Pseudospin doublet aligned structure in doubly odd ^{186}Ir

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^{186}Ir has been restudied through the ^{180}Hf(^{11}B,5n) reaction at 65 MeV using in-beam γ-ray and conversion-electron spectroscopy. The unfavored component of the doubly decoupled band was established and shown to be consistent with a description in terms of the $\pi h_{9/2}\otimes\nu[\widetilde{411}\ 1/2,3/2]$ structure, i.e., the coupling of an aligned proton and a neutron pseudospin doublet. [S0556-2813(97)05701-4]

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The possibility of existence of twin bands, defined as bands with identical transition energies, in neighboring nuclei of different number parity, i.e., odd and even mass number, depends on the existence of halfinteger alignment. The first example of such a behavior and the underlying mechanism were pointed out [1] in connection with very similar bands in the doubly odd nucleus ^{174}Lu [2] and its odd-mass neighbors ^{173,175}Lu [3] corresponding to the normal deformation regime. It can be shown analytically [1] that the coupling of an $\Omega=1/2$ excitation, with a decoupling parameter $a=1$, leaves the structure to which it couples invariant; this quasiparticle acts as a spectator just adding half a unit of spin to the collective angular momentum of the odd nucleus. It had previously been noted [4] that such an excitation effectively carries half a unit of spin aligned with the rotation axis. That effective angular momentum is in fact the pseudospin [5]. Subsequently, identical bands in neighboring nuclei were discovered in the domain of superdeformation [6–9] receiving considerable attention, and pseudospin aligned states were considered as the only means to produce quantized alignment [7–10]. In view of the intimate connection between the angular momentum aspects of the identical-band problem and the phenomenon of pseudospin alignment it is of interest to further explore structures in which pseudospins couple to other excitations. The present work is aimed at reexamining in greater detail the fingerprints of aligned pseudospin in doubly decoupled structures in the normal deformation regime [11,12], using the GASP γ-ray and the TANDAR conversion-electron spectroscopy facilities.

Double decoupling [13,14] is by now a well-established concept. It entails bands in doubly odd nuclei (or eventually also two-quasiparticle bands in even-even systems) in which both valence particles are decoupled from the rotational motion.

In this work we are concerned with a so far unique case of double decoupling, namely that of ^{186}Ir [11,15,16], where the valence neutron occupies a pseudospin doublet, characterized by $[\tilde{N}=N-1,n_3,\tilde{\Lambda}=\Lambda+1,\Omega_\pm=\tilde{\Lambda}\pm1/2]\equiv|\pm\rangle$ (here $[\widetilde{411},1\pm1/2]$ corresponding to the Nilsson orbits labeled conventionally as [512 3/2] and [510 1/2] which are almost degenerate in ^{185,187}Os [17]). In this case the pseudospin asymptotic property $\langle+|j_+|-\rangle=1$ leads to half-integer alignment $i_n=1/2$ (If a Nilsson calculation is performed for $\beta=0.20$, which corresponds to the ^{184}Os core, one obtains $\langle[512\,3/2]|j_+|[510 1/2]\rangle=0.973$ and $\langle[510\,1/2]|j_+|\overline{[510\,1/2]}\rangle=-a_n=-0.074$, which are very close to the pseudospin limit [5]). As already discussed in Ref. [11], this interpretation differs somewhat from the original one [15].

Here, both signature components in the doubly odd nucleus (namely the $\alpha=1$, I = odd and the $\alpha=0$, I = even sequences) correspond to $i_{np}=1/2+i_p$ and should not exhibit signature splitting [11], hence expecting a regular $I=5,6,7,8\ldots$ sequence. In spite of this prediction only one single $E2$ cascade $5\rightarrow7\rightarrow9\rightarrow11$, etc. had been observed [15]. The reason for this behavior is a puzzle and a reexamination with much better statistics is called for. The interest in this case is further enhanced by the fact that the dynamic moment of inertia for the pseudospin doublet band in ^{185}Os is almost identical to the one in the doubly decoupled band in ^{186}Ir [12], hence constituting a case of identical bands.

