EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-INTC-2003-018
INTC-P-175
19th-20th May 2003
Deadline 21st April 2003

Proposal to the ISOLDE and neutron Time-of-Flight Experiment Committee

STUDY OF NEUTRON-RICH ^{124,126,128}Cd ISOTOPES; EXCURSION FROM SYMMETRIES TO SHELL-MODEL PICTURE

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Abstract.
A short outline is given on a number of topics that are present in the long series of even-even Cd nuclei and therefore, may turn out to constitute an ideal test bench in order to verify a number of theoretical ideas on how collective motion, near closed shells, builds up taking into account both the valence and core nucleons when studying the nucleon correlations. Moreover, these experiments can reveal new challenges when moving towards very neutron-rich systems.

INTRODUCTION

General properties of the Cd nuclei

The Cd nuclei span essentially a full shell with neutron number changing from N=50 to N=82. The main features are those of an anharmonic quadrupole vibrator, in particular when the neutron number is beyond a few neutron particles or neutron holes away from the closed shells at N=50 and N=82, respectively. One approach that covers the systematics is given by the Interacting Boson Model [iac87,fra94]. For the Cd nuclei, in particular, the major parameters are rather well determined from the underlying shell structure. The comparison with known data is very good for the low-energy part of the energy spectra [ker95]. Because of the robust structure of this approach, the model has good predictive power and so we actually can provide both energy spectra and electromagnetic properties for the neutron-deficient (below N=58) and neutron-rich (beyond N=74) Cd nuclei. Experimental tests of these predictions are important for improving our understanding of collective vibrational structures.

PHYSICS MOTIVATIONS

Intruder states near closed shells in the Z=50 region

It has been shown, starting from various spectroscopic selective experiments e.g. transfer reactions in particular, that very near to closed shells (the In and Sb nuclei at Z=50 but also in other mass regions e.g. the Tl and Bi nuclei at Z=82) low-lying extra states, so-called intruder states, have been observed with a conspicuous energy dependence on the number of free valence neutrons, hinting for 2p-2h excitations as their origin (see [hey83] and references in there). If these excitations are proton excitations combined with the neutron degree of freedom appearing on both sides of the Z=50 closed shell, it is a natural step to suggest that low-lying extra 0^+ excitations will also show up in the even-even nuclei in between, e.g. in the Sn nuclei but also in other nearby even-even nuclei. Because the Sn nuclei with a large number of valence neutrons are situated near to the β-stability line, they could be studied more easily and in 1979 the group at the Free University of Amsterdam first observed those 0^+ excitations with a full band developing on top in $^{110\text{-}116}$Sn [bro79]. It took a pretty long time in experimental development in order to study similar excitations in the Pb nuclei because here one had to go far away from stability in order to find the conditions favouring the observation of the states at low excitation energy. The group of the IKS Leuven was successful with first results in 1984 in the nuclei $^{192\text{-}198}$Pb [dup84]. An extensive discussion has been reported by J. Wood et al. [woo92], covering the most important regions of even-even nuclei.

Since making a 1p-1h excitation across the closed shell at Z=50 takes about 4.5 MeV (the proton shell gap), the unperturbed energy for 2p-2h excitations comes up to about 9 MeV. Even though pairing amongst the particles and holes will lower the energy in an important way to 4-5 MeV, this is still far from the observed excitation energy of 1.7 MeV. Some essential element is missing when starting from the spherical intrinsic symmetry of the shell model.

One way to come around is breaking the spherical symmetry and allowing the mean field to acquire quadrupole deformation thereby giving rise to the possibility that spherical orbits split and the large spherical shell gap at Z=50 and also at Z=82 rapidly vanishes. Calculations have been carried out over the years using deformed mean-field studies (Nilsson model, deformed Woods-Saxon, Hartree-Fock-Bogoliubov studies) and we would like to cite in particular [ben89,naz93] with studies in the Pb region. The deformed field essentially points out to need for the quadrupole component in the mean field as the agent for the increased binding energy. Knowing this, and having experimental knowledge of the fact that 1p-1h (in odd-mass nuclei) and 2p-2h (in even-even nuclei) are present in these states, it is tempting to incorporate this in a spherical shell-model description. By invoking a schematic model that was discussed in detail in [hey87] it is possible to evaluate the excitation energy of a 2p-2h configuration

