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Identification of possible proton two-quasiparticle band in ^{158}Sm

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High-spin states in neutron-rich ^{158}Sm have been reinvestigated by measuring the prompt γ-rays emitted in the spontaneous fission of ^{252}Cf. A new negative-parity band has been established up to spin 12. By comparing with the theoretical calculations, a two-quasiparticle state with $\pi5/2[532] \otimes \pi5/2[413]$ configuration has been proposed for the band head. The systematics of the two-quasiparticle states and bands in this region are discussed.

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The neutron-rich nuclei with A$\geq$150 change discretely from spherical to large stable prolate deformed shapes as A increases. Static octupole deformation centered around Z=58 and N=88 also occurs in this region. In these well-deformed nuclei, multi-quasiparticle (qp) K-isomeric structures appear systematically. This kind of structure of qp states and the rotational bands built on them are of current interest. Historically, two qp states in ^{156,158,160}Sm and ^{152,154,156}Nd have been studied by γ-ray spectroscopy following β-decay [1, 2] and spontaneous and induced fission [3–7]. Lifetimes have been measured for some qp states and physical quantities have been compared systematically for the rotational bands built on them. A two qp state with $\nu5/2[642]\otimes\nu5/2[523]$ configuration was found in ^{158}Sm [6]. A rotational negative parity band was established up to 18^-. In this paper, we compare new analysis of ^{158}Sm and theoretical calculation to give evidence for a proton two qp band close in energy to the neutron two qp level as theoretically predicted [5, 8].

The experiment with ^{252}Cf was carried out at the Lawrence Berkeley National Laboratory. A 62 μCi ^{252}Cf source was sandwiched between two Fe foils of thickness 10mg/cm^2. By using 101 Ge detectors of Gammasphere, the data were sorted into 5.7×10^{11} γ-γ-γ and higher fold γ events and 1.9×10^{11} γ-γ-γ-γ and higher fold γ coincident events. These γ coincident data were analyzed by the RADWARE software package [9]. Gamma-ray energies of the strong transitions have errors of 0.1 keV while the errors on the weak transitions could be as much as to 0.5 keV. The details of the experimental techniques can be found in Refs. [10, 11].

The partial level scheme of ^{158}Sm obtained in the present work is shown in Fig. 1. Three bands are labeled on top with numbers (1),(2),(3). We only show the levels of the yrast band (1) up to 498.4 keV because we mainly discuss the structure of the negative parity bands in this paper. In the earlier experiments on the prompt γ-rays from the spontaneous fission of ^{252}Cf, band (1) was established [12, 13] and expanded [3, 6] to spin 16^+. In this work, we have confirmed all the previously observed transitions and a new 692.7 keV γ transition has been found to feed the 16^+ level. The 1279 keV bandhead of band (2) was identified by Zhu *et al.* [3] with three possible M1 transitions on top. Simpson *et al.* [6] expanded this band up to 4098 keV (18^-) level with 16 γ-ray transitions. Gauthein *et al.* [5] measured the half life of the 1279 keV (5^-) level by using the delayed γ-ray spectroscopy of ^{252}Cf SF fragments. The value obtained was 115ns. Simpson *et al.* [6] used a similar technique which gave a half life of 83(12)ns. Lately, our group measured this half life with a 72(6)ns value [14]. Based on theoretical calculation [5, 6, 8, 15], this level was assigned to 5^- with a $\nu5/2[642] \otimes \nu5/2[523]$ configuration. Note that Simpson *et al.* identified a second 5^- and 7^- level band in ^{156}Sm in their Fig. 9 [6].

All the levels and transitions in band (3) are newly identified in the present work. In contrast to band (2), only one interband transition between band (3) and band (1) has been found. However, because of the high contamination in the low energy region, we are not able to measure the lifetime of the new 1322.3 keV state.

