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The Low-spin Termination of the Superdeformed Band in ^{135}Nd

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Abstract

The decay of the superdeformed (SD) band in ^{135}Nd was investigated with the Early Implementation of Gammasphere in the reaction ^{40}Ar + ^{100}Mo at 176 and 182 MeV. The observed transitions linking the SD band to the normally deformed states account for 63% of the SD band intensity, determining its spin and excitation energy. The decay pattern, together with previous lifetime experiments, suggests that the SD band "terminates" at spin 25/2. Cranked Shell Model calculations explain this termination in terms of a transfer of a proton and neutron pair out of deformation-driving Nilsson orbitals.

PACS numbers: 21.10.Re, 23.20.Lv, 27.60.+j

In almost all cases, the decay path of superdeformed (SD) bands into lower-deformation states is not yet established experimentally[1]. Recent data [1] in the mass 150 region show a configuration dependence of this decay that is hard to understand microscopically on the basis of a barrier-penetration scenario [2]. Nuclei like ^{133,135,137}Nd [3,4,5] in the mass 130 region are interesting since the intensities of the SD bands are large and the change between smaller and larger deformation involves the rearrangement of only a few particles, giving us a chance to study the role of these changes in detail. We chose to look for linking transitions in the nucleus ^{135}Nd because: (i) the SD band is one of the most intense [3] (10% of the yield of ^{135}Nd in the reaction), (ii) some linking transitions were already proposed [3] and (iii) lifetime information is available for both the SD band [6] and some of these proposed linking transitions [7]. The lifetime in the upper part of the SD band [6] confirms the large deformation ($\varepsilon \approx 0.32$). In contrast, the recoil-distance lifetime measurements at the bottom of the band [7] indicate that the B(E2) value of the 621 keV transition is about 20 times smaller than that of the in-band transitions. At that point no more in-band transitions to lower-spin states are observed and the SD band "terminates". Band "terminations" of different types have been seen at high spins. Most SD bands depopulate at relatively low spin but the mechanism of depopulation is not clear and that they terminate at low spin is a new concept. This letter reports on a new measurement of the decay pattern of the ^{135}Nd SD band. The spin and excitation energy of the band are established and a microscopic explanation of the decay mechanism is proposed.

Two experiments were carried out with the Early Implementation of Gammasphere at the 88-Inch Cyclotron of the Lawrence Berkeley Laboratory. A target consisting of two 0.5 mg/cm^2 ^{100}Mo foils was bombarded by an ^{40}Ar beam at energies of 176 and 182 MeV. Only the events where at least three Compton-suppressed Ge detectors fired were recorded on

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[1] There is not a generally accepted definition of superdeformation. In this paper, we refer to SD states as those built on a second minimum at higher deformation in the potential-energy curve as a function of deformation.

magnetic tape, enriching the data in events with high angular momentum. In a triple-coincidence spectrum, double-gated on all SD transitions from 546 to 1215 keV (except the 602 keV transition), we found four more transitions at the top of the band than previously published [3] . These are lines at 1437.2(4), 1519.5(5), 1605.0(7), and 1692.0(10) keV. The dynamic moment of inertia calculated from the new transitions continues the decreasing trend that was observed previously. This is generally expected at high spins if there is no change in the band structure, so that it becomes more and more difficult to generate angular momentum.

To find the linking transitions between the SD band and the normally deformed states, we constructed an Eγ-Eγ matrix, gated by any one of the four clean (and background subtracted) lines in the SD band with energies 676, 817, 1010, and 1145 keV. One can then explore the various possible decay paths by selecting a second gate on the desired lines in that matrix. For example with the second gate set on the 727 keV line (Fig. 1), one clearly sees the strongest 621-1184 keV and the 529-965 keV branches, as well as the 949 keV line (appearing as a broadening of the 946 keV SD line). A total of 63% of the decay of the SD band has been placed in the level scheme of Fig.2.

The decay scheme, together with the angular correlation data (see Fig. 3) obtained in the reaction at 176 MeV, determines the spins of the SD states. In particular, the quadrupole character of the 621 keV transition and the dipole character of the 1184 keV transition, as well as the dipole character of the 767 keV transition give an unambiguous spin assignment of 25/2 for the 3.324 MeV state. The parity cannot be unambiguously determined but the value adopted is consistent with lifetimes expected for the various types of transitions. The proposed positive signature for the SD band is consistent with that of the configuration previously assigned, lowest neutron $i_{13/2}$. The relatively low excitation energy at the decay point may explain why rather strong (up to 15% of the SD band intensity) discrete linking transitions are observed.

