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Medium-spin excitations of the neutron-rich ^{84}Se isotope: Possible decrease in energy of the N = 50 neutron-core excitation

A. Prévost[1], M.G. Porquet[1,a], A. Astier[1], I. Deloncle[1], F. Azaiez[2,b], A. Buta[2], D. Curien[2], O. Dorvaux[2], G. Duchêne[2], B.J.P. Gall[2], F. Khalfallah[2], I. Piqueras[2], M. Rousseau[2], M. Meyer[3], N. Redon[3], O. Stézowski[3], Ts. Venkova[4], R. Lucas[5], and A. Bogachev[6]

[1] CSNSM, IN2P3-CNRS/Université Paris-Sud, 91405 Orsay, France
[2] IReS, IN2P3-CNRS/Université Louis Pasteur, 67037 Strasbourg Cedex 2, France
[3] IPNL, IN2P3-CNRS/Université Claude Bernard, 69622 Villeurbanne Cedex, France
[4] INRNE, BAS, 1784 Sofia, Bulgaria
[5] CEA/Saclay, DSM/DAPNIA/SPhN, 91191 Gif-sur-Yvette Cedex, France
[6] JINR, Joliot-Curie 6, 141980, Dubna, Moscow region, Russia

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Abstract. The ^{84}Se nucleus has been produced as fission fragment in the fusion reaction ^{18}O + ^{208}Pb at 85 MeV bombarding energy and studied with the Euroball IV array. Medium-spin states of this neutron-rich isotope have been identified for the first time. Its level scheme has been obtained up to 4.9 MeV excitation energy and spin $I \sim 7\hbar$. Its structure is interpreted by analogy with those of the stable heavier isotones. The evolution of the energy of the $N = 50$ neutron-core excitation is discussed as a function of the proton number.

PACS. 21.60.Cs Shell model – 23.20.Lv γ transitions and level energies – 25.85.Ge Charged-particle-induced fission – 27.50.+e $59 \leq A \leq 89$

1 Introduction

Study of nuclei close to ^{78}Ni is of primary importance to determine directly how the $N = 50$ shell gap evolves at such large neutron excess. A very efficient method to estimate the energy of a shell gap is to study the particle-hole states in which one nucleon is promoted across the gap. For instance the multiplet of the six states with spin values ranging from 2^+ to 7^+, corresponding to the $N = 50$ core excitation $(\nu g_{9/2}^{-1} \nu d_{5/2}^{+1})$ have been measured in ^{90}Zr using the neutron pickup reaction, $^{91}_{40}$Zr$_{51}$(t, α) [1] and in ^{88}Sr using the neutron stripping reaction, $^{87}_{38}$Sr$_{49}$(d, p) [2]. The extension of such measurements to nuclei far from the stability valley would need radioactive beams in inverse reactions.

In some cases, when they are located near the yrast line, the highest spin states of the multiplet are populated using heavy-ion–induced reactions and can be studied by γ-ray spectroscopy. For instance the 5^+, 6^+, and 7^+ states of the neutron-core excitation have been identified in ^{86}Kr produced by the reaction ^{82}Se(^{7}Li, p2n) [3]. Along the $N = 50$ isotonic chain, ^{86}Kr is the lightest even-even nucleus which can be produced using fusion-evaporation reaction with stable projectile. Another technique, fission induced by heavy ions, can be used to populate high-spin states of some stable or neutron-rich nuclei. As more than one hundred nuclei are produced in such a reaction, the great sensitivity and high efficiency of the germanium array are decisive [4].

We report here new results obtained in the $^{84}_{34}$Se$_{50}$ nucleus produced in the fusion-fission reaction ^{18}O + ^{208}Pb at 85 MeV bombarding energy and studied with the Euroball IV array. Its medium-spin states have been identified up to spin ($7\hbar$). From the comparison with the excited states known in the heavier $N = 50$ isotones, we propose configurations involving both proton and neutron excitations. Particularly three excited states with spin (5^+), (6^+) and (7^+) are assigned to the neutron-core excitation. The evolution of their energy is analyzed as a function of the proton number.

