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Abstract: The level scheme of the nucleus ^{150}Dy up to spin around 40 was obtained using the reaction $^{114}Cd(^{40}Ar,4n)$. Above spins 20 to 22--the highest obtainable from the valence nucleons--the breaking of the ^{146}Gd proton and neutron cores occurs in two parallel cascades. At higher spins, states with one-proton and several-neutron particle-holes dominate. This is the first time that the breaking of proton and neutron cores can be studied in such competitive parallel cascades.

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The nuclei in the vicinity of the doubly closed-shell nucleus ^{146}Gd have a rich variety of behaviors which is produced by the different number and types of valence nucleons. In the spin region up to around 30-40, the structure of these nuclei is mostly interpreted in terms of independent-particle shell-model configurations (with some residual interactions added), although ^{152}Dy, with 2 protons and 4 neutrons outside the core, already shows some collective behavior.[1-2] The nucleus ^{150}Dy is particularly interesting because it has two protons and two neutrons outside the ^{146}Gd core, and there are both neutron and proton orbitals that can carry high angular momentum ($h_{11/2}$ for protons, $f_{7/2}$, $h_{9/2}$, $i_{13/2}$ for neutrons). In ^{150}Dy the breaking of the proton and neutron cores is seen here at the same excitation energy in parallel cascades. These two cascades begin from the same state (at spin 29) which is a one-proton particle-hole (p-h), one-neutron p-h state. Between spins 32 and 39 the one-proton p-h, two-neutron p-h states are favored, because the neutrons offer more possibilities to generate angular momentum. The deformed independent particle model[3] is applied to interpret this behavior.

The nucleus ^{150}Dy was produced at the 88" cyclotron of the Lawrence Berkeley Laboratory by the reaction ^{114}Cd(^{40}Ar,4n) at 175 MeV, first with a 1 mg/cm^2 lead backed target and then with two stacked 0.5 mg/cm^2 self-supporting targets. In the backed target the residual nuclei were stopped in ~2 ps. For the unbacked targets, they were allowed to recoil out towards a stopper which was 13 cm away. Thus, in this case, the γ-ray lines emitted more than 3 ns after the reaction would not be seen by most of the array of 21 Compton-suppressed germanium detectors (the HERA array) surrounding the target. In addition, any lines which could have been emitted during the slowing down of the recoils in the lead backing of the first target (and therefore smeared out) would be seen in the second experiment (where the gains of the detectors were matched for the Doppler-shifted lines). There was no significant difference in the spectra, indicating that all the observed lines in this nucleus are emitted between ~2 ps and ~3 ns after the reaction. This absence of long-lived isomers is different from most of the neighboring nuclei but is probably just a result of detailed energy and spin values.

The complex level scheme (see Fig. 1) was constructed, using γ-γ coincidence and angular correlation techniques. The main difficulty of building the level scheme was to locate the transitions between spin 21 and 29 where many parallel branches occur. Fortunately we could use the triple (γ-γ-γ) coincidences (2.3×10^8 events) to resolve this complexity. For this purpose 13 (1000 x 1000) γ-γ matrices (plus 2 background matrices) were sorted in coincidence with the third transition which was critical to define a pathway. For example, it was determined (fig. 2a) that the 353 keV line contains only two transitions (at 9 and 10 MeV) . In addition, it was necessary to use the full double-coincidence matrix to place the weak transitions in the level scheme.

Figures 2b and 2c show the two main cascades deexciting the nucleus as revealed by coincidence spectra gated on the 2527 keV (7%) and 1455 keV (25%) lines, respectively. Both spectra show the same lines above the 29^- level at 10.33 MeV. The 25^+ level at 9.27 MeV is very well established by more than ten parallel pathways. It is de-excited by a series of cascades of low-energy (300-900 keV) transitions each in coincidence with a high-energy (2-2.5 MeV) transition. The low-energy transition has generally been placed on top, but only for some of the pathways is that order unambiguous due to connections with other levels. The spins and parities indicated form a consistent set, in agreement with experimental angular correlations, where determined. The difficulties here are that some transitions are multiple, a fair number of them are very likely unstretched, and the angular correlations are attenuated, probably due to the presence of several isomers in the 0.1 ns range.[4] Thus the simple angular correlation analysis of ref. 5 cannot be used extensively. Nevertheless, arguments based on lifetimes, observed angular correlations, and the constraints on different cascades ending at the same level give us confidence in the spins and parities adopted.