The decay pattern and the lifetime measurements suggest that the band "terminates" at the 3.324 MeV level. The first indication comes from the highly fragmented decay of that level without the energy available for high-energy statistical transitions. In this work, no observed transition directly deexciting the 25/2 level has an intensity greater than 14% of the band, nor an energy greater than 1 MeV. Another indication comes from the crucial information [7] that the lifetime of that state is (2.4 ± 0.8) ps, which is about the value expected if the SD band continued with the same collective strength and 100% intensity at the appropriate transition energy (about 500 keV). The fact that we see only transitions of intensity around 10% deexciting that state means that any E2 transition of about 500 keV (expected transition energy to the next lower SD band level) would have a reduced transition probability that is a factor ~ 10 lower than that of a SD-band transition. Thus the observed E2 transitions in this energy region, the 621 and the 549 keV transitions, do not belong to the SD band as it is known above the 3.324 MeV state. Finally, if a transition were continuing the band with the same B(E2) as the 546 keV transition, and an intensity of 10%, which is the order of the unobserved decay intensity of that level, its energy would have to be around 300 keV or less and this would imply a very different character for the SD band. Our conclusion is that the observations above are not consistent with the assumption that the SD band continues but is not observed. Therefore we propose that the band ceases to exist.

In order to understand such a termination we have investigated the structure and shape evolution of the SD band at low spin. The energy as a function of deformation and frequency is calculated for the positive parity, positive signature configuration, keeping the odd neutron always in the $i_{13/2}$ (6_1) level. The calculations were made using the Ultimate Cranker [8] program. The pairing gap parameter is fixed to Δ_p= 0.85 MeV and Δ_n= 0.75 MeV. The chemical potentials are fixed to give the correct particle number expectation values at ω=0. The wave functions are projected onto exact particle number for all ω values, thus correcting for the shifts in the Fermi level for ω>0. Fig. 4 shows the results of these calculations for cranking frequencies $\hbar\omega$= 0.25, 0.2 and 0.15 MeV.

As seen in Fig.4, there are two competing energy minima in the β-γ plane. The one with large nearly axially symmetric deformation (ε=0.3, γ=8°) is the lowest for $\hbar\omega > 0.2$ MeV. It represents the SD band. For $\hbar\omega = 0.15$ MeV the less deformed triaxial minimum (ε=0.22, γ=30°) is lower. Between $\hbar\omega = 0.2$ MeV and 0.15 MeV both minima have the same energy with a small barrier between them. We suggest that with decreasing angular frequency the nucleus slides over from the high-deformation to the low-deformation minimum, resulting in the observed band termination. The shape and deformation changes as a function of γ are indicated in Fig.4 for $\hbar\omega = 0.20$ MeV. Fig. 5 shows the single particle levels along this path. The two minima appear as a consequence of the N=74 gaps between the $g_{7/2}$ ([404]7/2) and $h_{9/2}$ ([541]1/2) neutron levels near γ=0° and 30°. The structures of the two minima differ by the rearrangement of one pair of neutrons ($h_{9/2} \leftrightarrow g_{7/2}$) and one pair of protons ($h_{11/2}$ (5_2) $\leftrightarrow g_{7/2}$ ([413]5/2)). Thus, the triaxial minimum differs from the known low-deformation bands in ^{135}Nd only by particle-hole excitations that lift one neutron into the $i_{13/2}$ level. Such a configuration will show the observed decay pattern. Relatively fast E1 transitions will connect it with the negative parity bands. Since the low-deformation $i_{13/2}$ structure lies about 500 keV above the yrast states, couplings to other positive parity states are expected, which will also favor out-of-band E2 transitions.

The fast slide-over from the high-deformation to the triaxial minimum is a consequence of the pair correlations, expected to be substantial at these low frequencies. The pair field will scatter pairs between the neutron levels ($h_{9/2} \leftrightarrow g_{7/2}$) and proton levels ($h_{11/2} \leftrightarrow g_{7/2}$) distinguishing the two minima. Bertsch [9] gives an estimate of the scattering matrix element of the order of 1 MeV, being quite sensitive to the strength of the pairing. This allows a fast transition from the SD minimum.