[a] e-mail: porquet@csnsm.in2p3.fr
[b] *Present address*: IPN, IN2P3-CNRS and Université Paris-Sud, 91406 Orsay, France.

2 Experimental procedures and analysis

In our experiment, the ^{84}Se nuclei have been produced as fission fragments following the fusion reaction ^{18}O + ^{208}Pb at 85 MeV bombarding energy. The beam was provided by the Vivitron accelerator of IReS (Strasbourg). The target consisted of a self-supported 100 mg/cm^2 ^{208}Pb foil thick enough to stop the recoiling nuclei. The gamma-rays were detected with the Euroball IV array [5]. The spectrometer contained 71 Compton-suppressed Ge detectors (15 cluster germanium detectors placed in the backward hemisphere with respect to the beam, 26 Clover germanium detectors located around 90°, 30 tapered single-crystal germanium detectors located at forward angles) and an inner ball of 210 BGO crystals. Each cluster detector is composed of seven closely packed large-volume Ge crystals [6] and each Clover detector consists of four smaller Ge crystals [7].

The data were recorded in an event-by-event mode with the requirement that a minimum of three unsuppressed Ge detectors fired in prompt coincidence. A set of 4×10^9 three- and higher-fold events were available for a subsequent analysis. The offline analysis consisted of both multi-gated spectra and three-dimensional "cubes" built and analyzed with the Radware package [8].

More than one hundred nuclei are produced at high spin in such experiments, and this gives several thousands of γ transitions which have to be sorted out. Single-gated spectra are useless in most of the cases. The selection of one particular nucleus needs at least two energy conditions, implying that at least two transitions have to be known. The identification of transitions depopulating high-spin levels which are partially unknown is based on the fact that prompt γ-rays emitted by complementary fragments are detected in coincidence [9,4]. For the reaction used in this work, we have studied many pairs of complementary fragments with known γ-ray cascades to establish the relationship between their number of protons and neutrons [10]. The sum of the proton numbers of complementary fragments has been found to be always the atomic number of the compound nucleus, $Z = 90$. The total number of emitted neutrons (sum of the pre- and post-fission neutrons) is mainly 4, 5, and 6. This number has been used to identify the γ-ray cascades of the ^{84}Se nucleus, as explained in the next section.

3 Experimental results

The low-spin part of the ^{84}Se level scheme had been already studied from two-neutron transfer reactions and from ^{84}As β-decay. The first excited state has been identified with excitation energy 1454 keV and spin 2^+. Different spin values have been successively assigned to the second excited state (2121 keV) which only decays to the first excited state (E_γ = 667 keV). A first assignment, $I^\pi = (2^+)$, was proposed [11] from the analogy with other $N = 50$ isotones. Afterwards another value (1^-) has been chosen in the 1989 compilation [12], because of the population of a state around 2.1 MeV excitation with $L = 1$ in

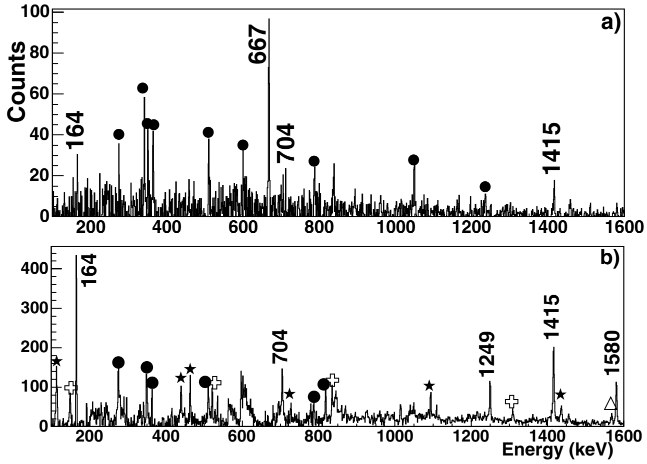

Fig. 1. Double-gated spectra a) set on the 818 keV and 1454 keV yrast transitions of ^{136}Ba and ^{84}Se, respectively, and b) set on the 1454 keV and 667 keV yrast transitions of ^{84}Se. Transitions emitted by the complementary fragments, ^{136}Ba (circles), ^{137}Ba (triangles), ^{138}Ba (stars) and ^{139}Ba (crosses) are indicated in the spectra.