$$E_{\mathrm{int}\,r.}\left(0^{+}\right)=\left\langle 0_{I}^{+}\middle|H\middle|0_{I}^{+}\right\rangle-\left\langle 0_{GS}^{+}\middle|H\middle|0_{GS}^{+}\right\rangle \ , \tag{1}$$

in which the index I denotes the nucleon distribution in the intruder state and GS the distribution in the ground state. Using a pair distribution for the neutrons, combined with a 2p-2h excitation and a 0p-0h excitation for the intruder and regular state, respectively, one can derive the expression

$$E_{intr.}(2p-2h)\cong 2\left(\varepsilon_{p}-\varepsilon_{h}\right)+\Delta E_{M}(2p-2h)-\Delta E_{pair}+\Delta E_{Q}(2p-2h) \ , \tag{2}$$

where the various terms describe the unperturbed energy to create the 2p-2h configuration, a monopole correction due to a change in proton single-particle energy while changing the neutron number, the pairing-energy correction because 0^+-coupled pairs are formed, and the quadrupole binding energy originating from the proton-neutron force, respectively.

In calculating the neutron number dependence of the 2p-2h intruder 0^+ configurations we have to determine the quadrupole energy contribution and this we do by using the SU(3) expression given in [hey87], i.e.,

$$\Delta E_{Q}\cong 2\kappa\Delta N_{\pi}N_{\nu} \qquad , \tag{3}$$

in which ΔN_π denotes the number of pairs excited out of the closed shell configuration at Z=50, i.e., $\Delta N_\pi = 2$ for a 2p-2h excitation.

This approach points out that the essential elements are the strong pairing interactions amongst the particles and the holes that make up for the excited configuration and the strong quadrupole proton-neutron forces. It is precisely here that early contacts between the disconnected ``spaces" of interacting boson within a valence space only and the p-h excitations of the core itself showed up. In a lowest order approximation, one can think of the 2p and the 2h parts to bring in two extra bosons increasing the active model space from N to N+2 bosons and carry out separate calculations for both spaces introducing a coupling between them by using a mixing Hamiltonian

$$H_{mix}=\alpha\left(s^{\dagger}s^{\dagger}\right)^{0}+\beta\left(d^{\dagger}d^{\dagger}\right)^{0}+h.c. \qquad , \tag{4}$$

This approach was introduced by Duval and Barrett [duv82] and has been used with success in the Cd nuclei and nearby even-even nuclei (Mo,Pd,Ru,.. nuclei)(see e.g.[jol90,hey95] and references therein). The presence of these extra states, characterized by 2p-2h excitations across the Z=50 shell closure, has become a fingerprint especially near the N=66 mid-shell region. Moreover, the interference between the regular vibrational states and these intruder states that contain a much larger collectivity, shows up as drastic modifications of the regular vibrational E2 intensity ratios. Detailed calculations have been carried out for all Cd nuclei from A=110 up to A=118 (see also [wan01,wan02,wan03] for a recent study and references in therein). The drawback of those calculations is that one easily gets involved with a lot of parameters and unless one has some physics guidance the detailed agreement needs some caution. An attempt to lower the number of free parameters has been suggested [jol90] and used in the Cd nuclei with quite some success but it was clear that something extra was needed besides the numerical configuration mixing approach.

Using symmetries and multiplets

First hints showed up in the Sn region, where the Cd intruder states could be put into a multiplet by adding the Ru and Ba ground state bands as well as the intruder members in Te nuclei. Recently, it has been shown [yat03] that this holds rather well for the E2 reduced transition probabilities too. Ideas on how to make use of the presence of these multiplets and the subsequent reduction in the number of parameters have been discussed making use of certain symmetries that may hold in the IBM where particle and hole excitations are considered on equal footing [hey92]. For the Cd region, in particular, a symmetry was discovered that explained why certain states were coupling much stronger than others [jol95,leh95]. Details relating to the coupling of two different dynamical symmetries, with applications to the Cd nuclei have been worked out by De Coster et al. [cos96] and Lehman et al. [leh97]. Knowing this, one can make use of the information on the underlying symmetry structure of the interacting boson system where both particle and hole-type bosons are present and go back to the numerical configuration mixing calculations. It is possible to reduce the number of parameters by invoking the idea of I-spin symmetry, which seems to hold rather well in the Sn, Cd, Pd, ... region. Experimental work on intruder states in these nuclei can bring a better understanding of how well this symmetry holds.

