Nuclear structure of the odd-odd $N = 85$ neutron-rich nucleus ^{140}Cs

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High-spin excited states in the neutron-rich nucleus ^{140}Cs were re-investigated from the spontaneous fission of ^{252}Cf with the Gammasphere detector array. Seven new transitions at low and moderate spin and 13 at high spin were observed in ^{140}Cs and the level scheme of ^{140}Cs was extended to 3794 keV with a new sideband. Spins and parities were assigned to levels based on angular correlation measurements and the systematics in the $N = 85$ isotones.

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The odd-odd neutron-rich nucleus ^{140}Cs ($Z = 55$, $N = 85$) has three neutrons outside the $N = 82$ closed shell and is close to the octupole deformation region centered on $Z = 56$, $N = 88$ [1–5]. The β decay [6] and fission of ^{252}Cf [7] were used to populate excited states in ^{140}Cs. Many transitions at low excitation energy were observed in the β decay of ^{140}Xe [6]. A few high-spin levels were identified in the spontaneous fission of ^{252}Cf by Hwang *et al.* [7]. In this work, we report a new level scheme of ^{140}Cs based on the results of Hwang *et al.* with seven new transitions at low and moderate spin and 13 at high spin. The new structure may be related to octupole excitations.

Data for the present work were obtained by using the Gammasphere detector array with 101 detectors at Lawrence Berkeley National Laboratory. A ^{252}Cf spontaneous fission source of a 62 μCi α activity was placed between two 10 mg/cm^2 Fe foils. A total of 5.7×10^{11} triple and higher fold γ-ray coincidence events were collected. Data were analyzed with the RADWARE software package [8]. A newly developed technique for measuring angular correlations with the Gammasphere detector array by sorting our high statistics data into 17 angle bins was used here to assign spins and parities to excited states in ^{140}Cs. More details of this technique can be found in Ref. [9].

The level scheme of ^{140}Cs proposed by Hwang *et al.* [7] was solely based on the observation of the 80.1 keV transition, which was also found in the previous β-decay studies [6]. Here, a measurement was performed to firmly determine the mass number of the transitions in Ref. [7], as used in our recent reports [10,11]. In the 595.5/475.2 keV (^{139}Cs) [10], 594.6/640.9 keV (^{140}Cs) [7], 369.5/481.0 keV (^{141}Cs) [7], and 205.4/404.7 keV (^{142}Cs) [7] double gates, the fission yield ratios of the 292.6 keV transition in ^{107}Tc [7,12,13] to the 154.1 keV transition in ^{108}Tc [7,14] were measured to be 0.10(1), 0.16(2), 0.31(4), and 0.47(7), respectively. The variations of these ratios follows those of similar ratios of ^{105}Mo to ^{106}Mo in $^{141-144}$Ba double gates [6], which confirms that the mass number for the 640.9 → 594.6 keV cascade is 140.

The level scheme of ^{140}Cs reported in Ref. [7] is extended with a sideband in the present work. One coincidence spectrum, created by double gating on the 80.1 and 563.5 keV transitions [7], is shown in Fig. 1. In addition to the previously observed transitions in Tc isotopes [7,12–15] and ^{140}Cs [7], one sees five new transitions of energies 35.5, 54.8, 90.3, 551.2, and 552.6 keV, the latter two forming a doublet peak in Fig. 1. To further confirm the existence and positions of the above five new transitions, two spectra were obtained, as presented in Fig. 2, where the gate transitions are indicated as well. Figure 2(a), gated on the known 594.3 and 640.9 keV transitions in ^{140}Cs in Ref. [7], shows the coincidence relationship among the known transitions in ^{107,108,109}Tc [7,12–14], ^{140}Cs [7], and the newly observed transitions, for example, the 35.5, 54.8, 90.3, 472.5, and 702.2 keV transitions. The spectrum, gated on the new 551.2 in Fig. 1 and known 563.6 keV transitions in Ref. [7], is given in Fig. 2(b), where the newly identified transitions of energies 35.5, 552.6, 652.6, and 876.5 keV are seen. Note that the new 54.8 keV transition seen in Fig. 2(a) is not found in Fig. 2(b). This observation is very important for us to place newly observed transitions in the level scheme. All of the new transitions are marked with an asterisk in the above spectra. Careful cross checking of numerous coincidence spectra leads to the final transition identifications and placements in the ^{140}Cs nucleus. Eight new excited levels with 13 new de-exciting transitions at high spin and three new excited levels with seven new de-exciting transitions at low and moderate spin are observed in the present work. The level scheme established here is presented in Fig. 3, where excited states are extended up to 3794 keV with a new sideband (band 3).