This interpretation is also in accordance with the lifetime measurements. The decrease of the transition quadrupole moment in Fig. 4 of ref. [7] between the 602, 546 and 621 keV transitions is then consistent with a detailed scenario in which the $29/2^+$ state is superdeformed, the $25/2^+$ state at 3.324 MeV is a mixture of low deformation and high deformation with about equal amplitudes, and the $21/2^+$ states at 2.704, 2.774 (and probably 2.795 MeV) have a low deformation, still with the $i_{13/2}$ neutron orbital populated.

A similar calculation for ^{133}Nd (see Fig. 4, lower right) shows that there is not a competing triaxial low-deformation structure. The reason is apparent from Fig.5, which shows that for N=73 the $g_{7/2}$ level, which favors the triaxial shape, is empty. This result is consistent with the experiment of ref. [4] where it is found that the population stays in the high-deformation minimum down to I=17/2, decaying prior to this point only via band mixings generated by accidental degeneracies. We should note that the decay at lower spin in ^{133}Nd is also due to the fact that the crossing of the SD band and the yrast line occurs at lower spin in this nucleus than in ^{135}Nd. Although most of the decay intensity is accounted for in ^{133}Nd, there is no lifetime information for the 17/2 state and it is therefore somewhat difficult to conclude how similar the two cases may be. The intensity out of the $17/2^+$ state is fragmented, possibly indicating that a process similar to that in ^{135}Nd is occurring at that point.

The example of ^{135}Nd clearly demonstrates the importance of the underlying structural changes in the decay of highly deformed configurations. Pairing is important, allowing the nucleus to "slide" easily from the high-deformation to the low-deformation triaxial minimum, resulting in the sudden termination of the band. In the neighboring nucleus ^{133}Nd, this is not possible because the appropriate neutron level generating the low-deformation triaxial minimum is above the Fermi level. It seems possible that a similar microscopic description is also important for the decay of SD bands in the A=150 and A=190 regions. There, the number of pair rearrangements is larger (typically 8 or 10 instead of 2) and it may become difficult to follow the intermediate steps in a calculation. Nevertheless, as in the case discussed here, the configuration reached by the first rearrangement of a neutron and/or a proton pair , when going into the barrier from the SD side, may play the role of "doorway states". Their energy will determine whether some SD configurations can decay easier than others. This conclusion is in agreement with a recent report of some configuration dependence of the decay of SD bands in the mass 150 region [1].

This work has been supported in part by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract Nos. DE-AC03-76SF00098 (LBL) and W-7405-ENG-48 (LLNL). The work of the Bonn group was supported by NATO grant CRG 930496.

References

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[1] Curien et al., Phys. Rev. Lett. **71**, 2559 (1993).

[2] Y.R. Shimizu et al., Phys. Lett. **B274**, 253 (1992).

[3] E. M. Beck et al., Phys. Rev. Lett. **58**, 2182 (1987).

[4] D. Bazzacco et al., Phys. Rev. **C49,** R2281 (1994).

[5] S. Lunardi et al., Proceedings of the "Conference on Physics from Large γ-ray Detector Arrays", Berkeley, U.S.A., August 2-6, 1994.

[6] R.M. Diamond et al., Phys. Rev. **C41**, R1327 (1990).

[7] P. Willsau et al., Phys. Rev. **C48**, R494 (1993).

[8] T. Bengtsson, Nucl. Phys. **A496**, 56 (1989).

[9] G. Bertsch et al., Nucl. Phys. **A574** 169c (1994).

Figure Captions

Fig. 1. Triple-coincidence spectra at 182 MeV (see text) with one gate on any of the SD band members and one on the 727 keV line.

Fig. 2. Lower part of the level scheme of ^{135}Nd, showing the lower states of the SD band, the lower part of the previously known normally deformed states, and the newly established decay pattern of the SD band into them. The widths of the lines represent the measured γ-ray intensities. The transitions represented by a dashed line are tentative. The uncertainties in the transition energies in the SD band are typically 0.25 keV except for the new transitions (see text). For the linking transitions, they are 0.4 keV for the most intense lines and 1 keV for the multiple and tentative lines.

Fig.3. "Angular correlations" for some linking transitions and some other known transitions. The ratio (28°/90°) of γ-ray intensities is determined from spectra gated by the background subtracted clean SD lines at 676 and 817 keV in the forward and backward detectors. The dashed and solid lines represent an average value of this ratio measured for known stretched quadrupole and stretched dipole transitions respectively.

