Beta-decay studies of neutron-rich ${}_{21}$Sc - ${}_{27}$Co nuclei at GANIL

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Abstract

The neutron-rich nuclei ${}^{57,58}_{21}$Sc, ${}^{58-60}_{22}$Ti,${}^{60-63}_{23}$V, ${}^{62-66}_{24}$Cr, ${}^{64-68}_{25}$Mn, ${}^{67-70}_{26}$Fe and ${}^{69-71}_{27}$Co have been produced at Ganil via interactions of a 61.8 A.MeV ^{76}Ge beam with a ^{58}Ni target. Beta-decay studies have been achieved, bringing new half-lives and a better nuclear structure knowledge in this region. These results could help for understanding the over-abundances of the neutron-rich stable ^{58}Fe, ^{64}Ni in certain inclusions of meteorites.

1 Introduction

The strength of the sub-shell *closure* at N=40 is characterized by the size of the gap between $f_{5/2}p_{1/2}$ and $g_{9/2}$ and by the possibilities to generate excitations across it. The study of neutron-rich nuclei below ${}^{68}_{28}$Ni$_{40}$ is of special interest since many fascinating physics aspects are involved to model the evolution of the sub-shell closure at N=40. The valence orbital $g_{9/2}$ is extremely important since it governs the properties of the neutron-rich N$\sim$40 nuclei. Its effects are multiple, and act in favour or against an increase of a sub-shell closure. The two arguments in favor of a sub-shell closure are as follows.

A weakening of the spin-orbit surface term is predicted for very neutron-rich nuclei as their surface is expected to be more diffuse [1]. Consequently, the $g_{9/2}$ orbital would move closer to the next upper orbital, increasing the size of the N=40 gap. In addition to this, the presence of this positive parity orbital above fp negative parity ones strongly hinder excitations which preserve parity-symmetry. As a result, quadrupole excitations across the N=40 gap are substancially reduced in $^{68}_{28}Ni_{40}$ [2]. However, pairing correlations between $f_{5/2}p_{1/2}$ and $g_{9/2}$ orbitals result in an apparent superfluidity of the nuclei, since neutrons are 'attracted" by the presence of the $g_{9/2}$ valence orbital [2]. In addition to this, the removal of protons from the filled $\pi f_{7/2}$ orbital in $^{68}_{28}Ni$ would induce a dramatic reduction of the energy difference between the $f_{5/2}$ and $g_{9/2}$ neutron orbitals. As a result, the N=40 gap would shrink already in $^{64}_{24}Cr$, and a new sub-shell should appear at N=34 in the Ca-Ti neutron-rich nuclei. Hannawald et al. [3] have deduced that the neutron-rich $^{66}_{26}Fe_{40}$ is deformed, from the determination of the low energy of its first 2^+ excited state, $E(2^+)$=562.5 keV. However, given all the competing effects mentioned above, reliable theoretical predictions are difficult to establish for the neutron-rich nuclei around N=40. The study of these neutron-rich nuclei at/around N=40 subshell closure is also of astrophysical relevance. Recent astronomical observations of old stars in the galactic halo reveal the probable existence of a 'weak" r-process component which would produce nuclei of masses below A=130 from neutron-rich progenitors. This 'weak" process could extend down to light masses, and be responsible for the observation of correlated isotopic anomalies in the neutron-rich ^{48}Ca-^{50}Ti-^{54}Cr-^{58}Fe-^{64}Ni-^{66}Zn in certain inclusions of meteorites. Therefore, the presence and strength of any shell or sub-shell effect at N=28, N=32 and N=40 far-off stability is still actively researched.

Beta-decay studies provides the first tool which can be used for understanding the evolution of nuclear structure in the neutron-rich Cr isotopes. This paper focus on the beta-decay studies of Sc-Co nuclei at GANIL, aiming to deduce nuclear structure information from their half-lives and from their main γ transitions.