Angular correlations were measured for some strong transitions in Fig. 3 by using the method described in Ref. [9]. This method was successful in assigning spins and parities in ^{134}I and ^{139}Cs in our recent reports [10,11]. The measured A_2 and A_4 values are 0.096(17) and −0.005(25) for the 640.9 → 594.3 keV cascade and −0.087(28) and −0.005(42) for the 454.7 → 594.3 keV cascade, respectively, which are consistent with the theory of $\Delta I = 2$ character for the 594.3 and 640.9 keV transitions and $\Delta I = 1$ character for the 454.7 keV transition [16]. We argue that the 594.3 and

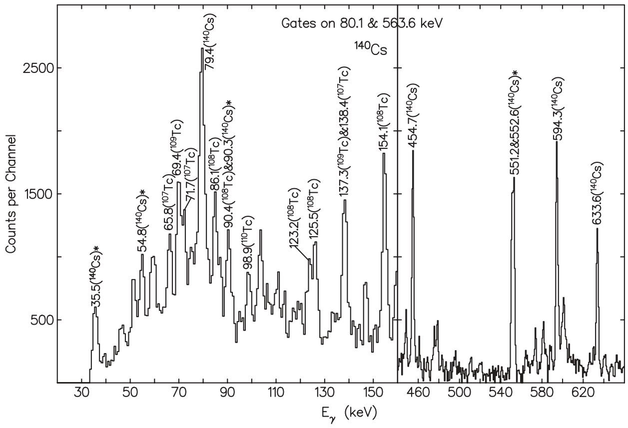

FIG. 1. Coincidence spectra gated on the 80.1 and 563.5 keV transitions [7]. The new transitions are marked with an asterisk.

640.9 keV transitions have a stretched $E2$ multipolarity, as commonly observed in fission products. From its mixing ratio as $0.07^{+0.14}_{-0.13}$ or $4.4^{+6.0}_{-1.8}$ [17], the 454.7 keV transition can be $E2$, $M1$, or $E1$. Based on the spin-parity assignments of levels in ^{138}I [18], an $N = 85$ isotone having a very similar structure to ^{140}Cs, we suggest that band 1 and 2 have the same parity, which yields an essentially $E2$ or $M1$ multiporlarity for the 454.7 keV transition. Consequently, other cascade transitions in bands 1 and 2 are proposed to be stretched $E2$, whereas the linking transitions are $E2 + M1$. This will make the multipolarity of the 54.8 keV transition as $M1 + E2$. However, since $\alpha_T \approx 17$ for this 54.8 keV transition [19], it must be essentially $M1$. As will be discussed in the following, the very probable I^π assignments for the 249.7 and 194.9 keV levels are 7^- and 6^-, respectively. A further comparison of the level patterns of ^{138}I and ^{140}Cs, as discussed in the following, allows us to assign spin parity to other low-lying levels. Spins are assigned to levels in band 3, assuming that the 702.2, 472.5, and 308.1 keV transitions are of $\Delta I = 1$ character and the cascade transitions are of a $\Delta I = 2$ nature. For the remaining three levels, their spins and parities cannot be assigned from the present experimental data. No further discussion is in order.