Fig.4. Total routhian surfaces as a function of deformation ε and triaxiality γ for the neutron $i_{13/2}$ configuration at three different frequencies $\hbar\omega$=0.25, 0.20 and 0.15 MeV in ^{135}Nd and at $\hbar\omega$=0.15 MeV in ^{133}Nd (bottom right). The lines corresponding to γ=0° and γ=30° are indicated. The contours are separated by 0.2 MeV and the energies of the minima are -1.421, -0.67, -0.097, and -0.319 MeV respectively.

Fig.5. Single-particle energies as a function of γ at $\hbar\omega$=0.2 MeV for a variable (ε, γ) path as indicated in Fig 4, for (top) protons and (bottom) neutrons. The intruder orbitals are labeled by the l_j quantum numbers. Orbital changes are schematically indicated.

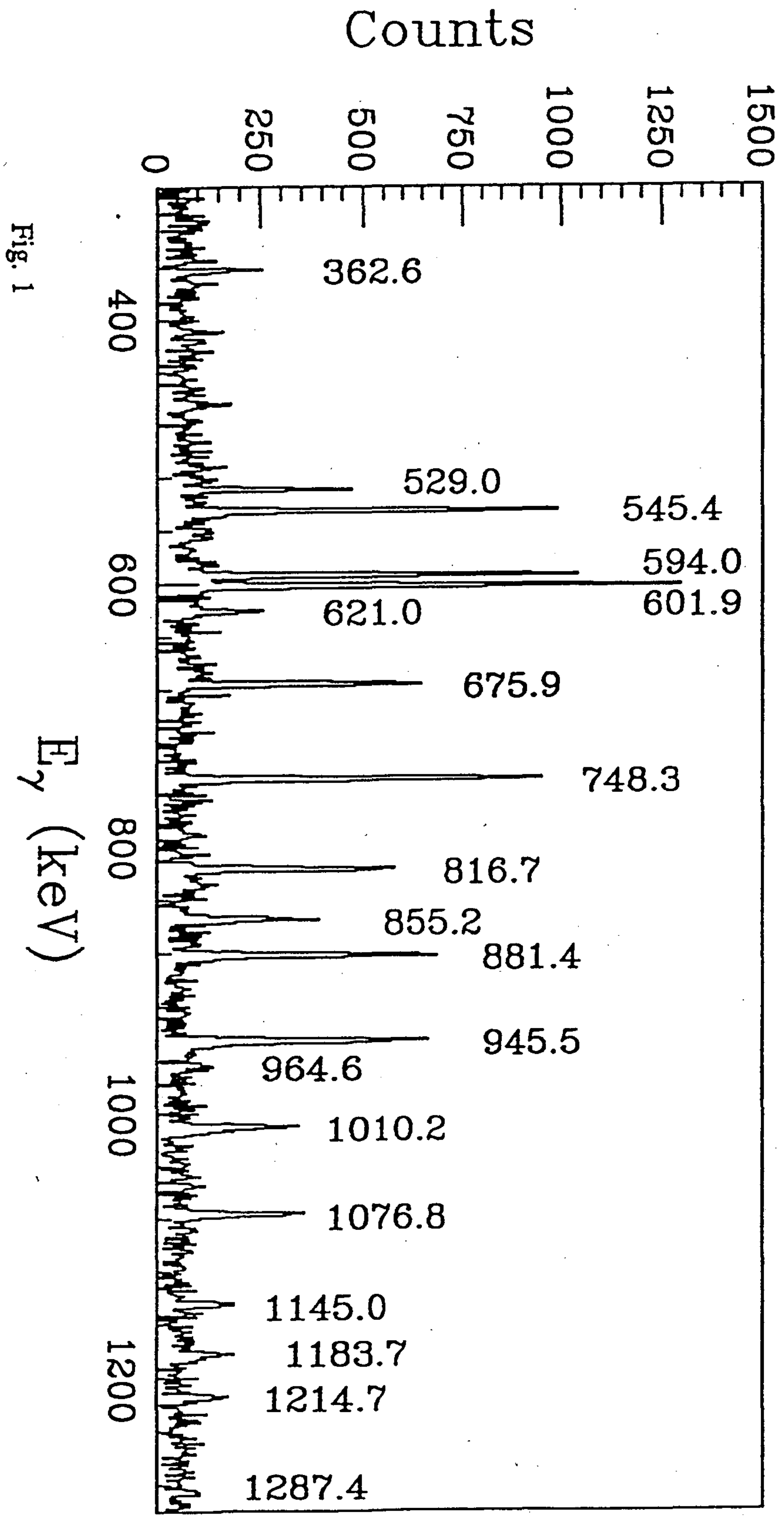
Counts
0
250
500
750
1000
1250
1500
400
600
800
1000
1200
E_γ (keV)
362.6
529.0
545.4
594.0
601.9
621.0
675.9
748.3
816.7
855.2
881.4
945.5
964.6
1010.2
1076.8
1145.0
1183.7
1214.7
1287.4