Table 1. Properties of the transitions assigned to ^{84}Se observed in this experiment.

E_γ (keV)	I_γ	$J_i^\pi \to J_f^\pi$	E_i	E_f
164.1(2)	11(6)	$5^\pm, 6^\pm \to 5^\pm, 6^\pm$	3700.9	3536.7
666.8(3)	100(5)	$4^+ \to 2^+$	2121.3	1454.5
704.4(4)	10(3)	$6^\pm, 7^\pm, 8^\pm \to 5^\pm, 6^\pm$	4405.3	3700.9
1248.7(2)	12(3)	$5^\pm, 6^\pm \to 4^+$	3370.0	2121.3
1361.4(4)	3(1)	$6^\pm, 7^\pm, 8^\pm \to 5^\pm, 6^\pm$	4898.1	3536.7
1415.3(2)	25(3)	$5^\pm, 6^\pm \to 4^+$	3536.7	2121.3
1454.5(2)	–	$2^+ \to 0^+$	1454.5	0
1579.8(3)	14(3)	$5^\pm, 6^\pm \to 4^+$	3700.9	2121.3

a two-neutron transfert reaction [13]. In the last compilation [14], a (4^+) value is assigned to the 2121 keV state, following another publication dealing with an extended decay study of ^{84}As [15], in which new level systematics of the even-even $N = 50$ has been taken into account.

In order to unambiguously identify the second yrast transition of ^{84}Se, we have looked for new transitions in all the spectra gated by the two most intense transitions of its complementary fragments, ^{136}Ba, ^{137}Ba, and ^{138}Ba. Two transitions (1454 keV and 667 keV) can be clearly assigned to ^{84}Se. For instance, as shown in fig. 1, the 667 keV transition is clearly observed in triple coincidence with the 1454 keV transition and the first transition of ^{136}Ba. The second spectrum shown in fig. 1 gives all the new transitions depopulating the medium-spin states of ^{84}Se observed in our experiment. They are given in table 1. The level scheme presented in fig. 2 has been deduced from further investigations of the coincidence data.

In fission experiments, spin values can be assigned from γ-ray angular correlation measurements (see, for instance, the results obtained in ^{136}Te, ^{138}Xe [16], in ^{133}Sb [17] or in ^{139}I [18]). The statistics of our ^{84}Se data was unfortunately

