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SYSTEMATIC TRENDS IN THE LEVEL STRUCTURE OF NEUTRON RICH NUCLEI

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Abstract: The empirical systematic low energy properties of very neutron rich isotopes of Cd, In and Sn are discussed. This region of the nuclear chart comprises many nuclei whose β-decays are dominated by a strong transition to some low lying level in the daughter nucleus, having a relatively simple structure in terms of the shell model. The observed regularities suggest that simple empirical predictions can be made regarding the main features of the decays of unknown or little known nuclei. The decay of ^{130}Cd is discussed as an example of such predictions. A very brief discussion of fast first forbidden β-decays is also made.

Introduction

Neutron rich nuclei are difficult to study, and consequently much less known than the neutron deficient ones. Fortunately the fission process provides an efficient means for production of a large number of relatively heavy neutron rich nuclei, and studies of fission products have made it possible to extend the knowledge of some nuclear properties far out from the line of β-stability. The high stability of the strong double shell closure at ^{132}Sn has a dominating influence on the yields of products from thermal fission of the most common fissionable nuclei. These high yields has to some extent facilitated experimental work on the nuclei in the heavy tin region where properties such as the low energy level structure and β- and γ-ray transition probabilities now have been studied experimentally for a number of nuclei in the vicinity of ^{132}Sn. Much knowledge is of course still missing. We know e.g. the positions of only about half of the basic single particle levels in the valence nuclei in this region, but on the other hand, some of the single particle level properties have been studied over nearly the entire N=50-82 neutron shell. In the following, only data on nuclei near the Z=50 shell will be discussed, with a special emphasis on the properties of neutron rich isotopes of Cd, In and Sn. In the following these nuclei will be said to comprise "the heavy Sn region". This region of the nuclear chart is of interest not only from the point of view of the shell model, but also for models of the r-process of nucleosynthesis and for modelling of the nuclear mass surface which has a complicated shape near the double shell closure. The heavy Sn region is also notable because the gross β-decay properties of many nuclei here, are essentially dependent on a small number of identifiable transition probabilities of both allowed and first forbidden nature.

Experimental studies

Collecting and evaluating enough data to build up a systematic knowledge of nuclear low energy properties over some ten mass numbers for isotopes of Cd, In and Sn is a time consuming occupation. The data discussed in the following stem mostly from experimental work performed by several people at the OSIRIS mass-separator facility/1/ in Studsvik during the past 10-15 years. The experimental difficulties increase with every step further away from stability, which has to be compensated by a continuous development of the facility. Some details/2,3/ of the development work has been published recently. A part of this work has as aim the production of clean samples of very neutron rich isotopes of Cd in order to extend the experimental studies to the practically unknown isotopes ^{129,130,131}Cd. The idea is to perform a chemical separation by means of thermochromatography after the collection of the mass separated samples and thus obtain Cd activity free from the higher Z isobars, which have much larger fission yields. As an example of the data obtained in the test runs, one may mention that the most strongly populated level in the even mass Cd decays now have been unambiguously identified as having $J^\pi=1^+$ in ^{126,128}In see fig. 1. These 1^+ states

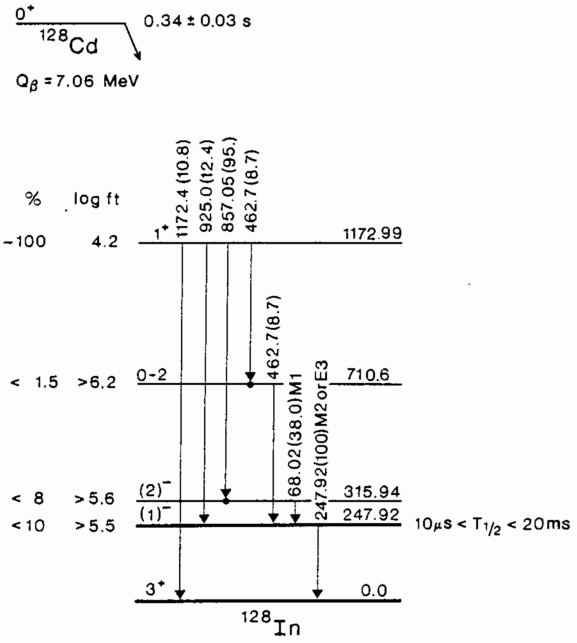

Fig. 1. Levels and transitions in ^{128}In as obtained in recent work/4/ at OSIRIS. The ground state transition from the 1173 keV level together with the known $J^\pi=3^+$ of the ground state ascertains a 1^+ assignment for the strongly β-particle populated 1173 keV level. This ground state γ-ray can only be observed by using chemically separated Cd samples due to strong interference from radiation following the decay of ^{128}In. Transition multipolarities were deduced from conversion electron measurements.