Fig. 1

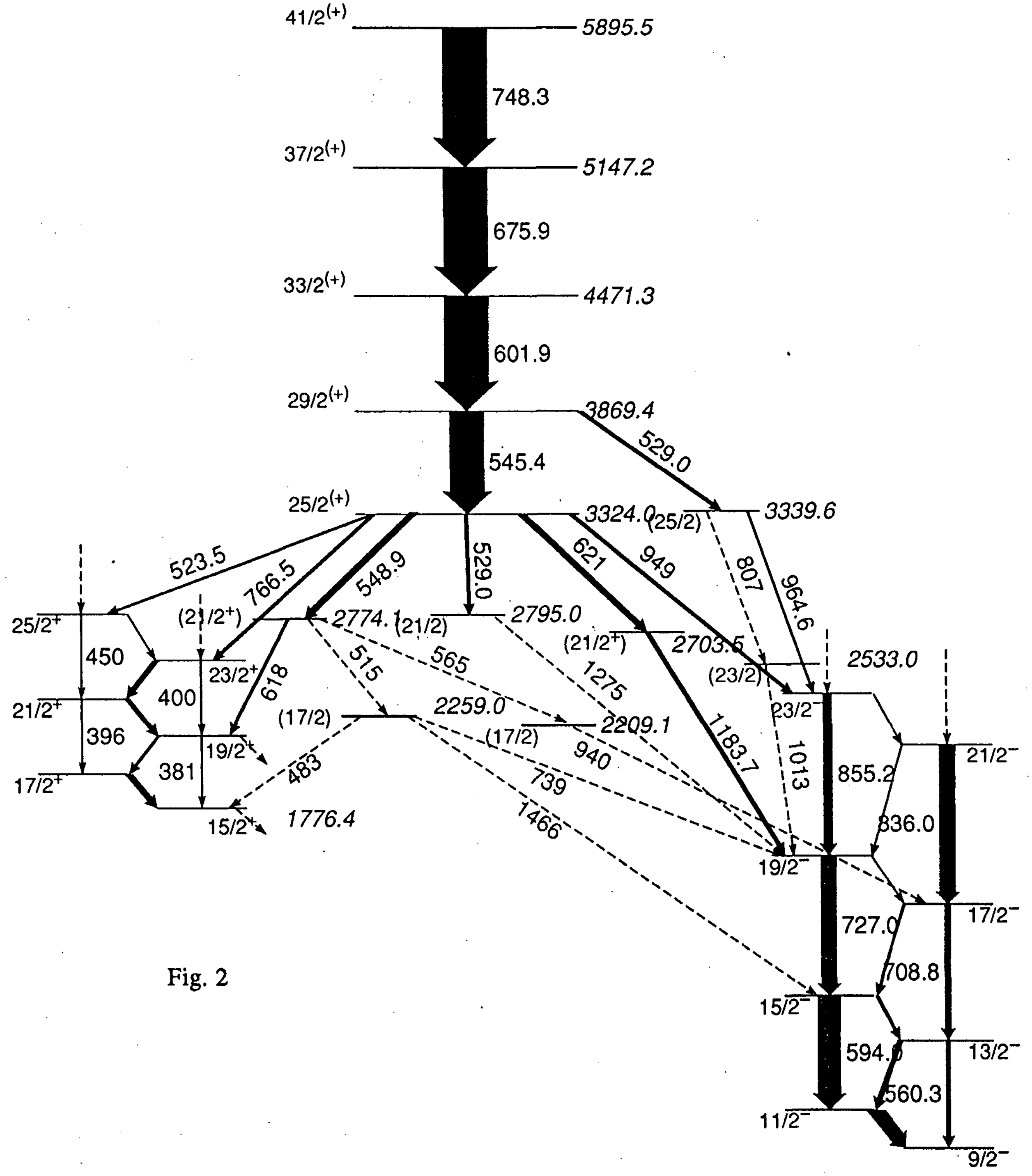
41/2(+)
5895.5
748.3
37/2(+)
5147.2
675.9
33/2(+)
4471.3
601.9
29/2(+)
3869.4
529.0
545.4
25/2(+)
3324.0
(25/2)
3339.6
523.5
766.5
548.9
529.0
621
949
807
964.6
25/2+
450
(21/2+)
2774.1
(21/2)
2795.0
(21/2+)
2703.5
2533.0
23/2+
400
618
515
565
1275
(23/2)
23/2−
21/2+
(17/2)
2259.0
2209.1
396
19/2+
(17/2)
940
1183.7
1013
855.2
21/2−
17/2+
381
483
739
15/2+
1776.4
1466
836.0
19/2−
17/2−
727.0
708.8
15/2−
594.0
13/2−
560.3
11/2−
9/2−