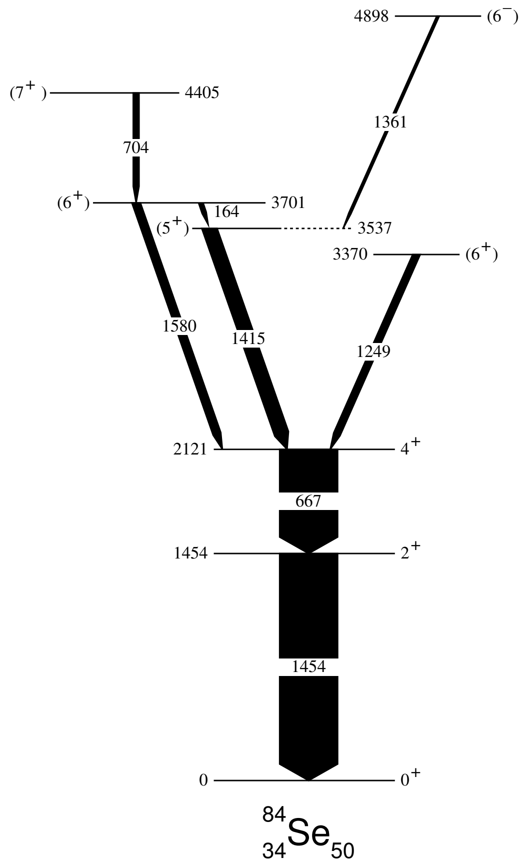

Fig. 2. Level scheme of ^{84}Se obtained as fission fragment in the fusion reaction $^{18}O + ^{208}Pb$ at 85 MeV beam energy. In most cases several values of spin and parity can be assigned to the excited states, they are all reported in table 1. According to the discussion (see text), only one selected value is given for each state.

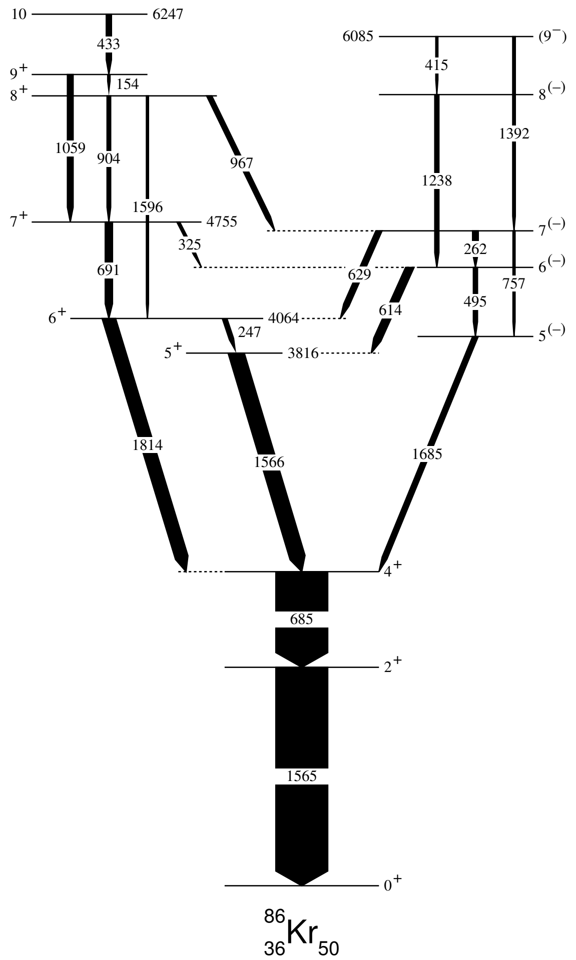

Fig. 3. Level scheme of ^{86}Kr obtained as fission fragment in the fusion reaction $^{18}O + ^{208}Pb$ at 85 MeV beam energy.

too low to perform such an analysis, except in one case which will be discussed later. Therefore spin assignments given in table 1 are based upon the assumption that in yrast decays, spin values increase with excitation energy and that the transitions are dipole or quadrupole (no delayed-coincidence events have been found in the ^{84}Se data). In the next section we will select some spin values (given in fig. 2) from the systematic behaviour of the heavier isotones and from some analogies with the level structure of the neighbouring ^{86}Kr isotone.

Its medium-spin level scheme has been already studied by $^{82}Se(^{7}Li, p2n)$ reaction up to 7.9 MeV excitation energy and spin around $12\hbar$ [3]. The levels located above 3.5 MeV have been grouped into two parallel structures with opposite parity values. ^{86}Kr is also observed in the present data. Therefore we have also studied its medium-spin states from our data set, in order to identify the levels populated in such a reaction and to have confidence when analyzing the similarities of the two isotones, ^{86}Kr and ^{84}Se. The ^{86}Kr level scheme, shown in fig. 3, is in complete agreement with the previous one [3] up to 6.3 MeV excitation energy and spin around 10. We could not confirm the location of three very weak transitions (1313, 1211 and 880 keV) placed in the top of the level scheme of ref. [3], whereas we agree with the existence of the two next ones (331 and 417 keV), which are clearly seen in coincidence with all the transitions involved in the de-excitation of the 6247 keV state (see fig. 3). One can notice that the populations of the two branches are similar to the ones from the previous experiment using the (^{7}Li, p2n) reaction.