With two protons and two neutrons outside the ^{146}Gd core, the nucleus ^{150}Dy can be described by an independent particle model in which residual interactions (pairing and quadrupole interactions--the latter described as a deformed static mean field) are included, as in the "deformed independent particle model" (DIPM) of Døssing, Neergård and Sagawa[3] (see also references therein). Before our study began, the nucleus ^{150}Dy was known[6] up to spin 21, and recently one cascade was found[7] extending up to spin 24 or 25. Below spin ~22, the angular momentum is generated by the valence nucleons which gradually align along a common axis, forming recognizable "multiplets,"[6] which correspond to sets of spins generated by reorienting the orbits of the nucleons in a given configuration. The states at spin 20 (with a 85% population) and 21 (with a 50% population) can be explained as energetically favorable states which produce about the maximum possible spin with valence nucleons, the aligned protons $(h_{11/2})^2$ producing spin 10 and the aligned neutrons in orbitals $f_{7/2}\ i_{13/2}$, or $h_{9/2}\ i_{13/2}$ producing spin 10 or 11, respectively. We also propose a 22^+ state at 7.1 MeV (calculated at 7.5 MeV in fig. 3) in which the two valence neutrons are aligned in the $i_{13/2}$ orbital, but this state, less favorable energetically, is not strongly populated (only 11%). This interpretation differs somewhat from that of ref. 7 which already involved p-h proton states at spins 20 and 21. However, both the results of the DIPM and the fact that rather high-energy γ-ray transitions, indicative of a gap in energy, are observed only above spins 20 and 21, suggest that the core is broken only above these spins. Another sign of the core breaking above spins 20, 21 is the large number of parallel cascades, indicating that many different ways to build angular momentum are offered by breaking the ^{146}Gd core.

The observed level scheme of ^{150}Dy suggests that both the proton and neutron cores are broken at about the same excitation energy (8-9 MeV) and spin (around 25). The most intense proton p-h sequence is formed by the 1455-267-267-602-495-199 keV transitions and the neutron one by the 2527-353-622-79 keV transitions. To our knowledge, this is the first time in medium or heavy nuclei that such competitive cascades occur. In contrast, for the nucleus ^{146}Gd, which has no valence particles, the proton core is broken first[6] in spite of the fact that the effective gaps (i.e., including both single-particle and pairing energies) are nearly equal[8] for protons and neutrons in this nucleus. The reason may be that the proton hole ($d_{5/2}$, $g_{7/2}$) and particle ($h_{11/2}$) orbitals combine more effectively to form high spins than the corresponding neutron hole ($s_{1/2}$, $d_{3/2}$) and particle ($f_{7/2}$) orbitals. This is probably less true in ^{150}Dy where the two most aligned ($m = 11/2, 9/2$) proton orbitals have already been used by the two valence protons while the neutrons still have many more possibilities to form high spins using the nearby $i_{13/2}$, $h_{9/2}$ orbitals. Thus, spin arguments alone would tend to favor the population of neutron-core-excited states. On the other hand, the proton pairing is smaller[3] in ^{150}Dy than in ^{146}Gd, thereby effectively decreasing the proton gap relative to the neutron one where the pairing is, in all cases, small. These two effects tend to cancel each other. Perhaps the most important difference in ^{150}Dy is that the neutron holes $s_{1/2}$, $d^{*}_{3/2}$ are strongly affected by the quadrupole deformation[3], which gives a considerable gain in the binding energy of states with neutron holes in combination with particles in high-j states. As they are interpreted here, the states at spin 20 and 21 in ^{150}Dy already contain four valence particles in high-j (equatorial) orbits, and this makes ^{150}Dy much more "deformable" than ^{146}Gd, which has no such particles present when the core is breaking. Figure 3 shows the most probable configurations assigned after comparison with the DIPM calculations, although these states may not be pure, and there are some uncertainties in parity assignments, mainly for the higher-lying states.