Fig. 2 a) shows a coincidence spectrum double gated on the 167.5 and 707.1 keV transition in ^{90}Kr (4n channel) fission partner. In this gate, we focus on the high energy region. One can see the 771.4, 799.3, 1022.5, 1043.4, 1056.9, 1123.2 keV γ-ray transitions in ^{90}Kr. These transitions are all correlated with the 707.1 keV one. The new 1082.0 keV transition is labeled with an asterisk in this gate. The peak height is about 1/3 of the 1039.5 one established earlier. This peak is not observed in the 258.1 and 707.1 keV double gate, which means this 1082.0 keV γ-ray transition directly feeds the 240.3 keV level. Fig. 2 b) shows a coincidence spectrum double gated on the 167.5 and 1082.0 keV transition. In this gate, we focus on the low energy region. In addition

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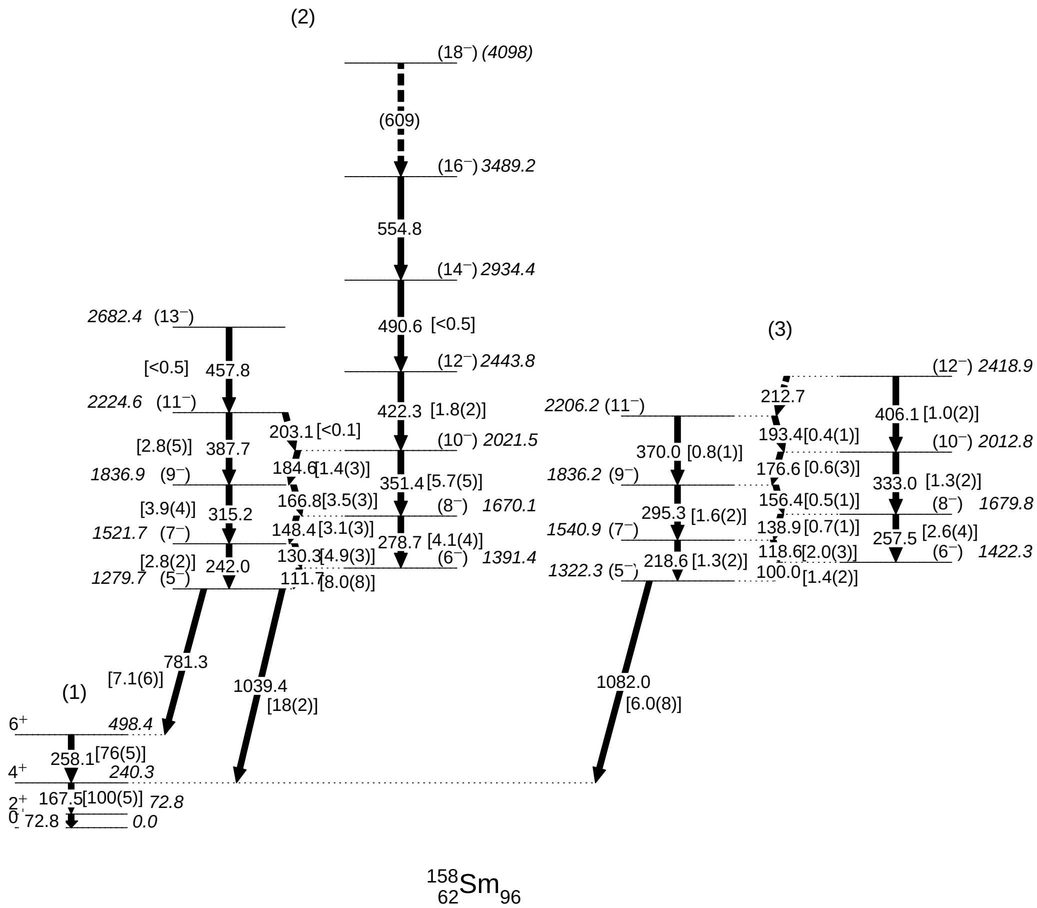

FIG. 1. The level scheme of ^{158}Sm in the present work. Band (2) from Ref. [6] is included for comparison.