The spin and parity values given in fig. 3 have been determined from the values of the angular distribution coefficients obtained in the fusion-evaporation reaction [3]. Moreover we have analyzed several γ-γ angular correlations in order to confirm some of the spin assignments. In angular-correlation measurement, the coincidence rate of two successive γ-transitions is analyzed as a function of the average relative angle between the two fired detectors. The coincidence rate is maximum at 90° for the dipole-quadrupole correlations, whereas it is maximum at 0° (and 180°) for the quadrupole-quadrupole ones. The Euroball IV spectrometer has C^2_{239} combinations of 2 detectors, out of which around 2000 involve different values of relative angle within 2°. In order to keep reasonable

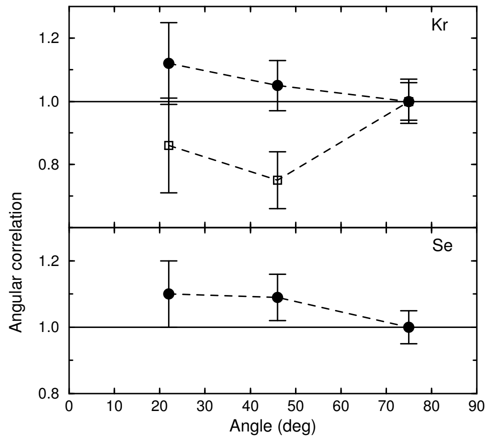

Fig. 4. Coincidence rate between γ-rays as a function of their relative angle of detection, normalized by the one obtained around 75°. Top, in ^{86}Kr: 1814-685 (Q-Q) (filled circles), 1685-685 (D-Q) (empty squares). Bottom, in ^{84}Se: 667-1454 (Q-Q) (filled circles). Dashed lines are drawn to guide the eye.

numbers of counts, all these angles have been gathered around three average relative angles: 22°, 46°, and 75°.

The results shown in fig. 4 indicate a quadrupole character for the 1814 keV transition and a dipole one for the 1685 transition. Unfortunately the existence of the 1565-1566 doublet in mutual coincidence hinders the analysis of the angular correlation involving the 1566 keV transition. It is expected to be dipole because of the location of the quadrupole 1814 keV transition (in parallel with the 247-1566 cascade). A negative parity can be tentatively assigned to the structure drawn in the right part of fig. 3, as medium-spin negative parity states are expected in this energy range, as discussed in the next section.

We can now go back to the spin values of the excited states in ^{84}Se. We have measured angular correlations between the 1454 keV and 667 keV transitions. The quadrupole character of the 667 keV transition is established (see fig. 4).

4 Discussion

Shell-model calculations in large model spaces had been already performed in order to describe the structure of the $N = 50$ and $Z < 50$ nuclei. For instance, effective interactions with active $f_{5/2}$, $p_{3/2}$, $p_{1/2}$, and $g_{9/2}$ orbitals for the valence protons had been obtained from an iterative fit to a lot of experimental energy levels from ^{82}Ge to ^{96}Pd [19]. Then the calculated structure of the $N = 50$ isotones with $A = 80$–87 has been compared to the experimental results [20], showing that properties of these lighter $N = 50$ isotones are dominated by well-mixed combinations of proton fp orbit configurations, the $\pi g_{9/2}$ orbit playing a minor role. Unfortunately we cannot rely on their predictions for ^{84}Se, as the values of the effective interactions have been fitted in order to reproduce the 2121 keV level with $I^\pi = 2^+_2$ instead of $I^\pi = 4^+_1$. This would lead to large discrepancies in the description of excited states of ^{84}Se, for instance the first 4^+ state is predicted at 2837 keV excitation energy. In another approach to describe the $N = 50$ and $Z < 50$ nuclei [21], the matrix elements of the effective two-body interaction had been calculated from a nucleon-nucleon potential, the Sussex interaction. Whereas the results are found to be in agreement with experiment for all nuclei with $38 < Z \leq 46$, the calculated levels of the isotones with $Z \leq 38$ have too high excitation energies. For instance the 2^+_1 state of ^{84}Se is calculated around 2.2 MeV and the 4^+_1 state around 2.7 MeV.