High-spin states were observed in odd-odd $N = 85$ isotones, such as ^{138}I ($Z = 53$), ^{146}Pm ($Z = 61$), and ^{148}Eu ($Z = 63$), in which high-spin levels are built on the (3^-), 9^+, and 9^+ isomers, respectively [18,20,21]. In the latter two nuclei, levels in the $13^+ \rightarrow 11^+ \rightarrow 9^+$ cascade are members of the $\pi(1h_{11/2})\pi(2d_{5/2})_0^{-2}\nu(2f_{7/2})^3_{7/2,11/2,15/2}$ multiplet, whereas those in the $14^+ \rightarrow 12^+ \rightarrow 10^+$ cascade are members of the $\pi(1h_{11/2})\pi(2d_{5/2})_0^{-2}\nu(1h_{9/2})\nu(2f_{7/2})^2_{0,2,4}$ multiplet. These two cascades are connected by $\Delta I = 1$ $(M1 + E2)$ linking transitions. ^{138}I also has two $\Delta I = 2$ cascades, $(11^-) \rightarrow (9^-) \rightarrow (7^-)$ and $(12^-) \rightarrow (10^-) \rightarrow (8^-) \rightarrow (6^-)$, connected by $\Delta I = 1$ $(M1 + E2)$ transitions [18]. The (6^-) and (7^-) in ^{138}I were interpreted as members of the $[\pi(g_{7/2})\nu(f_{7/2})]_j$ multiplet in semi-empirical calculations in Ref. [18], though the $\pi d_{5/2}$ orbital may significantly contribute to the wave functions of the levels in the $(12^-) \rightarrow (10^-) \rightarrow (8^-) \rightarrow (6^-)$ cascade in the shell-model calculations [18]. It is very interesting that the (7^-) (at $X + 295$ keV) level in ^{138}I is populated by the (9^-) and (8^-) levels and populates the (6^-) (at $X + 229$ keV) level by the 631.1, 360.1, and 65.6 keV transitions, respectively. The level at 249.7 keV in ^{140}Cs is quite similar to this (7^-) level in ^{138}I, connected to the 844.0, 746.1, and 194.9 keV levels by the 594.3, 496.4, and 54.8 keV

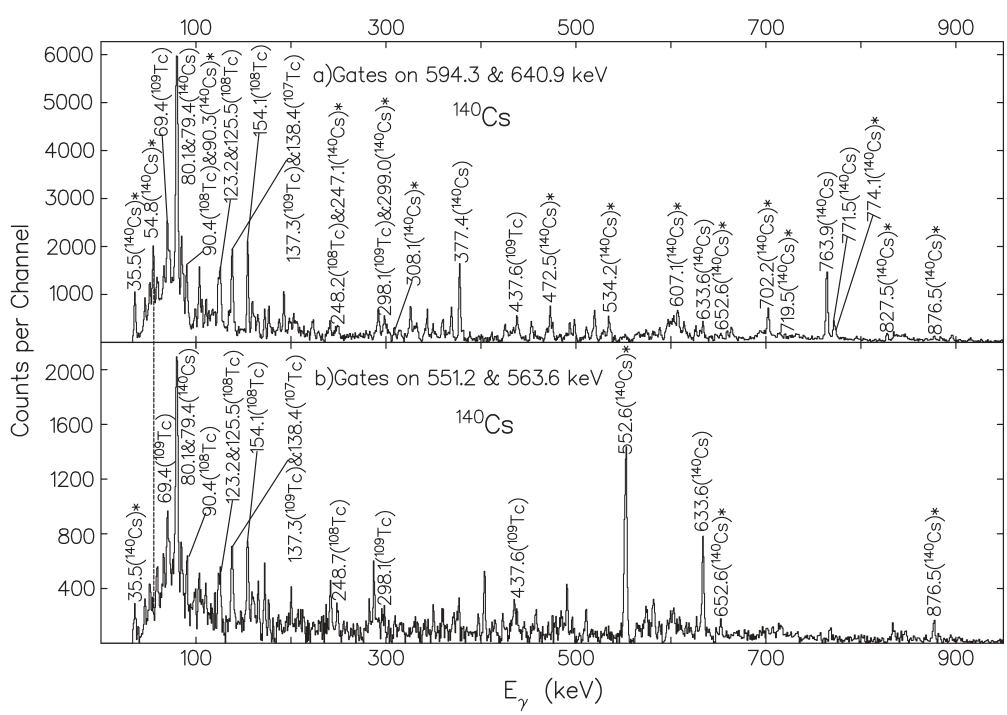

FIG. 2. Coincidence spectra gated on transitions in ^{140}Cs. The newly identified transitions are marked with an asterisk. A dashed line is drawn to illuminate the position of the 54.8 keV transition, which is not seen in (b).