Use of microscopic approaches in studies of Cd nuclei

A full shell-model study of the Cd nuclei, with neutrons moving all through the full valence space of N=50 towards N=82, at the same time incorporating, besides the two proton holes outside of Z=50, the 2p-2h excitations that show up in the mid-shell neutron region (around N~66), is out of reach. Only when approaching the neutron shell closure at N=50 i.e. N=52,54 and for the heavy nuclei near N=82 considering the cases with N=80,78 and also beyond, at N=84, full shell-model studies can become feasible. Therefore, the study of these extreme heavy nuclei is important since it may shed light on the way how collective quadrupole states (with anharmonicities included) may go over into the shell-model structure: there should be some region of overlap which can give us very interesting information.

As mentioned above, the nuclear shell model is not in a position to be used for a reliable computation of the low-energy properties of the full range of Cd nuclei. This means that one has to resort to a suitable truncation of the shell model. Such a model has been developed lately [del03]. In this model one starts from a realistic single-particle valence space and a microscopic many-body Hamiltonian which is used to generate the basic collective excitations, phonons, by the use of the quasiparticle random-phase approximation (QRPA). One can combine the QRPA phonons to two-phonon states and let the microscopic Hamiltonian mix then with the phonon states. By using this model, we have recently studied the anharmonic vibrational effects, contained in the calculated energies and B(E2) values, along the $^{110-120}$Cd isotopic chain [kot03]. We plan to advance these computations to heavier Cd isotopes and thus the experimental data for cadmium isotopes beyond ^{120}Cd is requested. At the same time we are studying the beta-feeding properties of the low-energy excited states for the $^{116-130}$Cd [kot03a].

EXPERIMENTAL KNOWLEDGE OF N-RICH Cd NUCLEI

Decay studies of neutron-rich Ag isotopes at ISOLDE

Beta-delayed neutron emission probabilities, which are of importance especially for nuclear astrophysical questions, like time scale, elemental abundance and r-process path in the waiting point region are addressed in another experiment (IS333) at ISOLDE-CERN. These studies have provided important information on gross properties like half-lives and beta-delayed neutron emission probabilities. In addition the lowest yrast states have been proposed for the heaviest Cd isotopes. For such studies a more detailed spectroscopic information to be gathered in the present proposal will provide a basis for interpretation of the results and further understanding of the evolution of the nuclear structure while approaching magic neutron number N=82 just below closed shell of Z=50. Theoretical studies of these aspects are presently being pursued by our group [kot03a].

Structure studies of neutron-rich Cd nuclei

A partial systematics of the known levels of Cd isotopes is given in figures 1 and 2. It illustrates rather constant energy of the first 2^+ state and well-separated groups of states identified as two- and three-phonon multiplets. In addition, one observes a characteristic V-shaped behaviour of the states with intruder configurations. For the most neutron-rich nuclei the data is solely based on the different fission experiments, of which we refer here to the studies of ^{116,118,120}Cd covering complete spectra of the states up to three-phonon quintuplet at IGISOL-facility [wan01,wan02,wan03] and the ^{124}Cd at ISOLDE [kau96]. In addition, as mentioned earlier the lowest yrast states, namely the first 2^+ and 4^+ state, have been proposed for ^{126,128}Cd, based on the comparison of laser on and laser off data with additional help from systematics [kau00]. The purpose of this proposal is to perform detailed spectroscopic studies to extend our knowledge about the two- and three-phonon multiplets and intruder states in the heaviest Cd-isotopes, up to ^{128}Cd. These experimental studies are closely connected with the theoretical efforts within our group.

EXPERIMENTAL METHODS

Production of neutron-rich Ag-nuclei

Neutron-rich Ag-isotopes are produced in fission reaction of U induced by 1 GeV protons. Laser ionisation scheme for Ag isotopes exists and is widely used at ISOLDE. It has been shown, that the production ratio of the isomeric and ground state can be affected by proper laser setting taking into account hyperfine splitting [kra97]. This possibility will be studied for ^{124,126}Ag, while its applicability in case of ^{128}Ag is not yet clear. It is worth of noticing that even Ag isotopes exhibit well known isomerism, which results in (at least) two beta decaying states, one with low spin and another one with higher spin. The beta decay of latter one allows the population of medium spin states in Cd daughters, thus providing access to two-quasiparticle states, as well as vibrational and intruder states with higher spin.