More recently the medium-spin states of ^{86}Kr have been interpreted [3] using shell-model calculations using four proton subshells and two neutron ones, $g_{9/2}$ and $d_{5/2}$ (allowing the neutron-core excitation). For the effective two-body interaction, different empirical Hamiltonians with results obtained from schematic interactions have been combined. It should be stressed that the first 7^+ state due to *proton* excitations is predicted around 7.5 MeV excitation energy since such a spin value needs the excitation of two protons towards the $g_{9/2}$ subshell very far from the proton Fermi level. When the neutron-core excitation is taken into account, the predicted excitation energy of the first 7^+ state is lowered by 2.2 MeV, its dominant configuration is then $\nu g^{-1}_{9/2} \nu d^{+1}_{5/2}$. It is the same for the first 6^+ and 5^+ states which are predicted with strong admixtures of neutron configurations. Therefore the 5^+, 6^+, and 7^+ yrast states of ^{86}Kr (located at 3816 keV, 4064 keV, and 4755 keV, respectively, see fig. 3) have been interpreted in terms of neutron-core $N = 50$ excitation [3].

We discuss now the new results we have obtained in ^{84}Se, using firstly the similarities with its neighbouring isotone, ^{86}Kr, and then the evolution of the *proton* states in the $N = 50$ isotones which can be foreseen when the proton Fermi level moves as a function of the Z number. A close examination of the level schemes of ^{84}Se and ^{86}Kr shows that i) the two first excited levels have almost the same energy and ii) the decay of the 4405 keV level in ^{84}Se is very similar to the one of the 4755 keV level in ^{86}Kr. So the spin values (5^+), (6^+), and (7^+) are assigned to the 3537, 3701 and 4405 keV levels, respectively, and these three states can be interpreted in terms of neutron-core excitation, as in ^{86}Kr.

The configurations of the first excited states of the light $N = 50$ isotones mainly involve four proton subshells, as said above. It is worth pointing out that their energies are not regularly spaced. It is well known from the analysis of the first excited states of nuclei in this mass region (for instance ^{88}Sr, ^{89}Y, and ^{90}Zr) that, whereas the $\pi f_{5/2}$ and $\pi p_{3/2}$ subshells are close, there are large gaps between $p_{3/2}$ and $p_{1/2}$, and between $p_{1/2}$ and $g_{9/2}$, giving rise to two semi-magic numbers, $Z = 38$ and $Z = 40$, respectively. The fact that the proton Fermi level of ^{90}Zr is closer to the $\pi g_{9/2}$ subshell than these of the three lighter isotones leads to a substantial lowering in energy of all the excited states of ^{90}Zr located below 4 MeV excitation energy (see fig. 5).

The first positive-parity excited states of ^{88}Sr, ^{86}Kr, and ^{84}Se involve re-orientation of the angular momenta of protons in the fp subshells which are not completely filled.

