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The mutable nature of particle-core excitations with spin in the one-valence-proton nucleus ^{133}Sb

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ABSTRACT

The γ-ray decay of excited states of the one-valence-proton nucleus ^{133}Sb has been studied using cold-neutron induced fission of ^{235}U and ^{241}Pu targets, during the EXILL campaign at the ILL reactor in Grenoble. By using a highly efficient HPGe array, coincidences between γ-rays prompt with the fission event and those delayed up to several tens of microseconds were investigated, allowing to observe, for the first time, high-spin excited states above the 16.6 μs isomer. Lifetimes analysis, performed by fast-timing techniques with $LaBr_3$(Ce) scintillators, revealed a difference of almost two orders of magnitude in B(M1) strength for transitions between positive-parity medium-spin yrast states. The data are interpreted by a newly developed microscopic model which takes into account couplings between core excitations (both collective and non-collective) of the doubly magic nucleus ^{132}Sn and the valence proton, using

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Particle-core couplings

the Skyrme effective interaction in a consistent way. The results point to a fast change in the nature of particle-core excitations with increasing spin.

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The structure of atomic nuclei can be viewed from two general and complementary perspectives: a microscopic one, focusing on the motion of individual nucleons in a mean field potential created by all constituents, giving rise to the quantum shell structure, and a mesoscopic perspective that focuses on a highly organized complex system, exhibiting collective behavior. Ideal systems to investigate this duality should be nuclei composed of one valence particle and a doubly magic core in which the coupling between collective core excitations (phonons) and the valence nucleon strongly influences the structure of the system [1]. The understanding of this particle-phonon coupling is of primary importance, being responsible, to a large extent, for the anharmonicities of vibrational spectra [1,2], the quenching of spectroscopic factors [3–7] and the reduction of β-decay half-lives in magic nuclei [8]; it is also the key process at the origin of the damping of giant resonances [9]. In general, the coupling between phonons and particles is at the basis of interacting fermionic many-body systems, both in nuclear physics and in condensed matter physics [10].

In reality, in nuclear physics a more complex scenario is realized: collective phonons are not the only excitations at low energy in doubly magic systems – usually states having genuine phonon character co-exist here with excitations that are less collective or have no collective properties. In this respect, a benchmark region is around ^{132}Sn, which is one of the best doubly magic cores and exhibits low-lying both collective and non-collective excitations. In the present work, we had the goal of investigating the nature of particle-core excitations in the corresponding one-valence-proton nucleus ^{133}Sb, populated in cold-neutron induced fission. First, we aimed at identifying, experimentally, new high spin yrast states above the long-lived 16.6 μs isomer. This required a demanding technique which relies on measuring coincidences between γ rays prompt with the fission event and those delayed up to several tens of microseconds. Then, we studied transition probabilities through lifetime measurements of selected states. To interpret the data, a new microscopic and self consistent model has been developed, containing particle couplings to core excitations of various nature: in such a heavy mass region this cannot be treated with a shell model (SM) approach as it would require full SM calculations in the configuration space that encompasses proton and neutron orbitals below and above ^{132}Sn [11,12]. We anticipate that experimental data on ^{133}Sb, in the light of model predictions, provide evidence for a fast change in the nature of particle-core excitations, from a collective character to a non-collective one with increasing spin.

So far, studies of particle-core excitations considered, almost exclusively, couplings with collective phonons of the core. The best known case is the multiplet in ^{209}Bi (one-proton nucleus with respect to the ^{208}Pb core) arising from the coupling of a $h_{9/2}$ proton with the 3^- phonon of ^{208}Pb (at 2615 keV), exhibiting one of the most collective – vibrational – transition strength, across the nuclear chart (34 W.u.) [1]. In other one-particle (1p) or one-hole (1h) nuclei around ^{208}Pb [13–15] and other magic nuclei [16–23], states originating from couplings of the 3^- phonon with single particle/hole have been located as well. In the past, the theoretical description of particle-phonon couplings relied on phenomenological models [1,2]. Now, microscopic approaches based on either Skyrme forces or Relativistic Mean Field (RMF) Lagrangians are feasible, but with applications limited to the description of single particle states [24–27] and giant resonances [28,29].