2 Experimental results

The study of neutron-rich $_{21}$Sc-$_{27}$Co nuclei has been started at GANIL in 1997. Three dedicated experiments have been performed, using the fragmentation of different primary beams of ^{65}Cu [4, 5], ^{86}Kr [6] and ^{76}Ge [7]. Beta-decay studies of more than 40 nuclei, which span from about 8 to 15 mass units away from the valley of stability, have been achieved during these experiments. The aim of these study was twofold: first, β-decay half-life $T_{1/2}$ is one of the easiest nuclear property accessible for weakly produced nuclei, and the very first nuclear structure information could be extracted from its value and from the γ-lines following the β-decay. Second, we wished to reach nuclei which could be play an important role in a weak r-process nucleosynthesis, with neutron-densities of up to 10^{21}cm^{-3}. Until 1997, only predictions were avalaible in order to fill the gap between nuclei close to stability and nuclei 15 mass units away. The present paper focuses on the very last results obtained at GANIL. A similar experimental technique has been applied for the three experiments mentioned above.

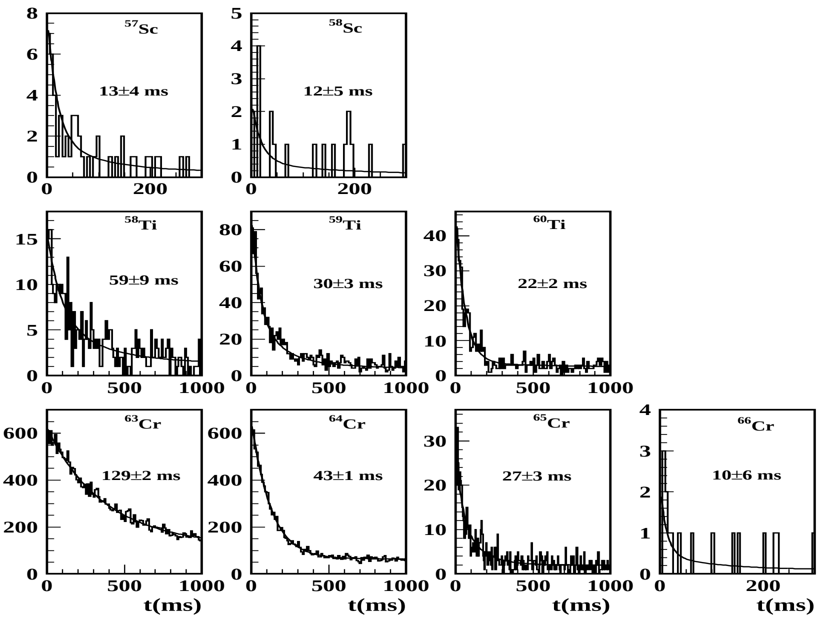

Figure 1: Beta-decay curves of Sc, Ti and Cr isotopes. The corresponding half-lives are included for each isotope.

The neutron-rich $^{57,58}_{21}$Sc, $^{58-60}_{22}$Ti, $^{60-63}_{23}$V, $^{62-66}_{24}$Cr, $^{64,68}_{25}$Mn and $^{68-70}_{26}$Fe iso-