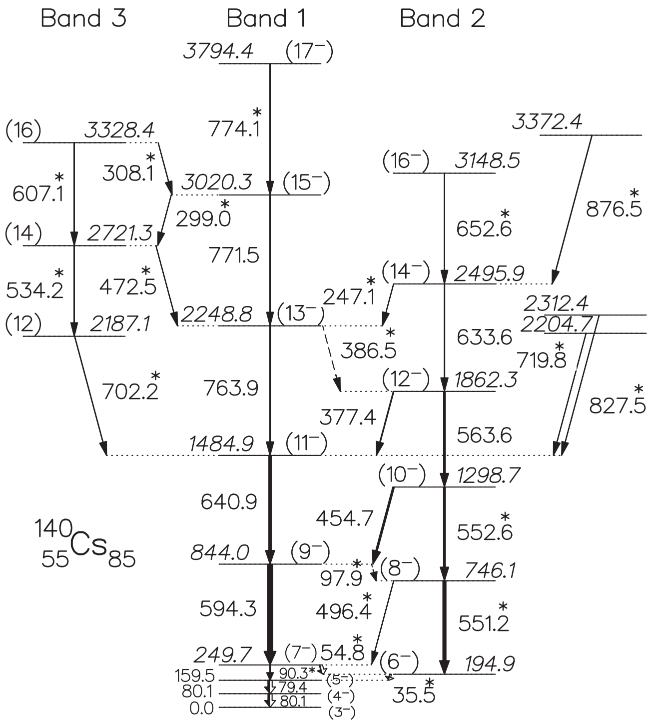

FIG. 3. Level scheme of ^{140}Cs built in the present work. The newly observed transitions are marked with an asterisk. Spins and parities of levels are tentatively assigned in the present work. See text for details.

transitions, respectively, as shown in Fig. 3. This remarkable similarity helps us in assigning spin parities and configurations to levels in ^{140}Cs. As shown in Fig. 4, where high-spin levels built on the (7^-) level (at $X + 229$ keV) in ^{138}I and the 249.7 keV level in ^{140}Cs are compared, one sees that the high-spin level pattern of band 1 and 2 in ^{140}Cs bears a remarkable resemblance to that in ^{138}I. So, it is reasonable to assign (7^-) to the 249.7 keV level. Since no isomer like the $11/2^-$ level in ^{145}Pm and ^{147}Eu was identified in ^{139}Cs, the 249.7 keV level cannot be an isomeric state, like the 9^+ and 9^+ isomeric states in ^{146}Pm and ^{148}Eu on which high-spin states are built, respectively. The same conclusion

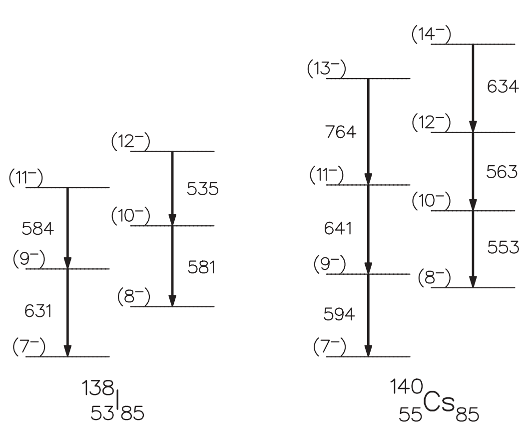

FIG. 4. High-spin levels built on the (7^-) level in ^{140}Cs and ^{138}I. Data are taken from the present work and Ref. [18].

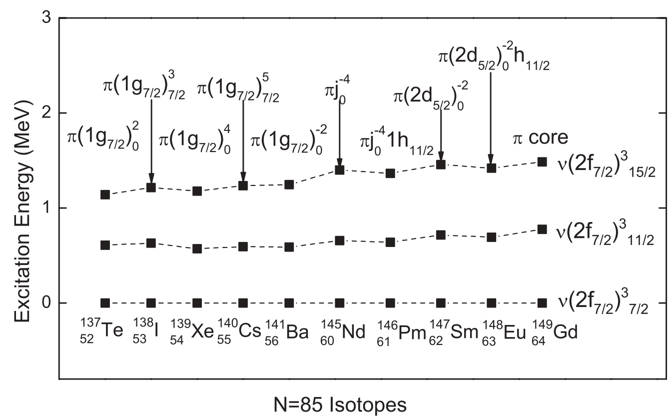

FIG. 5. Comparison of $\nu(2f_{7/2})^3_{7/2}$ states in $N = 85$ isotones. Experimental energies are given relative to the lowest state drawn in the figure. $[(2d_{5/2})_0^{-4} + (2d_{5/2})_0^{-2}(2d_{7/2})_0^{-2}]$ is denoted as j_0^{-4} [20]. Data of other nuclei are taken from Refs. [18,20,22,23].