While moving further from the stability, the ratios of isobaric background, mainly Cs and In compared to Ag increases. Applying a neutron converter target can reduce cesium background. The remaining isobaric background, namely surface ionised indium, can be reduced by means of high-resolution mass separator (HRS), which routinely reaches the value of 6000 for mass resolution $M/\Delta M$. The mass difference of Ag and In isobars ranges from 12 MeV to 18 MeV at masses A=122 and A=127, respectively. Thus the reduction of In background with a reasonable fraction is possible. Additional reduction of In background can be achieved by applying short beam gate optimised for short-lived Ag isotopes, while lowering the amount of longer-lived In activities.

Experimental set-up

Spectroscopy of beta decay of Ag isotopes requires an efficient beta gamma-spectroscopy set-up, which allows a observation of gamma-cascades from higher-lying collective states, intruder states and mixed states to ground state. We propose to use a 4π beta detector in coincidence with array of efficient Ge-detectors with fast timing applied between different detector pairs. With a proper geometrical arrangement, we can apply angular correlation to obtain detailed information about the spins of excited states. A second set-up will consist of electron spectrometer ELLI, developed in JYFL [par91], which allows parallel conversion electron measurement with gamma-measurements. The purpose of conversion electron set-up is to obtain information about the conversion coefficients of various transitions, but especially to obtain information about the decay of various 0^+ states appearing in the level schemes of Cd isotopes. In addition, conversion electron measurement allows obtaining information about isomeric transitions in Ag parent, thus restricting possible spins and parities of initial states. ELLI can be equipped with a tape transport system, which reduces the long-lived activity. ELLI-set-up will be applied for all even masses from ^{120}Cd to ^{128}Cd as such studies have not been performed so far beyond ^{122}Cd.

BEAM TIME REQUEST

Production of neutron-rich Ag isotopes has been a topic of various experiments in the past. Based on the gathered information, we expect to have 3E6 and 10 ions per second for ^{122}Ag and ^{128}Ag, respectively. As shown by recent studies on ^{116,118,120}Cd at IGISOL [wan01,wan02,wan03], a valuable data can be collected with intensities less than 1000 ions/s. The comparable studies can be performed at ISOLDE up to A=126. In the case of ^{128}Cd, the experimental conditions gets worse, but we expect to be able to cover the two phonon states and the lowest intruder states with a reasonable amount of beam time. Based on these arguments we propose the following schedule for the experiments on neutron rich Cd-isotopes studied by means of beta decay of their Ag-parents.

TABLE 1. A summary of the beam time request.

Beam	Expected Intensity	Target	Ion source	Sep	Shifts	Comment
^{x}Ag, x<123	1e6	UC$_{x}$ /graphite	RILIS	HRS	4	Set-up, test, tuning, check for ^{120}Ag and ^{122}Ag levels, e^{-} at A=120,122
^{124}Ag	5e4	-“-	-“-	-“-	6	^{124m,g}Ag, $\beta\gamma$, e^{-}
^{126}Ag	800	-“-	-“-	-“-	10	^{126m,g}Ag, $\beta\gamma$, e^{-}
^{128}Ag	10	-“-	-“-	-“-	16	^{128}Ag, $\beta\gamma$, e^{-}

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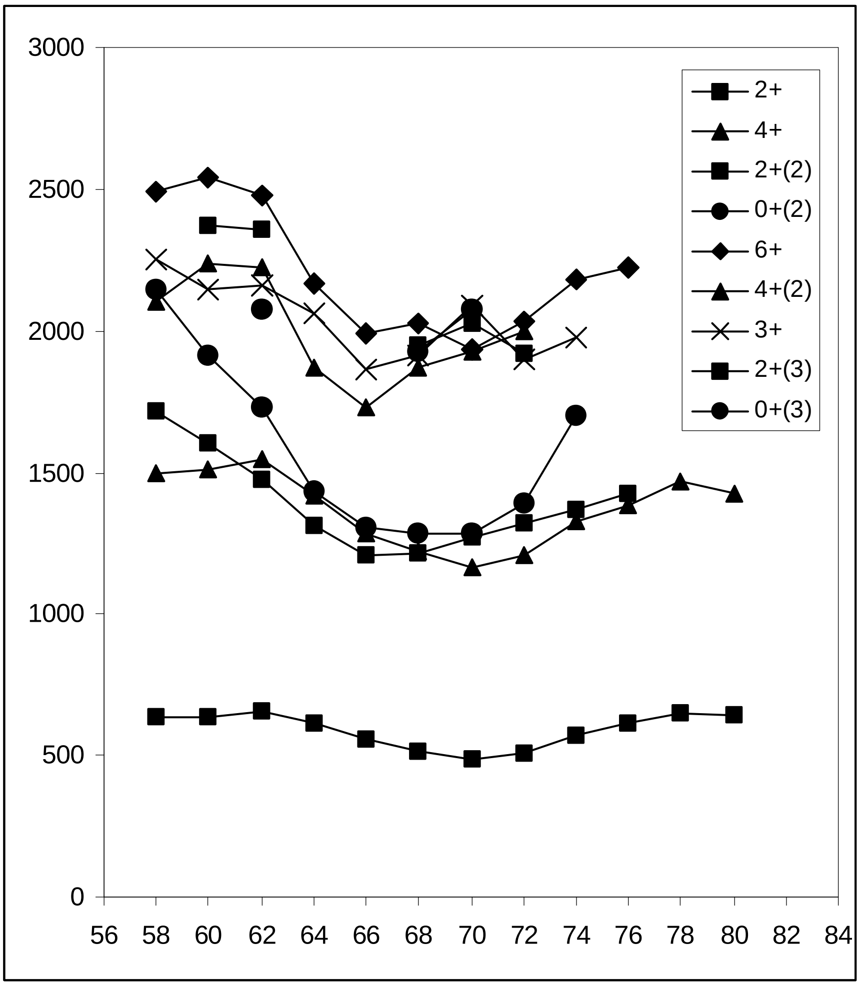

