Possible evidence for particle-hole intruder analog multiplets in the Pb region

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(Received 12 July 1993)

It is suggested that collective bands in ^{186,188}Pb built on a 0^+ intruder configuration, belong to a four-particle–four-hole (4p-4h) intruder analog spin $I = 2$ multiplet. The multiplet structure is presented and a suggestion for the energy of the 2p-2h 0^+ intruder bandhead in ^{186,188}Pb is made.

PACS number(s): 21.10.Re, 21.60.Fw

It has become clear in recent years that very near and even at closed-shell configurations excitations of particle-hole (p-h) nature occur at low energies. Because these p-h configurations are expected at a much higher excitation energies, the name "intruder states"' has been introduced. The study of intruder excitations in medium-heavy and heavy nuclei has by now been explored in a very extensive way, in both odd-mass [1] and even-even [2] nuclei.

Given that these intruder excitations and the collective bands built on them are very similar in structure (level spacings, $E2$ transition rates, etc.) to the low-lying collective bands in adjacent nuclei with the same number of active nucleons, an underlying symmetry was suggested by Heyde *et al.* [3]. Treating the multiparticle-multihole (mp-mh) excitations in terms of interacting boson particles [called $\mathrm{U}_p(6)$] and holes [called $\mathrm{U}_h(6)$], the combined group $\mathrm{U}_p(6) \otimes \mathrm{U}_h(6)$ contains most of the dynamics of the total system.

The physics contained in studying the group structure $\mathrm{U}_p(6) \otimes \mathrm{U}_h(6)$ where m particles outside the closed shell can be considered as $\frac{m}{2}$ "particle" bosons (index p) and n holes in the closed shell treated as $\frac{n}{2}$ "hole" bosons (index h) is rather interesting. If the nuclear Hamiltonian describing the interacting system of particle and hole bosons would be fully symmetric under the interchange of particle and hole variables, the nuclear dynamics would be independent of the specific nature of the valence nucleons outside the closed shell. Then, the "particle" and "hole" bosons could be treated on equal footing. Since in a number of nuclei the energy spectra associated with n holes nh, $(n-2)$h-2p, $(n-4)$h-4p,..., np (n particles), i.e., always *changing a hole pair into a particle pair* (or the other way around) are very similar (see, e.g., the 4h ground-state band, the 2p-2h 0^+ intruder band and the 4p ground-state band in Pd, Sn, and Xe nuclei, respectively, with equal neutron number), this particle-hole symmetry seems to hold to a rather good degree. The above idea of transforming a "particle" pair (or boson) into a "hole" pair (or boson) (or the other way around) very closely follows the idea of transforming a proton into a neutron (or a neutron into a proton) related to raising and lowering operators, isospin symmetry, and the use of isospin multiplets. It is now possible to reduce the $\mathrm{U}_p(6)\otimes\mathrm{U}_h(6)$ group such that a spin-1/2 variable, related to the SU(2) group, called "I" spin (from intruder state), explicitly appears. The technical details have been discussed in Ref. [3].

The similarity of the idea of intruder analog states and associated multiplets can be made even more transparent. Characterizing a particle boson by a "spin" $I = 1/2$ and projection $I_z = +1/2$ and a hole boson by "spin" $I = 1/2$ and $I_z = -1/2$, the same algebraic structure is obtained for building multiparticle-multihole configurations as the one which exists for neutron-proton systems composed of fermions (based on isospin or T spin) or bosons (based on F spin, see [4]). So, we obtain the intruder analog or I-spin states as

$$|I, I_z\rangle = \left|\frac{N}{2}, \frac{(N_p - N_h)}{2}\right\rangle \quad . \tag{1}$$

The first tests of this way of classifying various mp-nh configurations were performed in the Sn region [3,5]. In these nuclei, $I = 1$ multiplets contain the regular ground-state bands in even-even Pd and Xe nuclei as well as the proton 2p-2h 0^+ intruder excitation observed in the even-even Sn nuclei [2]. Even though "local" perturbations within the intruder analog classification can occur for certain states [5–11] (in particular at the low-spin 0^+, 2^+ part of the intruder band) a "global" intruder analog symmetry is rather well preserved. Application to the $I = 3/2$ multiplet for ^{110}Ru, ^{114}Cd, ^{118}Te, ^{122}Ba [3] and ^{108}Ru, ^{112}Cd, ^{120}Ba [5] has been performed. There seems a remaining problem with the unambiguous identification of a 0^+ intruder state (and eventual higher band member) in the even-even Te nuclei.

The same idea of trying to classify a number of collective bands, appearing in various nuclei, within a single intruder analog multiplet might be applicable to other mass regions too where 0^+ intruder states have been observed.