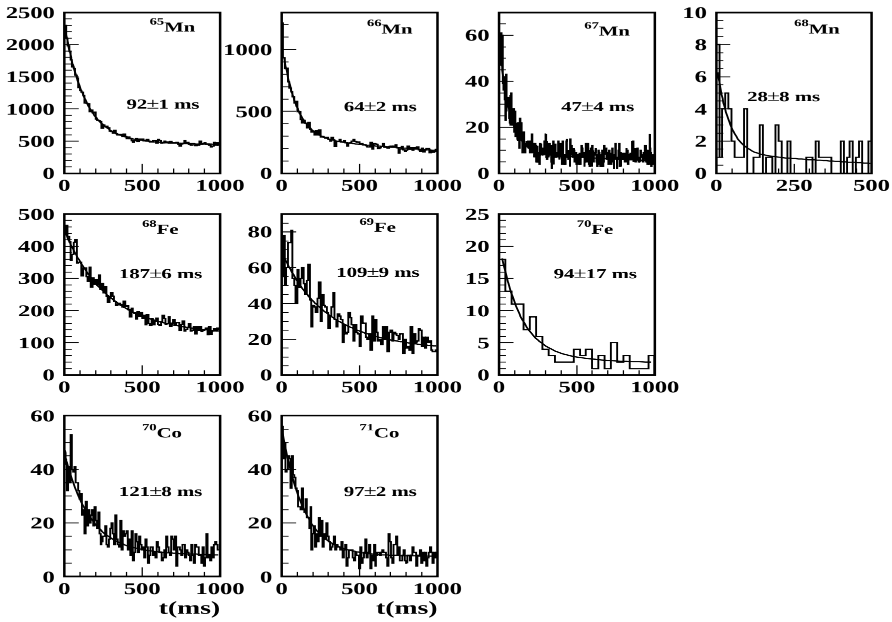

Figure 2: Beta-decay curves of Mn, Fe and Cr isotopes. The corresponding half-lives are included for each isotope.

topes have been produced at GANIL by the fragmentation of a 61.8 A.MeV ^{76}Ge^{30+} beam, of mean intensity 1 eμA, onto a ^{58}Ni target of 118 μm thickness. The nuclei of interest were separated by the LISE3 achromatic spectrometer which was tuned to optimize the transmission rate of very neutron-rich nuclei. The nuclei transmitted through the spectrometer were identified by means of 3 consecutive 300, 300, 1500 μm silicon detectors. The two first served for the energy loss and time-of-flight measurements, the last one to implant the nuclei and measure their residual energies. It was divided in sixteen 3 mm wide, 46 mm height vertical strips in order to make use of space correlation between the β-rays and the precursors implants. The rate of nuclei implanted was about one per second in total, and the primary beam was switched off during 1 second to collect the beta-rays following the implant of a precursor nucleus. The beta-decay time spectra correlated with the implantation of Sc-Co isotopes are shown in Figs 1 and 2. Results concerning the β-decay of $^{60-63}$V has been published in [7] and only the remarkable features are reminded here. The half-lives of $^{64-68}$Mn are in very good accordance with the results of Hannawald et al. [3] obtained with a different experimental technique at CERN/ISOLDE. Four Ge detectors were placed around the implantation detector for the detection of the main γ-transitions following the β-decay. Beta-gated γ-ray spectra of ^{60}V and ^{62}V exhibit γ-lines at 646(1) keV and 446(1) keV, corresponding to the $2^+ \rightarrow 0^+$ transitions in ^{60}Cr and ^{62}Cr, respectively [7]. From the comparison of the 2^+ energy levels in the Cr chain with the Fe and Ni ones, it is possible to deduce how the structure of these nuclei evolves when approaching the N=40 sub-shell closure. These Ge detectors were also used to detect delayed γ-transitions following the decay of an isomeric excited state. Indeed, it is possible that nuclei could be trapped into an isomeric state subsequently to their formation in the collision between the primary beam and the target. This isomer could survive through the 1μs flight-time in the spectrometer and eventually γ-decay at the implantation detector. In the case of ^{59}Ti, two isomers were found, attributed to E2 (electric quadrupole) and M2 (magnetic quadrupole) origins.

3 Discussion

Several experiments have been performed at this N=40 sub-shell closure, aiming to obtain the energy of the orbitals around the ^{68}Ni nucleus and the size of the N=40 gap [9, 10, 11, 12]. In addition to this, the Coulomb excitation of ^{68}Ni has brought some important information about the amount of collectivity (particule-hole excitations) which could develop in this nucleus [2]. In such experiment, a secondary beam of ^{68}Ni is passing through a Pb target where it could be excited to its first excited state by the Coulomb field of the target nuclei. In the case of ^{68}Ni, this Coulomb excitation rate to the 2^+ state B(E2) is extremely small; the smallest in all hitherto studied Ni isotopes. This extremely small rate of excitations across N=40 could be explained by the change of parity between filled and valence states in ^{68}Ni, as shown in Fig. 3 right. The filled states, denoted by $p_{1/2}$ and $f_{5/2}$, have a negative parity with an orbital momentum ℓ=1 and 3, respectively. The valence states g and d have a positive parity because of their even ℓ-values of 4 and 2, respectively. By crossing the N=40 sub-shell, only parity breaking excitations could in principle occur -therefore excluding quadrupole ones- except if a pair of neutrons is promoted to the higher state. Superfluid effects somewhat counteracts this parity-induced hindrance factor. Nuclear superfluidity can be characterized by pair-scattering to valence states. This effect scales approximately with the occupation probability of each level, e.g. as 2J+1. Therefore, a pair of nucleon from fp orbits is in average scattered to the $g_{9/2}$ valence state, bringing back few quadrupole excitations in the fp space which is not completely filled anymore. Most of the properties of ^{68}Ni can be explained with shell model calculations within the f,p and g valence space, denoted further as fpg. In particular, the B(E2) and 2^+ energy trend, can be explained throughout the Ni isotopic chain within the fpg space.