For the Dy isotopes, the proton core is most favourably broken by generating quasiparticle configurations of the type $d^{-1}_{5/2}\ h^{3}_{11/2}$, and multiplets of this type are probably seen in all Dy isotopes neighboring to ^{150}Dy. Thus, the pure configuration $d^{-1}_{5/2}\ h^{3}_{11/2}$ with maximally aligned angular momentum is probably found as the 16^- state in ^{148}Dy. Adding one neutron in the $f_{7/2}$ subshell, and subsequently neutrons in $h_{9/2}$, $i_{13/2}$ and $f_{7/2}$, one obtains a sequence of states with angular momentum and parity $39/2^+$, 24^-, $61/2^-$ and 33^+ in the isotopes $^{149-152}$Dy. The present experimental data complete the observation of these states (except for ^{151}Dy, where the parity has not been determined). They are all yrast states, and (except for ^{148}Dy) they decay by both a stretched M1 transition of typically 250 keV and an E2 transition of typically 500 keV to two lower-lying states, which can be assigned as members of the same multiplet. Also the assignment shown on Figure 3 of the higher-lying proton core-excited states up to spin 27 fits

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*Due to deformation[3] effects, $d_{3/2}$ refers most often to the 1/2 projection -- i.e., the 411 1/2 Nilsson orbital.

well into the systematics of these multiplets, and the calculated energies of the aligned states are in good agreement with experiment.

The decay of the proposed neutron branch from the 27^- state is more spectacular, especially when compared to the corresponding decay of the 27^- state in ^{152}Dy, which is indentified to have the same configuration, but without the double excitation of the neutron core (the holes are coupled to spin 0 in ^{150}Dy). The excitation energy from 21^- to 27^- is 3.6 MeV in ^{150}Dy and 1.8 MeV in ^{152}Dy. The fact that the difference between these energies is only 1.8 MeV in spite of the double breaking of the neutron core in ^{150}Dy is due to the deformation driving effect of the holes in the $d_{3/2}$ orbital. In ^{152}Dy the 27^- state decays[9] via three E2 transitions down to 21^-. The states participating in this decay can be interpreted in the shell model by the coupling of $(f^2_{7/2})_I$ particles with I=6,4,2,0 to the 21^- state. We suggest that the larger deformation of the corresponding states in ^{150}Dy brings down the aligned 27^- state relative to the others, which makes this sort of decay impossible. The appearance of the 26^- state, which is ruled out in the spherical interpretation, may be a signature of the deformation. The neutron p-h cascade is considerably more branched than the proton one. Although the 353-2527 keV cascade is one of the main (7%) decay branches of the 25^+ state, there are many other weak branches which add up to more than half of the total decay. Some of these branches are towards proton p-h states, suggesting that the structure of the 9.27 MeV state may be even less pure than the others. The most serious problem with the interpretation of the neutron cascade is that the 25^+ and 23^+ states are calculated at too low an energy in the DIPM.

The transition energies which span the one p-h gap tend to be higher in the neutron branch than in the proton branch. This is probably due to the fact that the neutron configuration changes (see Fig. 3) from including an $i_{13/2}$ orbital below the proton core breaking (in states 20^- at 6 MeV and 21^- at 6.4 MeV) to including only an $f_{7/2}$ or $h_{9/2}$ orbital just above it (in state 22^- to 24^- at 7.4 to 8 MeV). This change reduces the transition energy. This does not happen in the neutron p-h branch which always includes a $[\pi\ h^2_{11/2}]_{10}$ configuration both below and above the neutron core breaking. In addition, as mentioned, proton p-h configurations tend to decay down through multiplet structures, which are not present (due to deformation) in the neutron case.

Both proton and neutron p-h branches decay from a common state (29^- at 10.3 MeV) which is therefore most likely a one-proton p-h, one-neutron p-h state. Such states are also found lowest in energy for that spin region in the calculations. Whether it contains an aligned configuration, or belongs to a multiplet stretched at spin 31 (as shown in fig. 3) is not clear. Between spins 33 and 37, the one-proton p-h, two neutron p-h configurations seem to be favored, most likely because there are three high-j neutron orbitals available to build up angular momentum, compared to only one for the protons. The 39^+ state is assigned to be a one-proton, three-neutron p-h configuration.

In summary, it seems that the observed structure of ^{150}Dy up to spin 40 can be understood in terms of a deformed independent particle model. Although the detailed structure of each state is not clear, the general flow pattern proposed is quite likely correct. Particularly interesting is the competition between the breaking of the proton and neutron cores, which relates to the underlying orbital structure and interactions. Above spin 40, the discrete lines disappear and one might speculate that further core breaking will lead to a more complicated, probably collective, structure as is known to be true generally,[10] and in particular[1-2] in the neighboring nucleus ^{152}Dy.