The best doubly decoupled case studied so far is a structure which consistently appears in the upper rare-earth region and is associated with the configuration space $\pi h_{9/2}\otimes\nu[521\ \ 1/2]$. The $\pi h_{9/2}$ parentage orbitals have rather pure $j(=9/2)$ and the $\Omega=1/2$ component (i.e., [541 1/2]) is known to have a large positive decoupling parameter leading to a significant alignment i_p (This same proton excitation also participates in the doubly decoupled band in ^{186}Ir). The neutron orbital has a decoupling parameter very close to unity ($a_n\simeq1$) and allows a rather accurate description as a pseudospin ($=\tilde{s}$) ‘‘singlet,’’ $|+\rangle$, corresponding to pseudo-

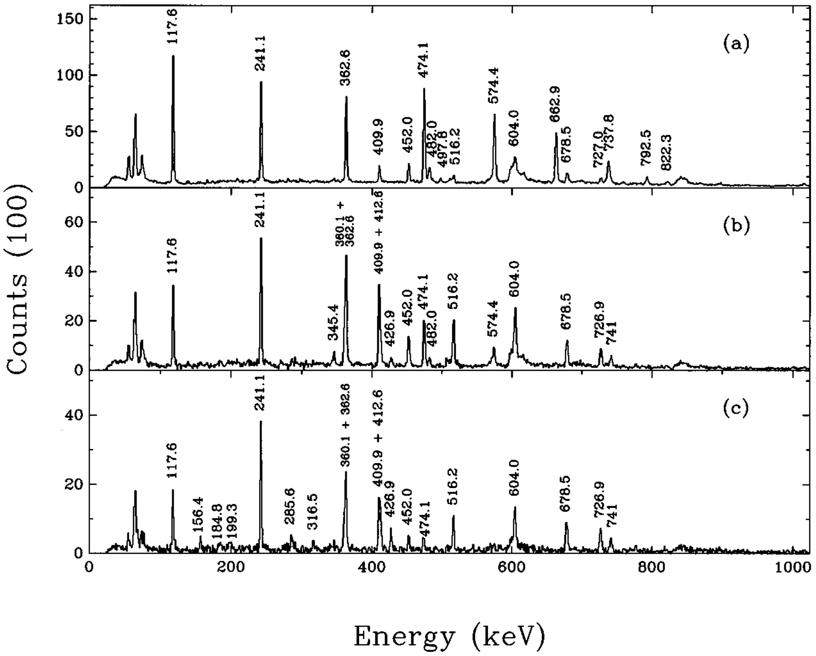

FIG. 1. Spectra gated on lines of the doubly decoupled band: (a) Sum of gates obtained from triples data where two of the gating transitions belong to the *f* part (117.6, 241.1, 362.6 keV, . . .). (b) Sum of gates obtained from triples data where two of the gating transitions belong to the *u* part (316.5, 412.6, 516.2 keV, . . .). (c) Sum of gates from triple coincidences, but with one of the gating transitions on the *f* part (e.g., 117.6 keV) and the other on the *u* part (e.g., 316.5 keV) in order to emphasize the connecting lines.

orbital angular momentum $\tilde{\Lambda}=0$ (hence $\tilde{s}_3=\Omega=1/2$). The appropriate pseudo-oscillator quantum numbers $[\tilde{N}=N-1, n_3, \tilde{\Lambda}=0, \Omega=1/2]$ for this orbit are hence $[\widetilde{420}\,1/2]$. Due to the property $\langle +|j_+|\overline{+}\rangle=\langle +|\tilde{s}_+|\overline{+}\rangle=-a=-1$ the neutron pseudospin is aligned (with a quantized value of $i_n=1/2$) and it adds this pseudospin to the proton alignment leading to a remarkable additivity rule $i_{np}=1/2+i_p$ in the favored (signature = α =1) yrast component of doubly decoupled bands (a Nilsson calculation for $\beta=0.20$ yields a_n = 0.809 and for $\beta=0.25$ it reaches the value a_n = 0.87). In none of these cases had the unfavored ($\alpha=0$) component been observed. In this component the neutron pseudospin should be antialigned to the proton ($i_{np}=-1/2+i_p$) leading (ideally) to a degenerate situation [namely a sequence of degenerate doublets (I_1, I_2) = (2,3); (4,5); (6,7); etc]. These predictions could recently be confirmed [18] in a GASP experiment on ^{176}Re and we shall discuss in detail here what the specific differences are between the pseudospin singlet and the doublet cases, which indeed are rather striking and provide strong support for the present interpretation.