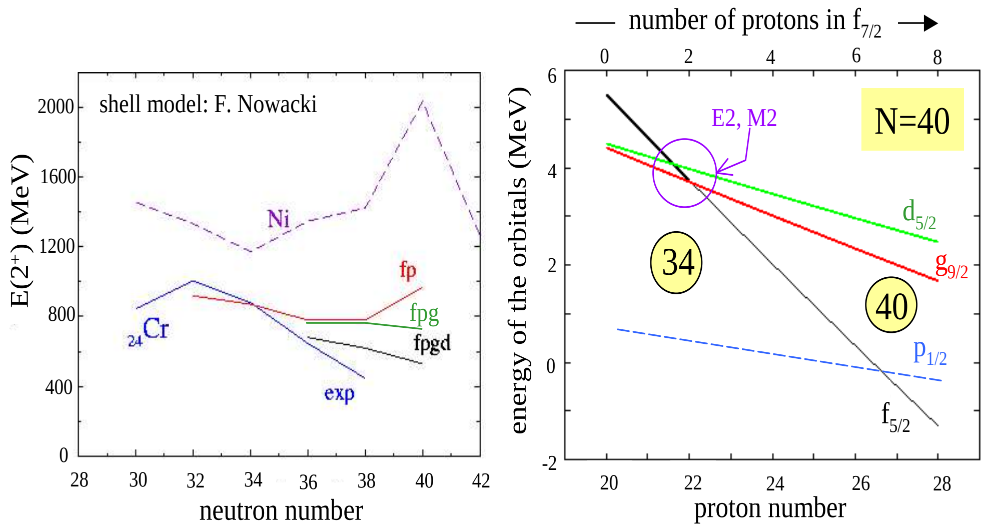

Figure 3: Left: Experimental and calculated energies of the first 2^+ excited state in the Ni and Cr isotopic chains. The curves labelled with fp, fpg, and fpgd for Cr isotopes correspond to shell model calculations assuming a valence spaces which progressively include the g and d orbitals. Right: Evolution of the energy of the neutron orbitals for the N=40 isotones as a function of the proton number.

It is clearly seen from Fig. 3 left that a major nuclear structure change has occured between the Ni and Cr isotopic chains. Instead of a sharp rise of the 2^+ at N=40 in the Ni chain (dashed line), a steady decrease is found in the Cr chain (full "exp" line). This later feature in the Cr chain can neither be explained by using the fp nor the fpg valence space [7].

The ${}^{64}_{24}Cr_{40}$ nucleus contains 4 protons less than ${}^{68}_{28}Ni$. These 4 protons have been removed from the $f_{7/2}$ orbital, which is filled by 8 protons in ^{68}Ni. At N=40, the neutron orbital $f_{5/2}$ is also completely filled. The strongly attractive proton-neutron interaction between these two orbitals of same angular momentum and opposite spin value drastically lowers the $f_{5/2}$ orbital energy, as shown in Fig. 3 right [7]. In ^{68}Ni, the energy of the $f_{5/2}$ orbital is minimum, whereas this orbital raises when decreasing the proton number, eventually crossing the g and d ones in Ti. Consequently, a sub-shell closure is present at N=40 for ^{68}Ni with a clear separation between fp and g orbitals. In the neutron-rich Cr isotopes, this gap has shrunk and the g,d orbitals lie closer in energy. The presence of these orbitals of J,J-2 spins brings a large amount of quadrupole excitations [13, 7]. The presence of E2 and M2 isomers in ^{59}Ti can be traced back through the crossing of the $f_{5/2}$, $g_{9/2}$ and $d_{5/2}$ orbitals.