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Figure Captions

Fig. 1: Level scheme of ^{150}Dy. The most intense transitions are shown as thick lines.

Fig. 2: Partial coincidence spectra with the following gates: (a) double gate on the two 353 keV lines; (b) gate on the 2527 kev line; (c) gate on the 1455 keV line. The transitions below spin 20 are not marked.

Fig. 3: Configurations assigned to some experimental levels (drawn as in fig. 1) above spin 19. When the hole configurations are not explicitly written, they are coupled to spin zero. The two numbers written above each level indicate the number of neutron p-h and proton p-h respectively, for its assigned configuration. For each configuration, the number in parenthesis is the energy calculated,[3] in the DIPM model, for the level with maximum spin.

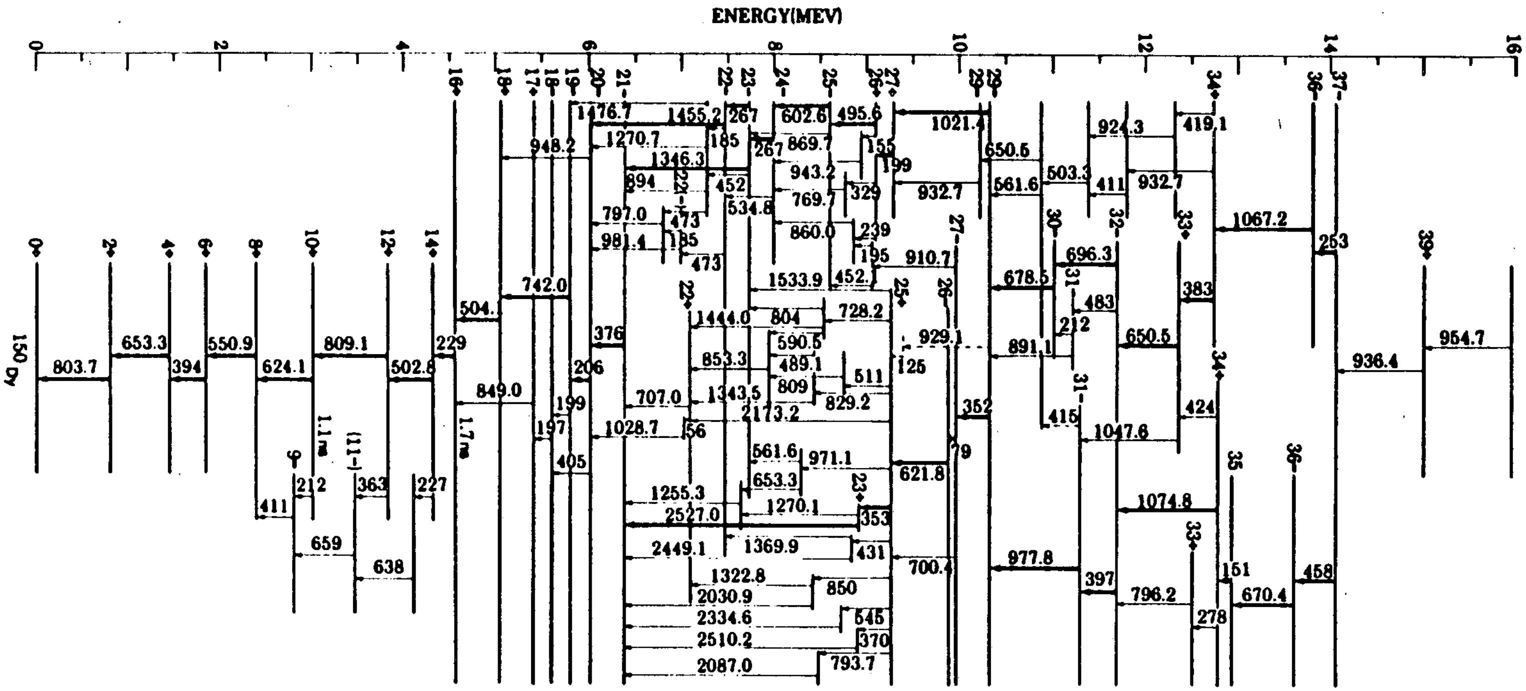
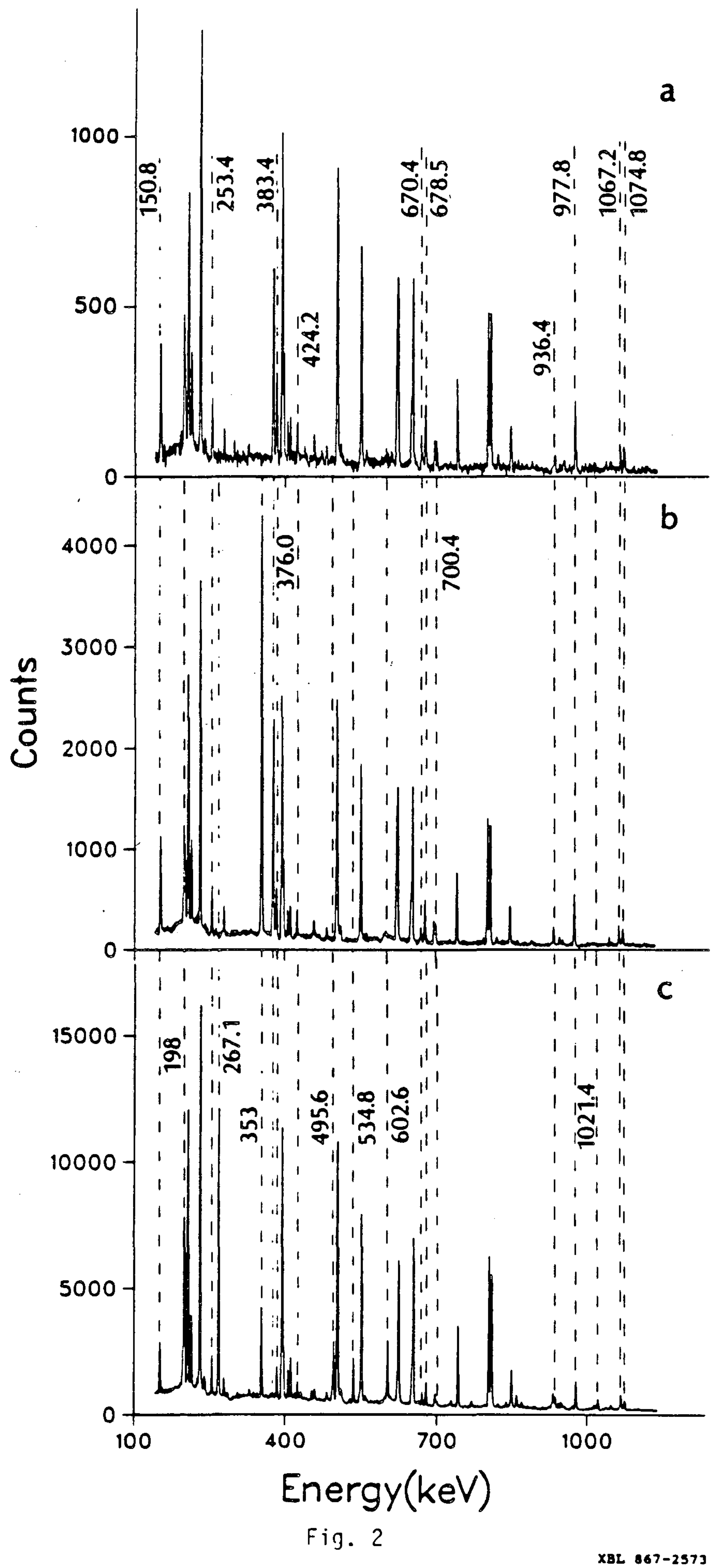

ENERGY(MEV)
0
2
4
6
8
10
12
14
16
150 Dy
0+
2+
4+
6+
8+
10+
12+
14+
16+
18+
17+
18-
19-
20-
21-
22-
23-
24-
25-
26-
27+
29-
28-
30-
31-
32-
33-
34+
35
36-
37-
39+
803.7
653.3
394
550.9
624.1
809.1
502.8
229
504.
742.0
849.0
948.2
1476.7
1270.7
1455.2
1346.3
1021.4
924.3
419.1
1067.2
936.4
954.7
1.1ns
1.7ns
XBL 868-3184

