Beta decay of ^{72}Co and excited levels in ^{72}Ni

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Abstract.
An experiment was performed at GANIL to observe isomeric- and beta-delayed gamma rays from very neutron-rich nuclei around ^{74}Ni. Fragmentation products of the ^{86}Kr beam at 58 AMeV were studied using new devices: the LISE 2000 spectrometer and detectors from the EXOGAM germanium array. The primary aim of the experiment was to find the 8^+ microsecond isomer in ^{76}Ni and to perform beta decay spectroscopy of Co nuclei. We have successfully measured the beta delayed gammas from the decay of ^{72}Co to ^{72}Ni. The energies for the lowest excited states in ^{72}Ni are proposed, with the first 2^+ state at 1096 keV. These findings suggest a solution of the problem of the disappearance of the 8^+ isomer in ^{72}Ni. We also measured beta decay of other neutron-rich Co isotopes including ^{70}Co. First evidence was found for a new short lived isomer, most likely the $I^\pi=8^+$ state, in ^{76}Ni.

INTRODUCTION

Experimental studies on neutron-rich nuclei near closed shells may provide clear data to test the predictive power of the nuclear models applied to these very isospin asymmetric systems. Unusual phenomena of changing or disappearance of magic numbers [1] are expected. While the microscopic origin for these phenomena is still disputed and remains to be understood [2], their signatures should be clearly manifested only for extremely neutron-rich systems, near the drip line, which is mapped experimentally only up to Z=8. The mean field theories predict sizable effects of neutron skin in heavier nuclei, some of which are already within experimental reach. It is the shell model which should be able to translate these nuclear properties into observable quantities like level energies and spins.

In recent years there were a variety of spectroscopic studies seeking to develop the systematics of neutron-rich nuclei near the magic proton number Z=28 [3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. The neutron-rich nickel nuclei are difficult to synthesize in known nuclear reactions, and thus, the observation of their ground and excited states properties is an experimentally challenging problem. The isotopes of interest have been produced in multi-nucleon transfer, fragmentation and fission reactions. These studies yielded a series of surprising facts which challenge shell model calculations. Notably there was great progress in theory in recent years, see a review in ref. [13], which has achieved a level of sophistication such that collective nuclear excitations [14] of deformed nuclei can be explained. Can the same models describe exotic neutron-rich systems which are expected to be simple closed shell nuclei, or is this assumed simplicity only a deception?

The specific difficulty for large-scale shell model calculations stems from filling the $\nu g_{9/2}$ orbital and its possible polarizing effect on the proton Z=28 shell, and thus, making questionable the choice of a ^{56}Ni core. Calculations using a ^{48}Ca core involving two major shells for neutrons have been attempted recently [9]. However, the large model space may not be able to account for the changes in nuclear potential in the neutron-rich nucleonic matter, and therefore, different approaches have to be undertaken. On the other hand the large monopole shift observed in the proton(π) - neutron (ν) multiplet $\pi f_{5/2} \nu g_{9/2}$ [15] may challenge the N=50 closure in ^{78}Ni.

Vanishing isomers

The experiment that discovered the "isomeric island" [5] near Z=28 and N=40 resulted in the first observation of excited states in ^{70}Ni populated in the decay of the $T_{1/2}$=230(3) [5, 16, 17] I^{π}=8$^+$ isomer. It decays via a cascade of four stretched E2 transitions connecting the 8$^+$, 6$^+$, 4$^+$, 2$^+$, 0$^+$ levels. This isomer is interpreted by the shell model to be a $(\nu g_{9/2})^{+2}_{J=8^+}$ excitation. The yrast 8$^+$ level is long lived because of the non-collective E2 transition (B(E2)=0.693(9) W.u.) and the small energy difference between the 8$^+$ and 6$^+$ levels.

Such high spin isomers resulting from the coupling of two identical nucleons in the same orbital j to a maximum allowed spin $J = 2j - 1$ are known across the Segré chart in nuclei near closed shells. They can be related to the diagonal elements of the two body interaction which are approximated by a delta type interaction [18], because of the short range of nucleon-nucleon interactions.