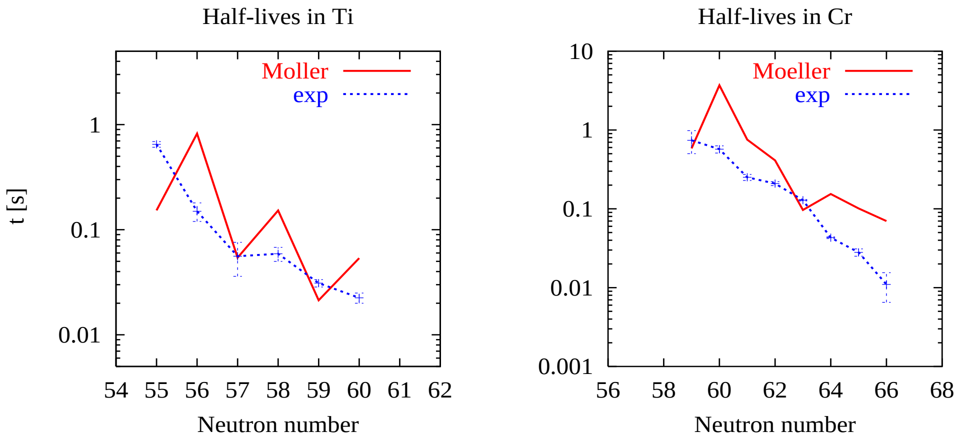

Figure 4: Comparison between calculated half-lives [8] (full line) and experimental ones (dashed line) in the Ti (left) and Cr (right) isotopic chain.

A comparison between the experimental and calculated [8] β-decay half-lives of Cr isotopes is shown in Fig 4 right. The theoretical values of P. Möller differ beyond N=39 by up to an order of magnitude due to the persistence of deformation at N=40, not predicted by the model. P. Möller finds that the potential-energy surfaces are very soft in the ^{64}Cr nucleus, with two shallow minima of different shapes separated by barriers of only 100 keV height. It is, therefore, hardly possible to determine which of these minima is the ground state. In addition to this, the Q_β value predictions differ by up to 3 MeV between different models. These uncertainties are making half-life predictions very difficult in this region.

On an astrophysical point of view, the overabundance of the neutron-rich Ca-Ti-Cr-Fe-Ni in certain inclusion of meteorites could be explained within a neutron-capture β-decay process (or weak r-process), from the β-decay of neutron-rich progenitors. In this scenario -which could occur in the outer core of type II supernovae- the neutron rich ^{48}Ca would be formed by the ^{48}Ar progenitor whose lifetime ($T_{1/2}$) is shorter than its calculated neutron-capture time (t_n) [14]. By using similar neutron-density conditions of 6.10^{20}cm^{-3} as used in the ^{48}Ca mass region to reproduce the correlated Ca-Ti-Cr anomalies, we have looked where branching points ($T_{1/2}$ <t_n) occur in each isotopic chain below the ^{58}Fe and ^{64}Ni nuclei. For this purpose, we have used the measured β-decay lifetimes presented here, and the calculated neutron-capture times from ref. [14]. It is noticeable that the proton-neutron interaction $\pi f_{7/2}$-$\nu f_{5/2}$ brings a re ordering of the neutron orbitals im the Ti and Cr chains around N=40. Consequently, the valence orbitals exhibit high angular momenta ($\ell \geq 3$) mainly and neutron-captures are strongly hindered by the high centrifugal barrier. Branching points occur at ^{58}Ti and ^{64}Cr in the Ti and Cr chains, respectively. This makes these nuclei very likely progenitors of the stable ^{58}Fe and ^{64}Ni in this neutron-capture β-decay scenario. Another consequence of the short half-life of ^{64}Cr -and its "long" neutron-capture time- is that further neutron-captures in the Cr are strongly suppressed and cannot reach A=66. Since any neutron-rich progenitor of mass A=66 is found in the higher Z chains, it is deduced that the abundance of the stable ^{66}Zn would be low, as found in the EK-1-4-1 inclusion of meteorite.

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