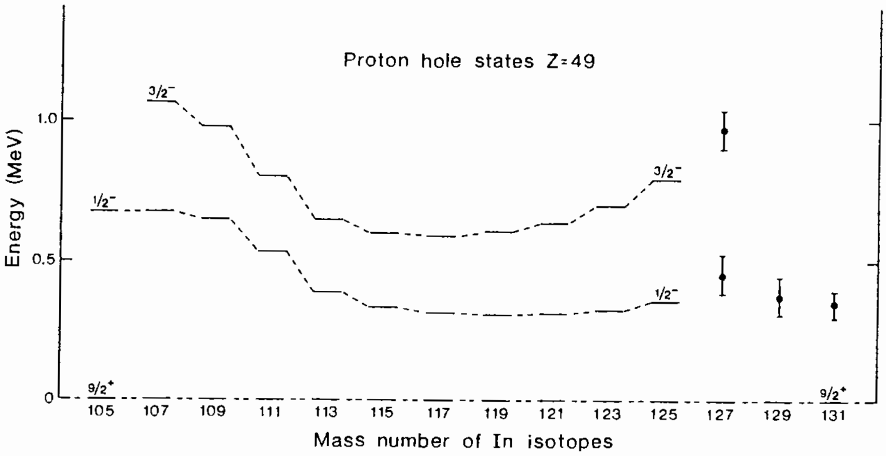

Fig. 2. The low lying proton hole levels in odd-mass In isotopes. Data for $A \geq 123$ are from recent experiments at the OSIRIS facility. Error bars are given for level energies deduced from total β-decay energies. The level systematics is discussed in the text.

are of importance for the main decay strength of the even mass Cd isotopes and will be discussed further later on. In addition to the nuclear spectroscopy studies the current experimental activity encompasses measurements of total decay energies, absolute branching ratios of delayed neutrons and γ-rays and measurements of fission yields.

Discussion

The decay properties and the low energy level structure of the nuclei discussed here are strongly dependent on the available shell model orbitals. In particular the proton $g_{9/2}$ and the neutron $g_{7/2}$ orbitals and their interactions have a decided import on many details of the basic decay properties in the heavy Sn region. One such detail is simply a consequence of the very fast β-transition connecting the $g_{9/2}$ and the $g_{7/2}$ orbitals. This transition dominates the β-strength in the decays of some 25 states in the heavy In isotopes having $N \leq 82$. The comparatively short half lives of these isotopes and many of their isomers are thus mainly determined by a single transition probability of an allowed favoured β-transition. The observed regularities were often quite helpful during the collection of experimental data in this region, because the main decay properties of still unknown nuclei could to some extent be predicted from the empirical information obtained for other decays.