Fig. 2

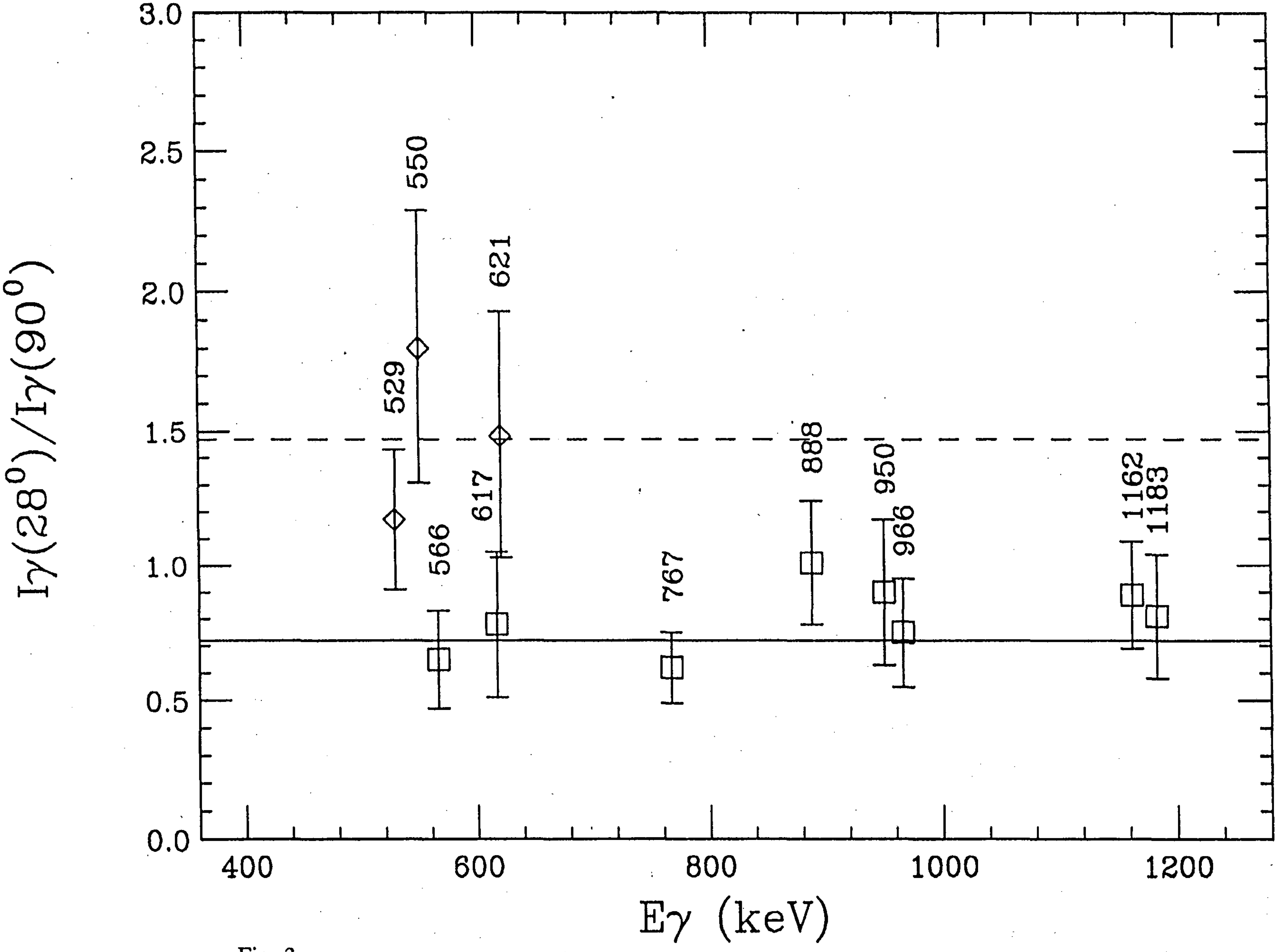
Iγ(28⁰)/Iγ(90⁰)
Eγ (keV)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
400
600
800
1000
1200
529
550
566
617
621
767
888
950
966
1162
1183