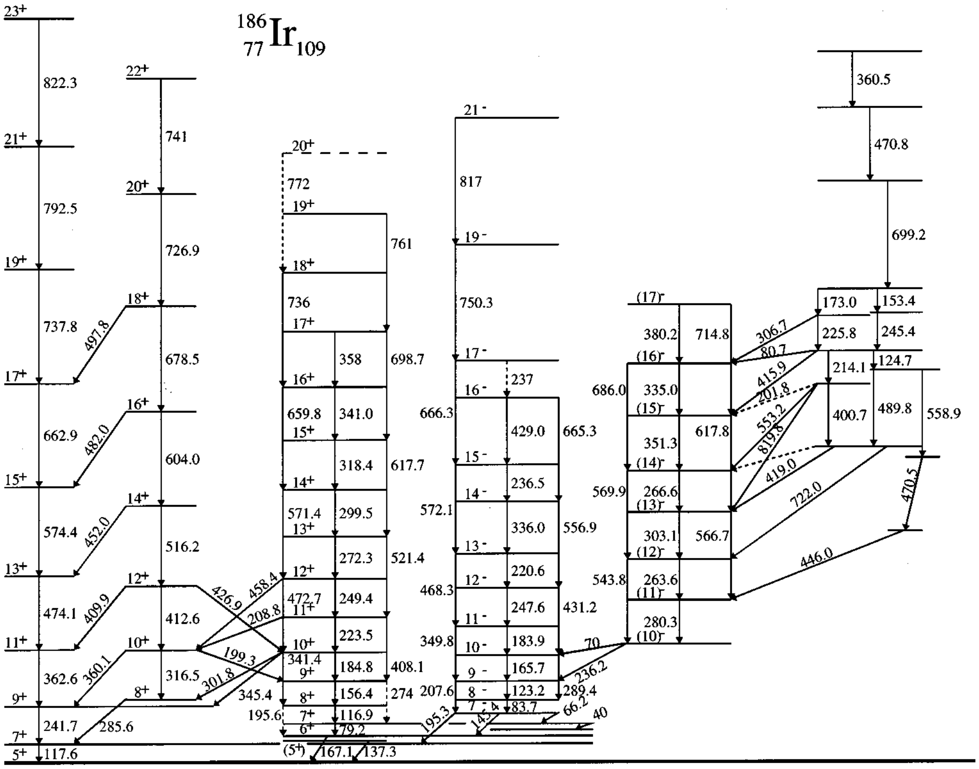

FIG. 2. Level scheme of ^{186}Ir showing the favored (I = odd) and unfavored (I = even) portions of the doubly decoupled $\pi h_{9/2}\otimes\nu[\widetilde{411}\,1/2,3/2]$ band and all other structures established at present. The structure second from left is interpreted as the $\pi h_{9/2}\otimes\nu 7/2[503]$ coupling (see text), while the third and fourth from left correspond, respectively, to the semidecoupled $\pi h_{9/2}\otimes\nu i_{13/2}$ prolate structure and to the less deformed $\pi h_{11/2}\otimes\nu i_{13/2}$ structure. The similarity of this last structure to the $\pi h_{11/2}$ band in ^{185}Ir [20] is striking.

TABLE I. Cranking model parameters J_0, J_1 and average alignments i for nuclei in the neighborhood of ^{186}Ir obtained from fits to the individual bands. I^π stands for spin and parity of the lowest lying state considered in the fit and α is the signature. DD stands for doubly decoupled: $\pi h_{9/2} \otimes \nu[\widetilde{411}\ 1/2,3/2]$, and f and u stand for favored and unfavored components, respectively.

