

FIG. 4. Time spectra of ion-γ coincidences for nuclei of (a) ^{158}Nd, (b) ^{160}Nd.

887- and 663-keV $E1$ transitions to the (8^+) and (6^+) states of ^{158,160}Nd, respectively, have the same $B(E1)$ values as the ones determined above, then peaks containing around 70 and 90 counts would be expected to be visible in Fig. 1. As these peaks are not present in any of Figs. 1–3 then spins of (7^-) and (5^-) can likely be excluded for the isomeric states of ^{158,160}Nd, respectively.

The configurations of the isomeric states of ^{158,160}Nd have been assigned with the aid of blocked-BCS (BBCS) calculations [18], using typical pairing strengths of $G_\pi = 21.0$ A MeV and $G_\nu = 20.0$ A MeV [18]. Quadrupole deformations of $\epsilon_2 = 0.32$ were used for both isotopes and hexadecapole ones of $\epsilon_4 = -0.040$ and -0.027 for ^{158,160}Nd, respectively. The same deformations have been used in project shell-model calculations of these nuclei [19].

For ^{158}Nd, the BBCS calculations predict a $K^\pi = 6^-$ state as the lowest lying 2-qp neutron excitation, at 1.42 MeV, with a $K^\pi = 7^-$ 2-qp proton one just below it. These two 2-qp states are the only ones with spins close to that of the isomer calculated below an energy of 2.1 MeV. The $K^\pi = 7^-$ level has a main $\pi 5/2[532]\pi 9/2[404]$ configuration which is energetically unfavored, according to the residual spin-spin coupling rule. Typically 200 keV is added to the energy of such states [9], placing it above the $K^\pi = 6^-$ level. The $K^\pi = 6^-$ state has a $\nu 5/2[523] \otimes \nu 7/2[633]$ configuration and is assigned to the (6^-) isomer at (1648.1) keV in ^{158}Nd. Recently reported (6^-) isomeric levels at 1416.6 keV in ^{164}Sm and 1601.4 keV in ^{166}Gd have the same configuration [17]. It has been shown that the presence of ϵ_6 deformation can modify the energies of 2-qp states by as much as 250 keV [9]. As ϵ_6 deformation is predicted to be significant in ^{158}Nd [20] and cannot be included in current BBCS calculations, then this may explain the difference between the calculated and experimental energies.

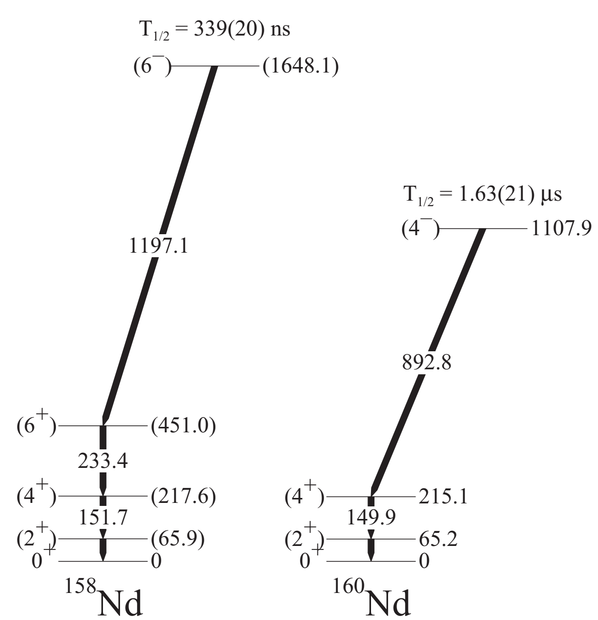

FIG. 5. Decay schemes of ^{158,160}Nd obtained from the present experiment.

In the case of ^{160}Nd the only 2-qp states predicted below an energy of 1.5 MeV have spins of the 4^- and 7^-. The former has a main $\nu 1/2[521] \otimes \nu 7/2[633]$ configuration and is calculated at an energy of 1.07 MeV, in good agreement with the experimental results.

Isomeric states with a 2-qp nature have been predicted in ^{158,160}Nd by both projected shell-model (PSM) [19] and deformed Hartree-Fock (HF) calculations. For ^{158}Nd the PSM predicts a 4^- 2-qp at an energy of $\sim$1.2 MeV, whereas a 4^- 2-qp isomeric state at 2.0 MeV, with a $\pi 3/2[541] \otimes \pi 5/2[413]$ configuration is calculated by HF. Both of these are incompatible with the experimentally observed γ-decay pattern. In the case of ^{160}Nd the PSM places the lowest 2-qp state at around 1.2 MeV, with a main $\nu 1/2[521] \otimes \nu 7/2[633]$ configuration, in agreement with the present work. The HF calculations predict a 4^- 2-qp isomeric state, with a $\pi 3/2[541] \otimes \pi 5/2[413]$ configuration, though at an energy of 700 keV. The variation of these these theoretical predictions shows the need for experimental data in this region.

The assignment of the $\nu 5/2[523]$ orbital as a main component of the $K^\pi = 6^-$ isomer of ^{158}Nd has potential significance for r-process calculations. The ground states of ^{155,157}Pm have been assigned a $\pi 5/2[532]$ configuration [21] and this orbital is expected to be low-lying in the more neutron-rich Pm isotopes, which are experimentally unknown. Both the $\nu 5/2[523]$ and $\pi 5/2[532]$ orbitals have a spherical $h_{9/2}$ origin allowing a Gamow-Teller transition between them, reducing the half-lives of parent nuclei. Until the half-lives and ground-state spins of the the parent and daughter nuclei have been experimentally determined this proposition remains speculative, though the data presented in the current work may provide first evidence for this mechanism.

V. CONCLUSION

In summary, delayed γ-ray spectroscopy has allowed excited states in the nuclei ^{158,160}Nd to be observed for the first time. These nuclei have 2-qp isomeric states with spins of (6^-) and (4^-) and have been assigned respective $\nu 5/2[523] \otimes \nu 7/2[633]$ and $\nu 1/2[521] \otimes \nu 7/2[633]$ configurations from a comparison with the results of BBCS calculations. PSM and HF calculations for ^{158}Nd predict 4^- 2-qp isomeric states, which are incompatible with the observed decay scheme, showing the need for experimental data in this region.

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