Experimental evidence for low-lying bands in ^{186,188}Pb recently obtained by Heese *et al.* [12] make it possible to test the validity of the intruder analog classification in the Pb region too. Until then, evidence for a steady decrease for the lowest-excited 0^+ intruder state in even-even Pb nuclei was made clear by the studies of Van Duppen *et al.* [13–15] but because of the beta-decay feeding, good evidence for a well-developed band structure, and thus of a good test of I spin was missing. Very recently, Nazarewicz made the suggestion [16] that the now observed bands could be due to an $I = 2$ (4p-4h) structure. This would, due to their membership in such an $I = 2$ multiplet, indicate a close similarity with 6h-2p configurations in even-even ^{182,184}Pt nuclei and with the 8h configurations in ^{178,180}W. The connection with a 6h-2p structure in the Pt nuclei indicates that this band would, in general, not be the ground band. In the Pt nuclei the ground-state structure changes at $A = 186$–188 from a narrowly spaced intruder band with a possible 6h-2p configuration, into a more widely spaced band with regular 4h structure for $A \geq 188$ (see also Ref. [2], Fig. 3.26). These band similarities were shown to hold rather well in ^{186}Pb-^{182}Pt and ^{188}Pb-^{184}Pt by comparing corresponding gamma-ray transition energies [16,17]. In order to complete the $I_z = 0, -1, -2$ part one should also consider the ^{178,180}W ground-state bands [18]. The illustration for ^{180}W-^{184}Pt-^{188}Pb is given in Fig. 1. The intruder analog multiplet is "normalized" at the spin $J^\pi = 8^+$ level in order to avoid possible "local" perturbations that are more probable to occur at the lower-spin states (i.e., for the 0^+, 2^+ levels) of the intruder bands in Pt and Pb nuclei. It remains to be seen if similar structures exist in the even-even ^{192}Rn and ^{196}Th nuclei.

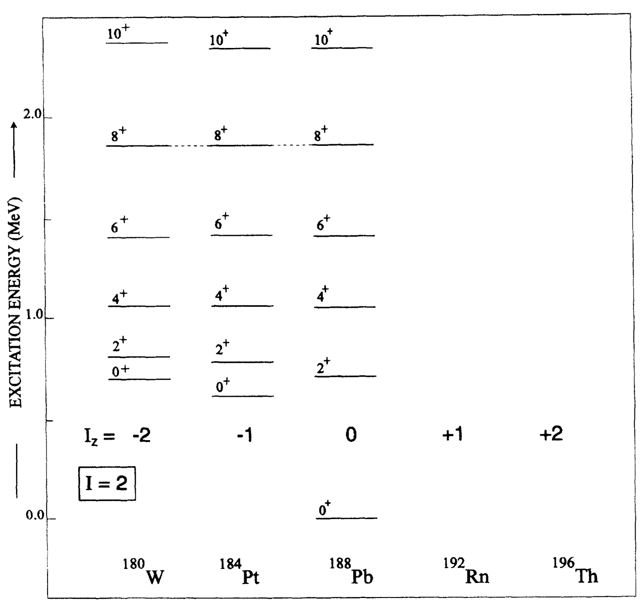

FIG. 1. Suggested members of the $I = 2$ intruder analog multiplet with an 8h (^{180}W) $I_z = -2$, 6h-2p (excited band in ^{184}Pt) $I_z = -1$, and 4p-4h (excited band in ^{188}Pb) $I_z = 0$ structure. The normalization is made at the spin $J^\pi = 8^+$ level. The very neutron deficient isotopes $I_z = +1$ (^{192}Rn) and $I_z = +2$ (^{196}Th) have no known corresponding bands.

If we now use the classification backwards and start from the known 0^+ excitation energies $[E_x(0_2^+) \approx 0.5$ MeV$]$ of the regular 4h band (members of an $I = 1$ multiplet) in the ^{182,184}Pt nuclei, one can estimate for a pure $I = 1$ multiplet the $I_z = 0$ 2p-2h member in the ^{186,188}Pb nuclei. On this basis one expects the 0^+ intruder state in these Pb nuclei to appear at $\Delta E_x \simeq 0.5$ MeV above the 0^+ bandhead observed by Heese *et al.* [12] (Fig. 2). Why in some Pb nuclei the 4p-4h states occur below the 2p-2h states still needs to be explained.

This classification implies that for Pt nuclei with mass number $A \geq 188$ (where the 4h structure becomes lowest), the equivalence with the band structure associated with the 2p-2h intruder states in Pb should result in a significantly wider band spacing. Because of the scarce amount of data on collective bands in $^{190-196}$Pb this is not easily verified but a detailed analysis of band mixing seems to support a wide band spacing in these Pb nuclei [13–15].

In conclusion, it is shown that a new classification of multiparticle-multihole intruder excitations near closed shells, based on the concept of an intruder analog I spin, can be used to classify various bands in the Pb region as members of an $I = 2$ multiplet. In this interpretation the lowest intruder configuration in the nuclei ^{186,188}Pb has 4p-4h character and constitutes the $I_z = 0$ member of the $I = 2$ multiplet. Using the known relative spacing between the $I = 1$ (2p-2h) and $I = 2$ (4p-4h) bands in ^{182,184}Pt ($I_z = -1$), a prediction is made of the excitation energy of the 2p-2h band in ^{186,188}Pb ($I_z = 0$).