Nucleus	Reference	Band	I^π	α [a]	$J_0/\hbar^2$ (MeV^{-1})	$J_1/\hbar^4$ (MeV^{-3})	i ($\hbar$)
^{186}Ir	[15], this work	DD, f	5^+	1	31.21	32.27	4.66
^{186}Ir	This work	DD, u	8^+	0	31.61	57.56	4.36
^{185}Os	[16]	$\nu\ [\widetilde{411}\ 1/2,3/2]$	$1/2^-$	+ 1/2	31.71	24.32	0.46
^{185}Os	[16]	$\nu\ [\widetilde{411}\ 1/2,3/2]$	$3/2^-$	− 1/2	31.85	54.41	0.41
^{185}Ir	[20]	$\pi\ h_{9/2}$, f	$9/2^-$	+ 1/2	26.76	61.42	3.92
^{184}Os	[20]	0^+	0^+	+ 0	25.20	77.10	0.00

[a] The signature quantum number α is defined in terms of the eigenvalue $e^{-i\alpha\pi}$ of the 180° rotation around an axis perpendicular to the symmetry axis.

To this end, the doubly odd nucleus ^{186}Ir was reexamined here in a collaborative effort between the National Laboratory of Legnaro, Italy and the TANDAR Laboratory of Buenos Aires, Argentina. A first experiment was performed utilizing the 40 Compton suppressed Hp-Ge, 80 BGO-element filter, GASP spectrometer [19], at the Legnaro Tandem Facility, and the ^{180}Hf(^{11}B, $5n$) reaction at 65 MeV bombarding energy. Only triple and higher-fold Ge coincidences (demanding also 3 or more hits in the filter) were stored, recording $\approx 1.710^9$ events in a three-day run at a rate of about 5 kHz on a stack of 3, 300 μg/cm^2 Hf oxide targets. From these events both E_{γ_1}-E_{γ_2}-E_{γ_3} cubes, projected double coincidence, DCO and γ-time (γ,filter) matrices were produced and extensively gated (see Fig. 1). A second experiment, using the same reaction, was performed at the TANDAR Laboratory in order to search for isomeric states and measure internal conversion coefficients utilizing a high-resolution planar Ge detector, a cooled Si(Li) electron detector coupled to a mini-orange spectrometer and an 11-element multiplicity filter. The level scheme obtained from these experiments is shown in Fig. 2 and the different structure assignments are outlined in the caption. The left-hand-side band corresponds to the doubly decoupled band (DDB), namely the coupling between the $h_{9/2}$ ([541 1/2]) proton and the pseudospin doublet $\nu[\widetilde{411}\ 1/2,3/2]$. This DDB could be extended [15] from spin 15^+ to 23^+ and its hitherto unknown unfavored part established up to $I^\pi = 22^+$. The band shown in Fig. 2, second from the left, has also been identified in this experiment. *Prima facie* it looks like a normal rotational band, but on closer inspection it reveals a distortion called compression [13]. A similar structure has been observed in ^{182}Ir [20] and its configuration is here most likely $\pi h_{9/2} \otimes \nu[503\ 7/2]$. Its similarity with the $\nu[503\ 7/2]$ band in ^{185}Os [17], from a certain state on, is striking and is indeed a characteristic feature of semidecoupled structures [13]. From an experimental point of view the spin-parity assignment of this band is based, among other arguments, on the accidental degeneracy of its 10^+ state and the 10^+ state of the unfavored portion of the DDB. Given the measured energy difference between these two states and the relative intensity of the in-band $12^+ \to 10^+$, 412.6 keV transition and the out-of-band $12^+ \to 10^+$, 426.9 keV line, it is possible to deduce the unperturbed position of these states as well as the proton-neutron residual interaction matrix element V (=6.9 ± 0.9 keV). The corrected $12^+ \to 10^+$ and $10^+ \to 8^+$ transition energies in the unfavored DDB turn out to be 417.7 and 311.4 keV respectively (originally 412.6 and 316.5 keV). With these corrected values it is possible to extract cranking-model inertia parameters and alignments which are given in Table I along with values for the $\nu[\widetilde{411}\ 1/2,3/2]$ band in the odd isotone ^{185}Os [17]. The first point to be noted concerns the relatively small difference in alignments, $\Delta i = 0.30$, for the two signature components, as compared to the pseudospin singlet case in ^{176}Re [18], in line with the fact that the two signature components of the ^{185}Os pseudospin doublet band have almost the same align-

TABLE II. Experimental and calculated BM1/BE2 ratios for transitions in the doubly decoupled band.