Fig. 3

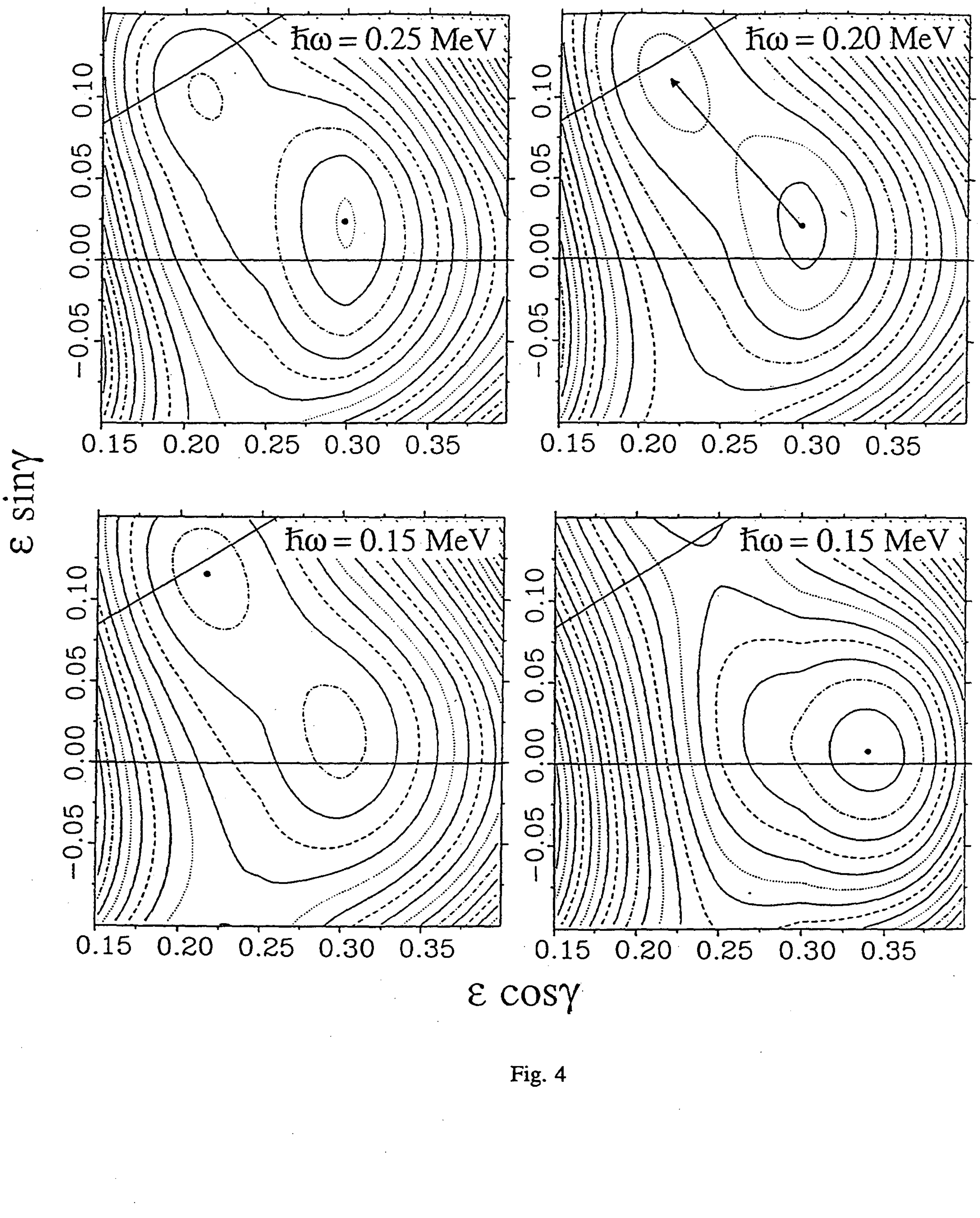
ħω = 0.25 MeV
ħω = 0.20 MeV
ħω = 0.15 MeV
ħω = 0.15 MeV
ε sinγ
ε cosγ
0.15
0.20
0.25
0.30
0.35
−0.05
0.00
0.05
0.10