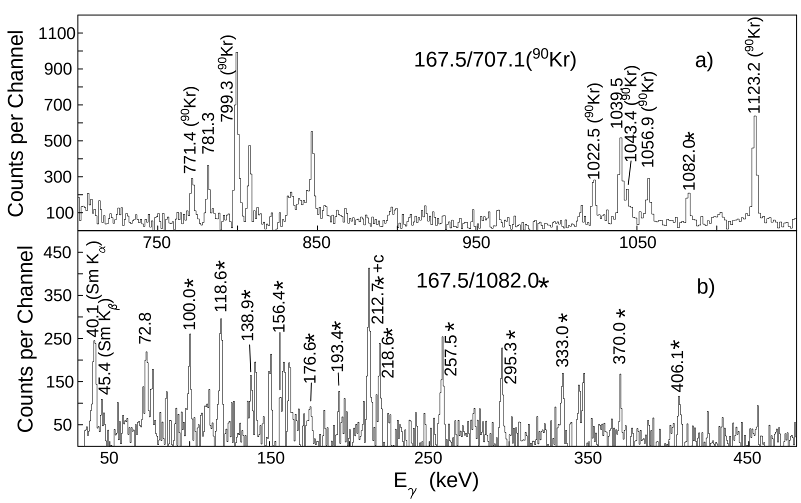

FIG. 2. Partial γ-ray coincidence spectrum a) by gating on 167.5 keV transitions in ^{158}Sm and 707.1 keV transition in ^{90}Kr fission partner, and (b) by gating on 167.5 and 1082.0 keV transitions in ^{158}Sm from ^{252}Cf SF data. The 212.7 keV transition has a strong contaminated component.

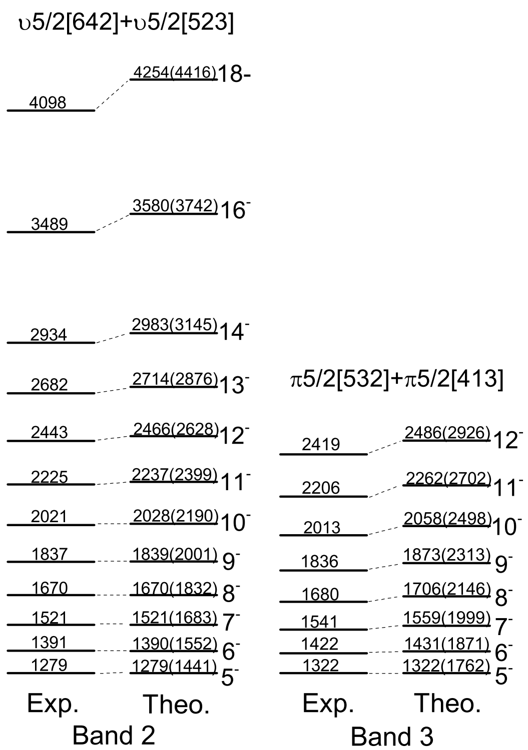

FIG. 3. Comparison of the level energies for ^{158}Sm with theoretical calculation. The band head energies have been taken as references.

to the known γ-ray at 72.8 keV in ^{158}Sm and the 40.1 and 45.4 keV x-ray in Sm element, new γ-ray transitions at 100.0, 118.6, 138.9, 156.4, 176.6, 193.4, 212.7, 218.6, 257.5, 295.3, 330.0, 370.0, 406.1 keV are observed. The 212.7 keV peak has some unknown strong contamination which makes the intensity larger than the others. The 257.5 keV peak may also contain some contamination of 258.1 keV yrast transition from the background of 167.5 keV.