Figure 1. A systematics of one-, two- and three-phonon multiplets in ^{106}Cd to ^{128}Cd

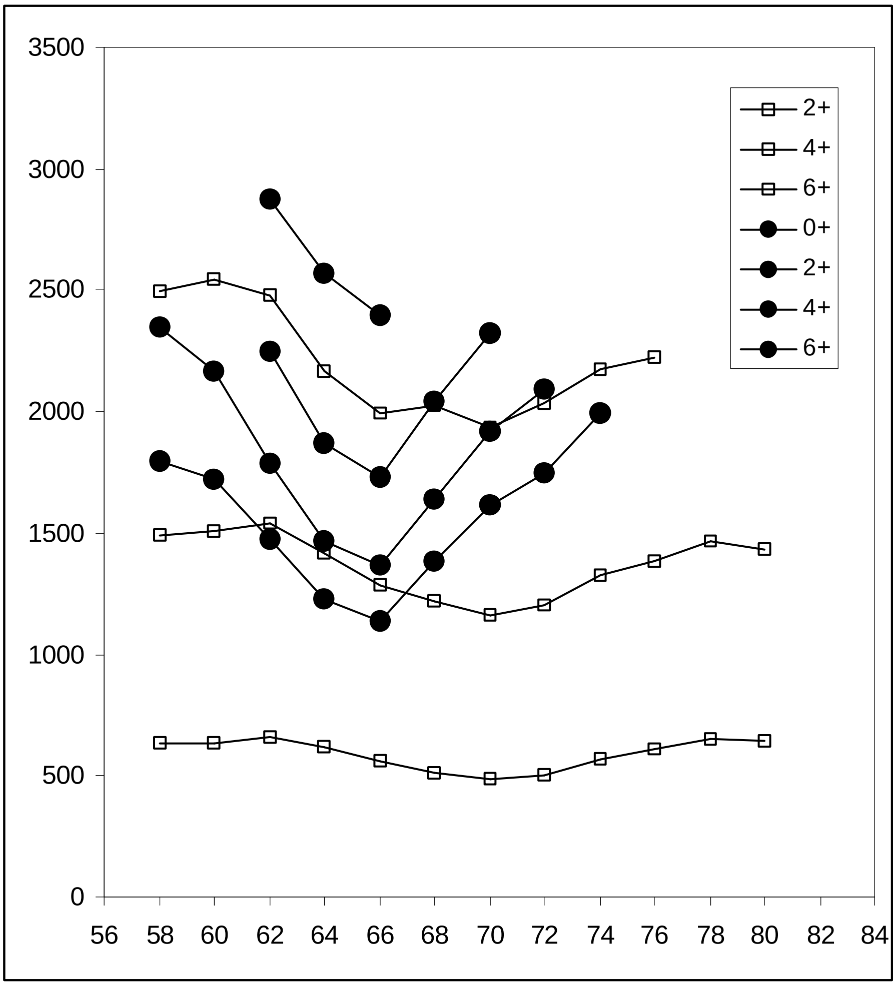

Figure 2. Systematics of the intruder states (filled circles) and the yrast 2^+, 4^+ and 6^+ states (open squares).