Fig. 1


a
b
c
Counts
Energy(keV)
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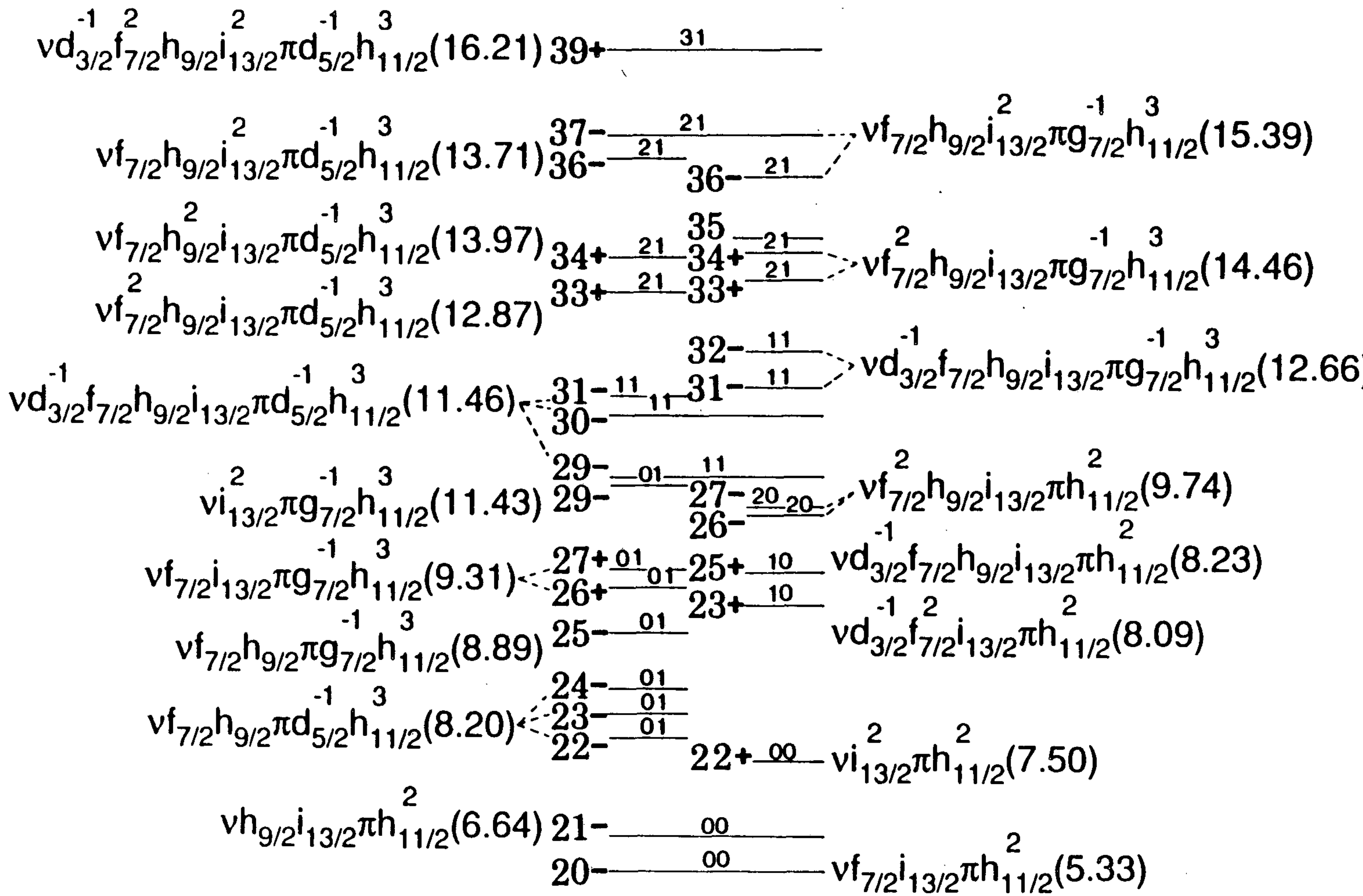
253.4
383.4
424.2
670.4
678.5
936.4
977.8
1067.2
1074.8
376.0
700.4
198
267.1
353
495.6
534.8
602.6
1021.4
XBL 867-2573

Fig. 2



XBL 868-3185

Fig. 3

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