Fig. 4

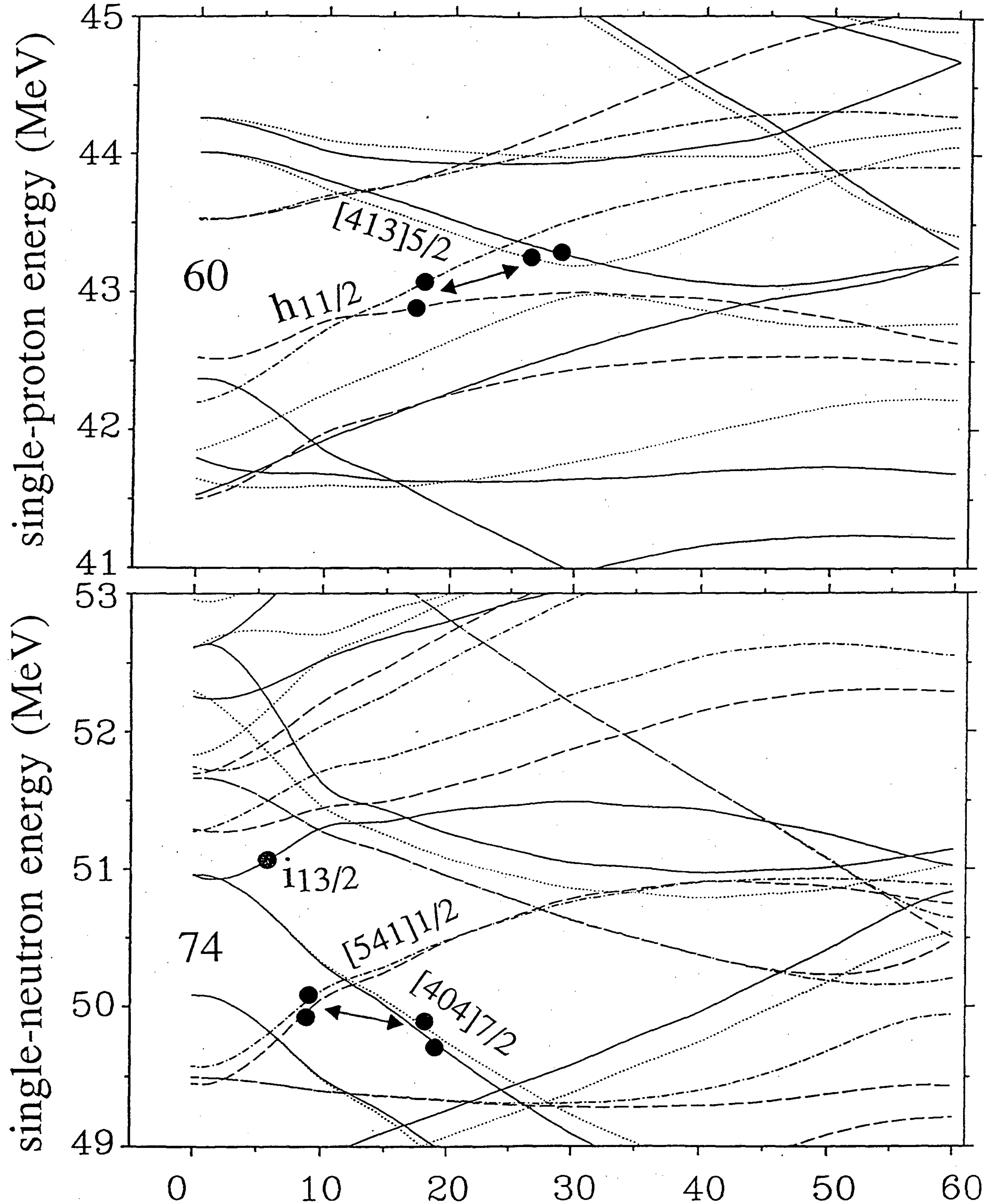
single-proton energy (MeV)
45
44
43
42
41
60
[413]5/2
h11/2
single-neutron energy (MeV)
53
52
51
50
49
i13/2
74
[541]1/2
[404]7/2
0
10
20
30
40
50
60
gamma

Fig. 5

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