Transition intensities and their errors in the new band (3) are labeled with parentheses in Fig. 1. The intensities of 167.5 and 258.1 keV γ-rays in the yrast band and 781.3 and 1039.4 keV interband γ-rays from band (2) to band (1) as well as those in band (2) observed in Ref. [6] are also remeasured for comparison. Internal conversion electrons are included to correct the intensities in the yrast band but not for the negative parity bands. We note that the intensity of the 1039.4 keV γ-ray measured in the previous work (6.1) [3] is significantly different from the current work (18). The reason might be the statistics, since the previous experiment [3] only collected two orders of magnitude fewer triple γ coincidence events compared to the current work.

The possible transition from the 1322.3 keV band-head level to the 6^+ level is not observed. Thus, if only the decay pattern is considered, this level could have 3^-, 4^-, 2^+ or 3^+ spin and parity rather than 5^-. Gautherin *et al.* [5] made a Hartree-Fock-Bogoliubov (HFB) calculation to predict the two lowest proton and neutron 2qp states at 1.3∼1.4 MeV(less than 100 keV separation) with $\nu 5/2[642] \otimes \nu 5/2[523]$ and $\pi 5/2[532] \otimes \pi 5/2[413]$ configurations, respectively. Simpson *et al.* [6] predicted the proton 5^- 2qp state at an energy 346 keV higher than the neutron 5^- 2qp state using the quasiparticle plus rotor model (QPRM). Yang *et al.* [8] calculated the rotational bands on these two configurations with the projected shell model (PSM) method. The results are shown in Fig 3. For comparison we have normalized the theoretical band head energies to the experimental ones. For the new band (3), considerable deviations are seen between the experimental excitations and the theoretical calculations, while in the case of band (2), deviations are relatively smaller. These deviations between the experiment and the theory in bands (2) and (3) are both within the errors of the theoretical calculations. Despite the band head energies, the rotational bands are well reproduced by the calculation. Thus, the 1322 keV level is tentatively assigned to 5^- in the current work based on this agreement. The intraband transition energies in band (3) are similar to those in band (2) and in other rotational bands built on 5^- 2qp states in ^{156}Nd and ^{156}Sm (almost identical to ^{156}Nd).

In conclusion, high-spin states of neutron-rich ^{158}Sm have been reinvestigated. A new band has been observed and compared to the known ones. The new level energies have been compared with theoretical calculations. The band head has been tentatively assigned to a 5^- proton two qp state with a $\pi 5/2[532] \otimes \pi 5/2[413]$ configuration.

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[1] M. Hellström *et al.*, Phys. Rev. C **46**, 860 (1992).
[2] M. Hellström *et al.*, Phys. Rev. C **47**, 545 (1993).
[3] S. J. Zhu *et al.*, J. Phys. G **21**, L57 (1995).
[4] X. Q. Zhang *et al.*, Phys. Rev. C **57**, 2040 (1998).
[5] C. Gautherin *et al.*, Eur. Phys. J. A **1**, 391 (1998).
[6] G. S. Simpson *et al.*, Phys. Rev. C **80**, 024304 (2009).
[7] E. Y. Yeoh *et al.*, Eur. Phys. J. A **45**, 147 (2010).
[8] Y-C Yang *et al.*, J. Phys. G: Nucl. Part. Phys. **37**, 085110 (2010).
[9] D. C. Radford, Nucl. Instrum. Methods Phys. Res. A

361, 297(1995).
[10] J. H. Hamilton *et al.*, Prog. Part. Nucl. Phys. **35**, 635 (1995).
[11] Y.X. Luo *et al.*, Phys. Rev. C **64**, 054306 (2001).
[12] J. B. Wilhelmy *et al.*, Phys. Rev. Lett. **25**, 1122 (1970).
[13] E. Chiefetz *et al.*, Phys. Rev. C **4**, 1913 (1971).
[14] N. T. Brewer *et al.*, Nuclear structure 2012; 5th Int. Conf. on "**Fission and properties of neutron-rich nuclei, Sanibel 2012**", eds. J. H. Hamiltom & A. V. Ramayya, World Scientific, 2013.
[15] R. Bengtsson *et al.*, At. Data Nucl. Data Tables **35**, 15 (1986).