Most of the following discussion will be devoted to the g-orbitals in view of their importance for the low energy properties of many nuclei in the heavy Sn-region. Although the systematic data to be discussed was not gathered with a specific goal in mind, I hope it will be instructive to show how the available data on single- and two-quasi-particle levels can be used for a simple empirical prediction of the main decay properties of a still practically unknown nucleus, ^{130}Cd. This decay is of some interest as the levels in the daughter nucleus are of a simple two-hole character, and also because ^{130}Cd is expected to be a "waiting point" in the r-process of nucleosynthesis. Let us begin with a glance at the proton hole states. The information obtained for odd mass In isotopes with $A \geq 123$ in recent experiments/5,6,7/ at our laboratory now permits drawing a level systematics, fig. 2, which spans nearly the entire 50-82 neutron shell. The larger separation between the $1g_{9/2}^{-1}$ ground state and the negative parity levels at the beginning of the neutron shell, is well known to be caused by the relatively strong interaction of the proton $g_{9/2}^{-1}$ hole with neutrons in the $g_{7/2}$ orbital. When this latter orbital is filled, which occurs at ^{113}In, none of the available neutron states should be able to interact with the lowest proton hole levels. At present we do not know the exact energy of the proton hole $p_{3/2}^{-1}$ level in ^{131}In, although inspection of fig. 2 suggests that its separation from the $p_{1/2}^{-1}$ state should be of the order of one MeV. This energy is very nearly the same as the phonon energy in the mid-shell Sn core nuclei, and thus readily explains the sensitivity of the $p_{3/2}^{-1}$ state to configuration mixing. This mixing permits the interaction resulting in the small $3/2^- - 1/2^-$ separation seen in the mid-shell region. For the present purposes the most important feature of fig. 2 is the manifest p-n interaction of the g-orbitals. The β-decay of ^{130}Cd, which can be expected to have a large amplitude of $(\pi g_{9/2}^{-2})_{0^+}$ in the ground state, should be similar to the $g_{9/2}$ decays of the In isotopes discussed previously, and consequently mainly populate the $(\pi g_{9/2}^{-1}, \nu g_{7/2}^{-1})1^+$ level of ^{130}In. The energy of this latter level is strongly dependent on the p-n interaction of the g-orbitals. A reasonable approximation of the level energy is given by

$$\varepsilon(1^+)=\varepsilon(\pi g_{9/2}^{-1})+\varepsilon(\nu g_{7/2}^{-1})+\Delta$$

where Δ is the p-n interaction energy. The Δ can be empirically estimated from a comparison of the level energies in the odd and even mass isotopes of In, see fig. 3. For simplicity, the interaction energy shown in the bottom part of fig. 3 has been derived using the ground states as reference, which corresponds to the assumption that the relative energies of the lowest lying neutron states in the odd mass Sn isotopes do not change appreciably when forming the lowest two-quasi-particle states of the even mass isotopes of In. The fig. also clearly illustrates a well known prediction of the shell model, namely that when the neutron $g_{7/2}$ state makes the transition from a particle to a hole, which occurs near A=114, the sign will change for the matrix element of the p-n interaction. The

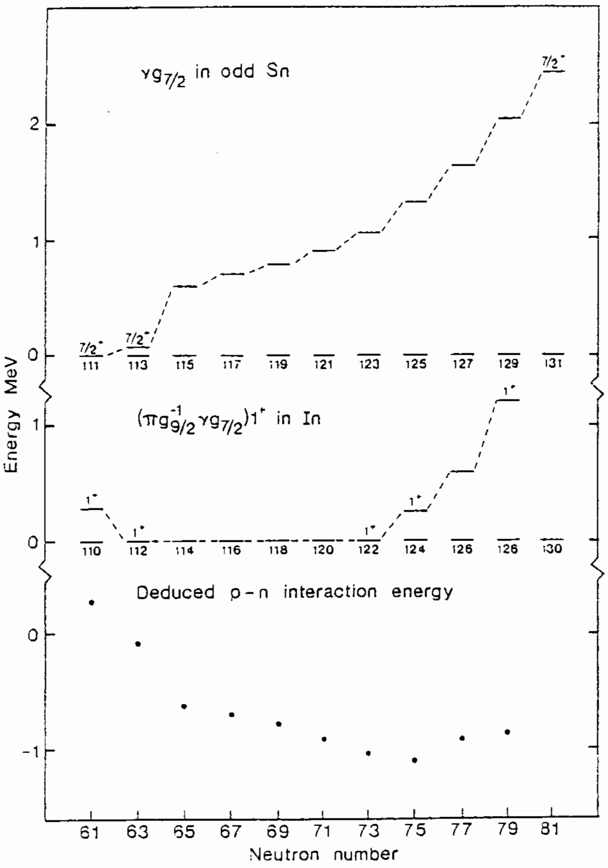

Fig. 3. An illustration of the derivation of an approximate p-n interaction energy between the g-orbitals in isotopes of In. More details are given in the text.