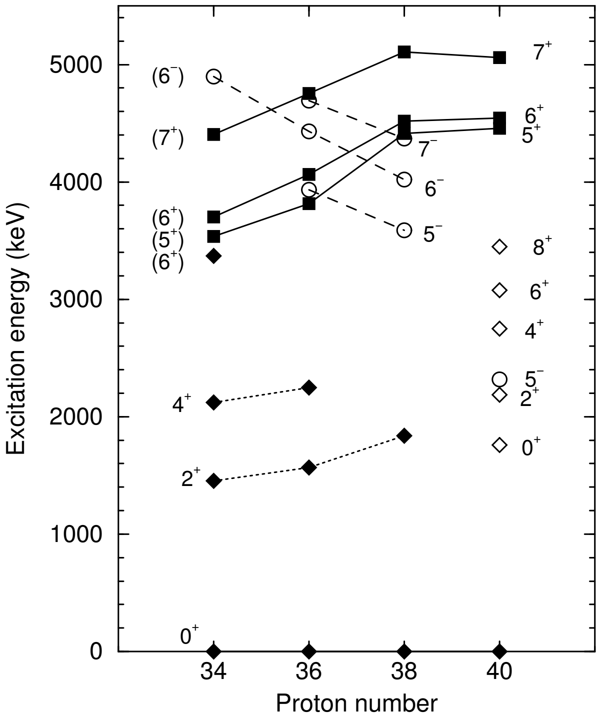

Fig. 5. Evolution of the medium-spin states of the four even-even $N = 50$ isotones, ^{84}Se (this work), ^{86}Kr [3], ^{88}Sr [22,2], and ^{90}Zr [23,1]. States with proton configurations within the fp shells are drawn with filled diamonds, those containing the $\pi g_{9/2}$ shell are drawn with empty symbols (diamonds and circles). States due to neutron-core excitation, $\nu g_{9/2}^{-1} \nu d_{5/2}^{+1}$, are drawn with filled squares.

Only one excited state (2^+) is expected in ^{88}Sr having two holes in the $\pi p_{1/2}$ subshell, whereas a 4^+ state can be obtained in ^{86}Kr from the first particle-hole excitation, $\pi f_{5/2} \to \pi p_{3/2}$, since its $\pi p_{3/2}$ subshell is partially empty. As said before, a very high energy is needed to obtain a 6^+ state in ^{86}Kr from *proton* excitation. On the other hand, a 6^+ excited state can be observed in ^{84}Se, as it only needs the excitation of two protons from the $\pi f_{5/2}$ subshell to the $\pi p_{3/2}$ one, which is very close in energy. The 3370 keV state which only decays to the 4^+ state can be assigned as this 6^+ state (see figs. 2 and 5).

The high excitation energies of the first negative-parity excited states increase from ^{88}Sr to ^{86}Kr, as the proton Fermi level gets further and further from the $\pi g_{9/2}$ subshell when the number of protons decreases. Then it could be assumed that the highest excited state we have identified in ^{84}Se at 4898 keV is a (6^-) state, as its decay is similar to the one of the 6^- state of ^{86}Kr (see figs. 2 and 3) and it has the expected energy (see fig. 5).

All the medium-spin states which have been observed in ^{84}Se from the present work are drawn in fig. 5, showing their possible counterparts in the heavier isotones. It is worth pointing out that, within such an interpretation, the evolution of the energy of the neutron-core excitation states as a function of proton number shows that the lowering in energy already known from ^{88}Sr to ^{86}Kr is going on from ^{86}Kr to ^{84}Se. Therefore a weakening of the $N = 50$ spherical shell gap would take place when Z is decreasing from 38 to 34 and would have to be taken into account when performing shell model calculations in the light $N = 50$ isotones.

5 Summary

Medium-spin structure of the neutron-rich $^{84}Se_{50}$ isotope have been populated using the fusion-fission reaction $^{18}O + {}^{208}Pb$ at 85 MeV bombarding energy. Transitions between the excited states have been measured with Euroball IV spectrometer. The medium-spin excited states have been observed up to 4.9 MeV excitation energy and the spin values have been mainly assigned from the similarities of the decay modes of the excited states in ^{84}Se and ^{86}Kr. The excited states of ^{84}Se have been interpreted in terms of both proton and neutron excitations. A possible weakening of the $N = 50$ spherical shell gap, when Z is decreasing from 38 to 34, has been pointed out.

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