can be drawn in ^{138}I and is supported by the observation and calculations done in Ref. [18] because one has not observed an isomeric state at high spin in ^{137}I either [10]. Therefore, we may argue that the 249.7 keV level has a $\pi(1g_{7/2})^5_{7/2}\nu(2f_{7/2})^3_{7/2}$ configuration, from the coupling of the $7/2^+$ ground state of ^{139}Cs [10] with the $7/2^-$ state in ^{139}Xe. (This level, 22.8 keV above the $3/2^-$ ground state, is one member of the $\nu(2f_{7/2})^3_{3/2,5/2,7/2}$ multiplet, which is a common feature of the $N = 85$ even-odd nuclei. High-spin states in ^{139}Xe are built on this level [22].) The systematics of levels in even-odd and odd-odd $N = 85$ isotones, presented in Fig. 5, supports such an argument. If one considers the maximum aligned coupling of the $7/2^+$ ground state of ^{139}Cs [10] with the $7/2^-$ state in ^{139}Xe, one will obtain a 7^- spin-parity for the 249.7 keV level in ^{140}Cs, analogous to the (7^-), $X + 295$ keV level in ^{138}I [18]. Then, one may assign $I^\pi = (6^-)$ to the 194.9 keV level, depopulating the (7^-), 249.7 keV level by the 54.8 keV transition, with a stretch-minus-one $(I_{\text{stretch}} - 1)$ configuration by coupling the the $7/2^+$ ground state of ^{139}Cs [10] with the $7/2^-$ state in ^{139}Xe [22]. However, one cannot exclude the possibility that this (6^-) level has a $\pi(1g_{7/2})^5_{7/2}\nu(2f_{7/2})^3_{5/2}$ configuration by coupling the the $7/2^+$ ground state of ^{139}Cs [10] with the $5/2^-$ state in ^{139}Xe [22] from the present analysis. In Fig. 6, a striking similarity of the entire level schemes of ^{140}Cs and ^{138}I up to the (12^-) state is seen to support the previous arguments and the spin-parity assignments to other low-lying states shown in Fig. 3. Therefore, the 0 keV level in ^{140}Cs is mostly likely to be an isomeric state with $I^\pi = (3^-)$ in analogy to the X keV, (3^-) state in ^{138}I. Its isomer character follows from the absence of any transitions to lower levels. The lowest 80.1 keV transition in ^{140}Cs is an $M1 + E2$ transition as the 118.3 keV transition in ^{138}I. The spin-parity assignments to levels in band 1 and 2 in ^{140}Cs based on the systematics of its $N = 85$ isotone ^{138}I in the previous discussion are well born out by the discussion on the systematics of ^{136}I and ^{138}Cs (two $N = 83$ isotones) in Ref. [24]. Of course, care should be taken in giving pure configuration assignments to odd-odd nuclei, especially

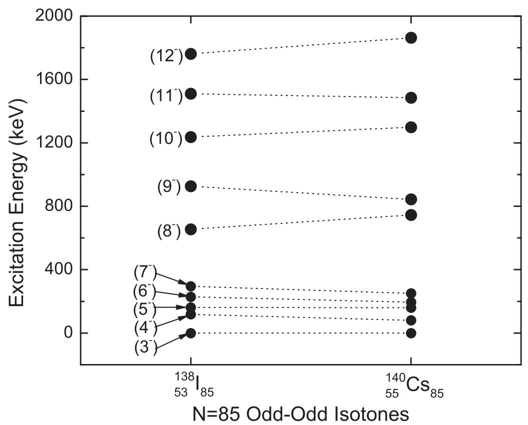

FIG. 6. Comparison of bands 1 and 2 in ^{140}Cs with the corresponding bands in ^{138}I. Excitation energies are given with respect to the 0 and X keV levels in ^{140}Cs and ^{138}I, respectively. Data are taken from the present work and Ref. [18].

ones located in a transitional region between spherical and deformed nuclear shapes. It is also worth mentioning that ^{140}Cs, with two protons more than ^{138}I, shows a more collective level pattern than ^{138}I at high spin, as presented in Fig. 4. The transition energies in ^{140}Cs regularly increase with spin, unlike in ^{138}I, which suggests that the addition of two protons to ^{138}I induces a change toward a collective motion. Thus, shell model calculations may be not feasible to describe the level character of ^{140}Cs. Bands 1 and 2, built on (7^-) and (6^-), respectively, showing features of rotation, are signature partners.