nearly constant interaction energy, Δ, derived for the heavier In isotopes suggest that the excitation energy of the 1^+ level in ^{130}In should be approximately 1.5 MeV. The main β-strength in the decay of ^{130}Cd is thus expected at this energy. Empirically, it is now known/9/ that at least a small part of the β-strength also goes to high lying levels since ^{130}Cd is a delayed neutron precursor. The total strength to levels other than the 1.5 MeV 1^+ state is in all likelyhood small. Assuming a typical log ft-value of 4.4 for this main β-transition, one can thus roughly obtain the half life of ^{130}Cd as 0.13 s. There is a reasonable agreement with the measured /9/ value of (0.195±0.035) s. The known data on the main decay branches of the heavy even mass Cd-isotopes are summrized in fig. 4. One may note that the β-transitions are faster for the light nuclei which are further removed from the closed neutron shell at N=82. This is most likely an effect of coherent addition of transition amplitudes from admixed configurations.

The experimental data discussed so far have been chosen to emphasize the importance of the fast allowed transition between the g-orbitals. It should also be pointed out that many of the β-decaying states of the nuclei in the heavy Sn region are having first forbidden transitions as the main decay channel. The transition probabilities can in many cases be substantial and approach the values commonly observed for allowed transitions. As an example, fig. 5 shows the log ft values derived for the transitions from the $\pi 2p^{-1}_{1/2}$ isomer of the heavy odd mass In isotopes to the $\nu 3s_{1/2}$ and $\nu 2d_{3/2}$ levels in Sn nuclei. It is obvious from the data given in fig. 5 that the transition probabilities of these first forbidden decays are rather sensitive to the purity of the final states. The low log ft of the transition to the $3/2^+$ level in ^{131}In follows from the good overlap of initial and final states having the same number of nodes in the wave functions, with a corresponding less good overlap for the $1/2^+$ level which belongs to the next major oscillator shell. When departing from the valence levels at N=81 the differences between the two transition probabilities are quickly washed out since the forbidden transitions are a second order process which can be quite sensitive to minor impurities in the wave functions.

Several additional examples of very fast first forbidden transitions can be found in nuclei which generally are situated near closed or doubly closed shells. Still further cases can be expected in the region "to the right of" ^{132}Sn. Studies of the little known nuclei in this region will be the subject of future experiments.

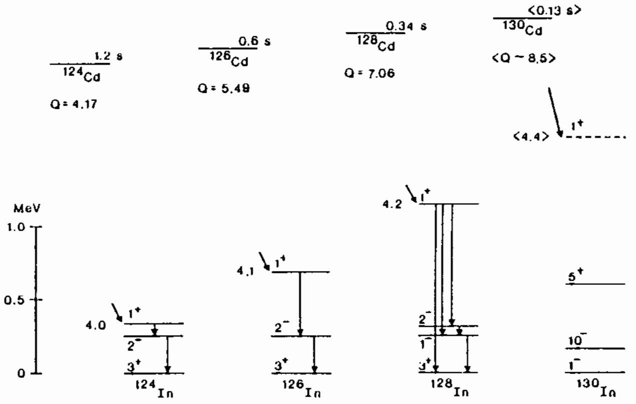

Fig. 4. Systematic features of the decays of the heavy even Cd isotopes. The extrapolation to ^{130}Cd has involved an estimate of the total decay energy. The estimate makes use of the difference between measured values of Q_β and the predictions of the droplet model/8/ of Myers. The lowest lying levels of ^{130}In have so far only been observed as β-decaying states.

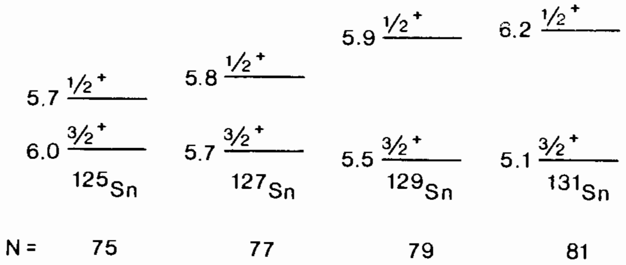

Fig. 5. The first forbidden β-transitions to the $s_{1/2}$ and $d_{3/2}$ levels in the heavy odd mass Sn isotopes dominate the decay of the $p^{-1}_{1/2}$ isomers of In. The log ft values given here are derived using data from a current study/10/ of absolute γ-ray intensities and should be regarded as preliminary values. The numbers are somewhat different from previously published/11/ values.

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