In the case of the ^{132}Sn core, the first three excitations, 2^+ at 4041 keV, 3^- at 4352 keV and 4^+ at 4416 keV show a less pronounced collectivity (of the order of 7 W.u.) with respect to the 3^- of ^{208}Pb, and the other states have 1p–1h character [30,31]. In consequence, the one-valence-proton nucleus ^{133}Sb, being bound up to 7.4 MeV (unlike ^{133}Sn with a neutron binding energy of only 2.4 MeV), is a perfect case to test, simultaneously, the coupling of a particle with core excitations of various nature.

An extension of γ-spectroscopy of ^{133}Sb is challenging: so far, all states having a single proton on one of the $d_{5/2}$, $h_{11/2}$, $d_{3/2}$ and $s_{1/2}$ orbitals, as dominant configuration, have been located. Also, a series of excitations with $J^\pi = 7/2^+, 9/2^+, 11/2^+, 13/2^+, 15/2^+$, $17/2^+$ and $21/2^+$, of which the $21/2^+$ state is isomeric with 16.6 μs half-life, are known from isomer and β-decay studies [32–35]. On the contrary, no information exists on positive-parity levels above the long-lived $21/2^+$ isomer, which is known with $x <$ 30 keV uncertainty in energy [33,36].

The γ-ray coincidence data on ^{133}Sb were obtained with a highly efficient HPGe array, installed at the PF1B [37] cold-neutron facility at Institut Laue-Langevin (ILL, Grenoble, France). The ILL reactor is a continuous neutron source with an in-pile flux up to 1.5×10^{15} neutrons cm^{-2} s^{-1}. After collimation to a halo-free pencil beam, the capture flux on target was 10^8 neutrons cm^{-2} s^{-1}. Two detector setups were used, the first consisting of 8 EXOGAM clovers [38], 6 large coaxial detectors from GASP [39] and 2 ILL-Clover detectors, with a total photopeak efficiency of about 6% at 1.3 MeV. In the second setup, the GASP and ILL detectors were replaced by 16 $LaBr_3$(Ce) detectors, named FATIMA array [40], for lifetime measurements by fast-timing techniques. This is the first time a large HPGe array has been installed around such a high intensity, highly collimated cold-neutron beam [41–43].

The campaign, named EXILL, lasted two reactor cycles (each ≈50 days long) and its main part consisted of two long runs of neutron induced fission on ^{235}U and ^{241}Pu targets. The use of a fully digital, triggerless acquisition system (with time stamp intervals of 10 ns) allowed event rates up to 0.84 MHz to be handled and to study coincidences among γ transitions separated in time by several tens of microseconds [44] – with analogue electronics, coincidences only across a few μs isomers could be studied with large Ge arrays.

In ^{133}Sb, the $21/2^+$ isomeric state decays via a cascade of five transitions: an unknown isomeric transition with $E_\gamma < 30$ keV followed by 62, 162, 1510 and 2792 keV γ rays that feed the $7/2^+$ ground state (see Fig. 1). Therefore, a search for high spin structures of ^{133}Sb was undertaken by considering coincidences between two classes of γ-rays: i) *prompt* γ-rays – coincident (within 200 ns) with a fission event (defined by γ-ray multiplicity equal or larger than 4, within 200 ns) and ii) *delayed* γ rays – emitted within 20 μs after the fission event and coincident (within 200 ns) with at least one of the four known transitions deexciting the $21/2^+$ isomer. First, we investigated a *prompt–delayed* matrix. Fig. 2 (a) and (b) show spectra of γ rays preceding the 16.6 μs isomer, obtained from the ^{241}Pu and ^{235}U targets, respectively. The γ rays observed in both data sets at 207.9(4), 318.0(4), and 561(1) keV are candidates for transitions occurring higher in the level scheme of ^{133}Sb. In addition, by exploiting the *prompt–prompt* coincidence histogram, constructed in coincidence with a *delayed* γ ray deexciting the isomer, a new weak 243-keV line was identified in coincidence with the 318-keV transition (see insets of

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