Various interactions predict the isomerism of the 8$^+$ level in ^{70}Ni, though varying in detailed prediction of lifetimes or level energies. These 8$^+$ isomers are also expected to exist in the more neutron-rich nickel nuclei ^{72}Ni, ^{74}Ni and ^{76}Ni, which can be studied with the same experimental technique. Several experiments were performed to search for these isomers using the ion-gamma correlation technique in fragmentation reactions, with negative results. It has been concluded that the lifetimes of the ^{72m}Ni and ^{74m}Ni isomers places them outside the observation limits of the method. The number of detected ions of ^{72}Ni and ^{74}Ni allowed us to set the half life limits for non-observation of these isomers to be $T_{1/2}$< 20 ns or $T_{1/2}$> 2.5 ms for ^{72}Ni and $T_{1/2}$< 60 ns or $T_{1/2}$> 0.2 ms for ^{74}Ni [19, 20]. The search for isomerism in ^{76}Ni remained to be done.

These experimental findings are at variance with the shell model predictions. For example, the calculations [21] performed as in ref. [22], using a ^{56}Ni core and a full $f_{5/2}pg_{9/2}$ neutron shell with a realistic interaction adopted for the nickel region in ref. [23], predicted very small B(E2) values for the 8$^+ \rightarrow$ 6$^+$ transition. This would result in isomeric lifetimes of the order of tens of microseconds, which is well within experimental sensitivity. The expected B(E2) quenching is due to mid-shell effects [24] and can be observed, e.g. for the N=50 isotones in the ^{100}Sn region.

From these results it can be concluded that there is a different hitherto not considered structure feature which could cause the disappearance of isomerism for these mid-shell nuclei. That could happen if the strong neutron $g_{9/2}$ polarizing effect would result in a Z=28 shell breaking leading to deformation and collectivity. Such effects would possibly be accompanied by the disappearance of the N=50 closed shell, which would also result in the absence of the $\nu(g_{9/2})^{-2}_{J=8^+}$ isomer in ^{76}Ni. However, the recent observation of an 8$^+$ isomer in ^{78}Zn [6] suggests that its magic analog ^{76}Ni will have an isomer. It is important to confirm it experimentally. The production of a sufficient number of ^{76}Ni ions is at the limit of the production in the presently operating fragmentation facilities.

β^- decay of Co isotopes

It became clear that the isomer spectroscopy in fragmentation is not a viable method to measure excited levels in ^{72}Ni and ^{74}Ni and one has to attempt to measure them with a different method. One way is through beta-delayed gamma-ray spectroscopy of ^{72}Co and ^{74}Co. This task is experimentally difficult because these cobalt isotopes are even farther away from stability, and thus, more difficult to produce than their nickel isobars.

The beta-decay of odd-odd cobalt isotopes is characterized by the spin-flip Gamow-Teller transformation of the $f_{5/2}$ neutron into an $f_{7/2}$ proton. The decays of ^{66,68,70}Co isotopes have been thoroughly studied by Mueller et al. [12, 25] using fission and the laser ion source technique. It has been found that odd-odd cobalt isotopes have two close lying states: a $J^{\pi} = 3^+$ state claimed to be isomeric with a $\pi f^{-1}_{7/2} \nu p^{-1}_{1/2} \nu g^{+4}_{9/2}$ configuration and assigned to be above the $J^{\pi} = 7^-, 6^-$ ground state with a $\pi f^{-1}_{7/2} \nu g^{+3}_{9/2}$ configuration. The positive parity isomeric state decays predominantly to the 2$^+$ states. Decay of the high spin ground state populates the lowest lying negative parity $J^{\pi} = 8^- - 5^-$ states with configurations like $\pi f^{-1}_{5/2} \nu g^{+3}_{9/2}$, which can then decay to the yrast positive parity states. The observation of the ^{72}Co decay would shed light on the lowest levels in ^{72}Ni. In particular the observation of rotational type structures would suggest the onset of collectivity and provide a simple explanation for the non-existence of isomers, and more im-