However, it is worth mentioning that the assignment of $I^\pi = (4^-)$ to the 80.1 keV level is not consistent with the spin parity of either 1^- or 0^- for the 80.1 keV level identified in the β decay of ^{140}Xe to ^{140}Cs [6]. Therefore, we propose that the observed 80.1 keV transition in the ^{252}Cf fission is not the one found in β-decay studies [6]. This may be true because often there is no overlap between levels obtained in the spontaneous fission of ^{252}Cf and those with low spin known from the β decay of odd-odd isotopes.

For band 3, we tentatively argue that this band along with band 1 forms a parity doublet because a possible octupole deformation was proposed in the Cs isotopes at $N = 85$–88 in Ref. [25] and such an effect was confirmed in ^{141}Cs [26]. More experimental evidence is required to make a clear conclusion.

In conclusion, the nuclear structure of the odd-odd $N = 85$ nucleus ^{140}Cs was re-investigated from a study of the prompt γ rays emitted in the spontaneous fission of ^{252}Cf with the Gammasphere detector array. A measurement was performed to firmly assign the mass number 140 to the previous known transitions. Eight new excited levels with 13 new de-exciting transitions at high spin and three new excited levels with seven new de-exciting transitions at low and moderate spins are observed to enable us to establish the level scheme of ^{140}Cs up to 3794 keV with a new sideband. Spins and parities of levels in ^{140}Cs are tentatively assigned on the basis of angular correlation measurements and the systematics of $N = 85$ isotones. Configuration assignments were briefly discussed.

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[1] W. Nazarewicz *et al.*, Nucl. Phys. **A429**, 269 (1984).
[2] W. Nazarewicz and P. Olanders, Nucl. Phys. **A441**, 420 (1985).
[3] G. A. Leander *et al.*, Phys. Lett. **B152**, 284 (1985).
[4] W. Nazarewicz and S. L. Tabor, Phys. Rev. C **45**, 2226 (1992).
[5] I. Ahmad and P. A. Butler, Annu. Rev. Nucl. Part. Sci. **43**, 71 (1993).
[6] http://www.nndc.bnl.gov/ensdf/.
[7] J. K. Hwang *et al.*, Phys. Rev. C **57**, 2250 (1998).
[8] D. C. Radford, Nucl. Instrum. Methods Phys. Res. A **361**, 297 (1995).
[9] A. V. Daniel *et al.*, Nucl. Instrum. Methods Phys. Res. B **262**, 399 (2007).
[10] S. H. Liu *et al.*, Phys. Rev. C **79**, 067303 (2009).
[11] S. H. Liu *et al.*, Phys. Rev. C **80**, 044314 (2009).
[12] Y. X. Luo *et al.*, Phys. Rev. C **70**, 044310 (2004).
[13] L. Gu *et al.*, Phys. Rev. C **79**, 054317 (2009).
[14] Q. Xu *et al.*, Phys. Rev. C **78**, 064301 (2008).
[15] Y. X. Luo *et al.*, Phys. Rev. C **74**, 024308 (2006).
[16] H. W. Taylor, B. Singh, F. S. Prato, and R. McPherson, At. Data Nucl. Data Tables A **9**, 1 (1971).
[17] DELTA, ENSDF Analysis Program, http://www.nndc.bnl.gov/.
[18] T. Rząca-Urban *et al.*, Phys. Rev. C **75**, 054319 (2007).
[19] http://www.rsphysse.anu.edu.au/nuclear/bricc/.
[20] T. Rząca-Urban *et al.*, Nucl. Phys. **A588**, 767 (1995), and references therein.
[21] J. R. Jongman *et al.*, Nucl. Phys. **A581**, 165 (1995).
[22] Y. X. Luo *et al.*, Phys. Rev. C **66**, 014305 (2002).
[23] W. Urban *et al.*, Phys. Rev. C **61**, 041301(R) (2000).
[24] T. Rząca-Urban *et al.*, Eur. Phys. J. A **32**, 5 (2007).
[25] R. K. Sheline, A. K. Jain, and K. Jain, Phys. Rev. C **38**, 2952 (1988).
[26] Y. X. Luo *et al.* (accepted in Nucl. Phys. A).