Transition $I \to I-1$ $I \to I-2$	$\frac{BM1(I\to I-1)}{BE2(I\to I-2)}$ exp. [$\mu_N^2/(e\mathrm{b})^2$]	$\frac{BM1(I\to I-1)}{BE2(I\to I-2)}$ calc. [$\mu_N^2/(e\mathrm{b})^2$]
10 → 9 10 → 8	0.16(4)	0.275
11 → 10 11 → 9	—	0.003
12 → 11 12 → 10	0.26(4)	0.223
13 → 12 13 → 11	—	0.003
14 → 13 14 → 12	0.12(4)	0.190
15 → 14 15 → 13	—	0.004
16 → 15 16 → 14	0.11(3)	0.167

ment. However, the remaining difference ($\Delta i = 0.30$) is somewhat larger than expected, taking into account the alignment difference of 0.05 for the two signature components of ^{185}Os. This fact can be correlated with the circumstance that the unfavored members (even spin states) are shifted up in energy with respect to the position predicted by a model without residual interactions, as outlined above. This behavior can indeed be qualitatively reproduced by introducing a Newby shift [21] of about 100 keV acting in the $K=0$ ($\Omega_n - \Omega_p = 1/2 - 1/2$) configuration (similarly to the case in ^{176}Re [18]). This term breaks the degeneracy between the $K=0$ and 1 configurations pushing the energy of the $K=0$ term up, for even spin states thus inhibiting the pseudospin alignment to occur. It is worth noting that (see Fig. 2), as the spin increases, the even spin states I, tend to place themselves in an intermediate position between the favored states of spin $I+1$ and $I-1$, as predicted by the model without interaction and consistent with the fact that the effects of the residual interaction become small compared to the Coriolis interaction which increases linearly with I. This behavior is clearly different from the one displayed in ^{176}Re where the favored states of spin I tend to degenerate with the unfavored states of spin $I-1$, as predicted for a pseudospin singlet. Further inspection of Table I shows that the moments of inertia of the two signature components in ^{186}Ir are very similar to each other (as in ^{176}Re) and to the ones of both signatures in ^{185}Os, hence constituting a set of identical bands. This aspect has been discussed already in Ref. [12].

Finally an analysis of the electromagnetic decay properties of the DDB provides additional strong support for the present interpretation. Table II shows the experimental and calculated BM1($I \rightarrow I-1$) /BE2($I \rightarrow I-2$) ratios. [The calculated mixing ratios $\delta(I \rightarrow I-1)$ are very small in all cases.] Just opposite to the case of ^{176}Re, here the $I_{\mathrm{even}} \rightarrow (I-1)_{\mathrm{odd}}$ M1 transitions are strong while none of the $I_{\mathrm{even}} \rightarrow (I+1)_{\mathrm{odd}}$ transitions could be observed. In fact the $I_{\mathrm{even}} \rightarrow (I-1)_{\mathrm{odd}}$ $M1$ transitions compete with the $I_{\mathrm{even}} \rightarrow (I-2)_{\mathrm{even}}$ $E2$ transitions bringing the intensity of the $\alpha=0$ branch into the $\alpha=1$ sequence. This very strong signature dependence can be traced to the value of the magnetic decoupling factor, b_n [22], of the $[\widetilde{411}\,1/2]$ orbit which takes a value close to unity at $\beta=0.2$ (a value of the quadrupole deformation considered appropriate for ^{186}Ir). In fact the BM1 value for the doubly odd nucleus in this case is basically proportional to $[1+(-1)^I b_n]$. Hence, in ^{176}Re [18], the opposite behavior is related to the value -1 of the magnetic decoupling factor of the $[\widetilde{420}\,1/2]$ neutron pseudospin singlet. It is worth noting that similar effects are known [23] in odd nuclei.

The reinvestigation of ^{186}Ir has permitted us to establish a revised and more complete high-spin level scheme. In particular the unfavored portion of the doubly decoupled band has been assigned showing that all its features, including the electromagnetic properties, are consistent with the interpretation in terms of the aligned $h_{9/2}$ proton and the $[\widetilde{411}\,1/2,3/2]$ neutron pseudospin doublet.

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