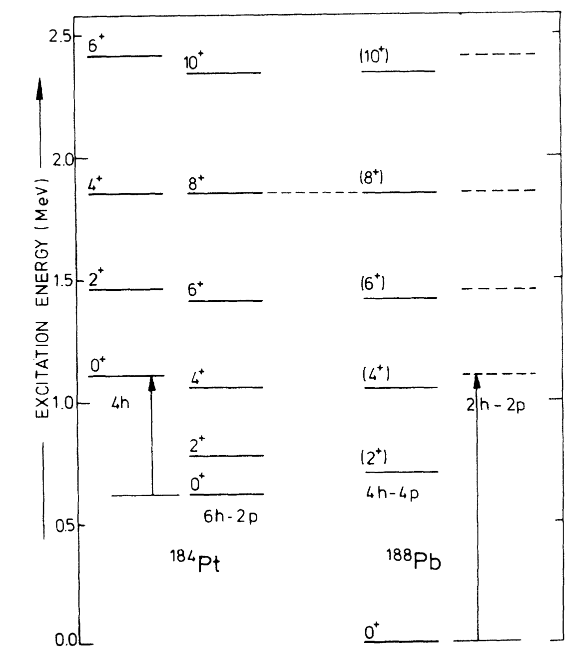

FIG. 2. Comparison of the $N = 106$ ^{188}Pb and ^{184}Pt collective bands. The bands are suggested as members of an $I = 2$ intruder analog multiplet and are normalized at spin $J^\pi = 8^+$. From the excitation energy of the less deformed 4h band in ^{184}Pt, an energy for the related multiplet member $I = 1$, $I_z = 0$ in ^{188}Pb is suggested (dashed lines on the extreme right side of the figure).

One of the authors (K.H.) is grateful to G. Dracoulis and S. Kuyacak for stimulating discussion and use of data on the neutron-deficient W nuclei prior to publication. He would like to thank B. Robson from ANU, Canberra, where the present manuscript was finished. The authors are grateful to R. F. Casten and J. Jolie for discussions. This research was supported by U.S. Department of Energy Grant No. DE-FG05-87ER 40330 and partly by a NATO Research Grant No. NATO RG 92/0011 and a British Council Exchange Grant. K.H. would also like to thank the NFWO and IIKW for financial support and P.V.I. acknowledges support by the Science and Engineering Board.

[1] K. Heyde, P. Van Isacker, M. Waroquier, J.L. Wood, and R.A. Meyer, Phys. Rep. **102**, 291 (1983).

[2] J.L. Wood, K. Heyde, W. Nazarewicz, M. Huyse, and P. Van Duppen, Phys. Rep. **215**, 101 (1992).

[3] K. Heyde, C. De Coster, J. Jolie, and J.L. Wood, Phys. Rev. C **46**, 541 (1992).

[4] A. Arima, T. Otsuka, F. Iachello, and I. Talmi, Phys. Lett. **66B**, 205 (1977); T. Otsuka, A. Arima, and F. Iachello, Nucl. Phys. **A309**, 1 (1978).

[5] M. Délèze, S. Drissi, J. Jolie, J. Kern, and J.P. Vorlet, Nucl. Phys. **A554**, 1 (1993).

[6] J. Kumpulainen, R. Julin, J. Kantele, A. Passoja, W.H. Trzaska, E. Verho, J. Väärämäki, D. Cutoiu, and M. Ivascu, Phys. Rev. C **45**, 640 (1992).

[7] J. Jolie and K. Heyde, Phys. Rev. C **42**, 2034 (1990).

[8] M. Délèze, S. Drissi, J. Kern, P.A. Tercier, J.P. Vorlet, J. Rikovska, T. Otsuka, S. Judge, and A. Williams, Nucl. Phys. **A551**, 269 (1993).

[9] A. Aprahamian, D.S. Brenner, R.F. Casten, R.L. Gill, A. Piotrowski, and K. Heyde, Phys. Lett. **140B**, 22 (1984).

[10] K. Heyde, C. De Coster, J.L. Wood, and J. Jolie, Phys. Rev. C **46**, 2113 (1992).

[11] R.F. Casten, J. Jolie, H.G. Börner, D.S. Brenner, W.V. Zamfir, W.-T. Chou, and A. Aprahamian, Phys. Lett. B **297**, 19 (1993).

[12] J. Heese *et al.*, Phys. Lett. B **302**, 390 (1993).

[13] P. Van Duppen, M. Huyse, and J.L. Wood, J. Phys. G **16**, 441 (1990).

[14] P. Van Duppen, E. Coenen, K. Deneffe, M. Huyse, and J.L. Wood, Phys. Rev. C **35**, 1861 (1987).

[15] P. Van Duppen, Ph.D. thesis, University of Leuven, 1985 (unpublished).

[16] W. Nazarewicz, Phys. Lett. B **305**, 195 (1993).

[17] Y. Xu, K.S. Krane, M.A. Gummin, M. Jarrio, J.L. Wood, E.F. Zganjar, and H.K. Carter, Phys. Rev. Lett. **68**, 3853 (1992).

[18] P.M. Walker, K.C. Yeung, G.D. Dracoulis, P.H. Regan, G.J. Lane, P.M. Davidson, and A.E. Stuchbery, Phys. Lett. B **309**, 17 (1993).