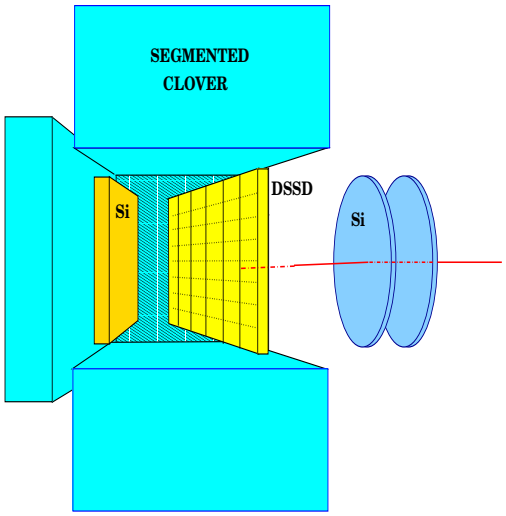

FIGURE 1. Experimental setup

portantly would be an evidence for a dramatic breaking of the Z=28 shell closure. On the other hand, observation of shell-model type excitations would suggest to look for more subtle effects within the shell model approach.

EXPERIMENT

The experiment was performed at the GANIL laboratory using fragmentation of a 58 AMeV ^{86}Kr q=+36 beam impinging on a ^{nat}Ta target of 30 μm thickness with 125 μm carbon backing. The data were collected over a 160 h period and the average beam intensity amounted to 50 pnA. The selection of ions was done with the new LISE2000 spectrometer. The standard time-of-flight and energy-loss event-by-event ion identification technique was used [26]. A thin foil of ^{nat}Be was placed in the achromatic focal plane to limit the number of nuclei reaching the implantation telescope. The A/q selection was chosen such that the ^{76}Ni and ^{72}Co ions were transmitted with the maximum efficiency. A stack of four silicon detectors was placed at the final focus of LISE2000 with thicknesses were 300μm, 300 μm, 1 mm and 3.5 mm. The ions of interest were stopped in the third one - a double-sided silicon strip detector (DSSD) with 16x16 strips of 2 mm pitch, see fig. 1. The pixelation provided a clean spatial correlation between the implanted ion and detected beta decay. The silicon telescope was surrounded by four clover-type EXOGAM germanium detectors. The beta detection efficiency of the DSSD, amounting to about 20 %, was determined from analysis of the ^{66}Co decay, using branching ratios from ref. [25]. The gamma detection efficiency measured with calibrated sources amounted to 6 % at 1.3 MeV and

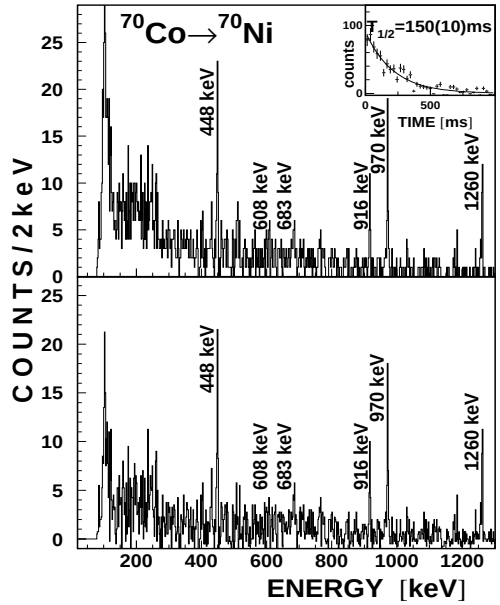

FIGURE 2. Beta delayed gamma spectrum of ^{70}Co. Top spectrum: gammas observed within 500 ms after ion implantation. Bottom spectrum: top spectrum with subtracted background from gammas observed from 500 ms to 5 s after ion implantation. Normalization factor set to 0.3. In the inset, the decay curve of the beta delayed gammas within 200 and 2000 keV energy range.

23 % at the maximum around 120 keV. The data analysis involved ion-beta-gamma correlations for selected ions. Because the rate of implanted ions per pixel was low, the average time between two implants was longer than the average beta decay lifetime usually of the order of 100 ms for the nuclei of interest. An example of a similar type of data analysis can be found in ref. [27].

The experiment was also designed to be sensitive to the decay of short lived isomers using the standard technique as described in [28].

RESULTS

β^- decay of ^{70}Co

The ^{70}Co ions were transmitted with low efficiency through the spectrometer due to the magnetic field and wedge selection. About 3330 ions have been implanted into the DSSD detector. The beta-delayed gamma-ray spectrum (fig. 2) reveals gamma-ray lines observed previously in a fragmentation experiment [5] and a beta decay experiment [25]. This provided proof of the correct

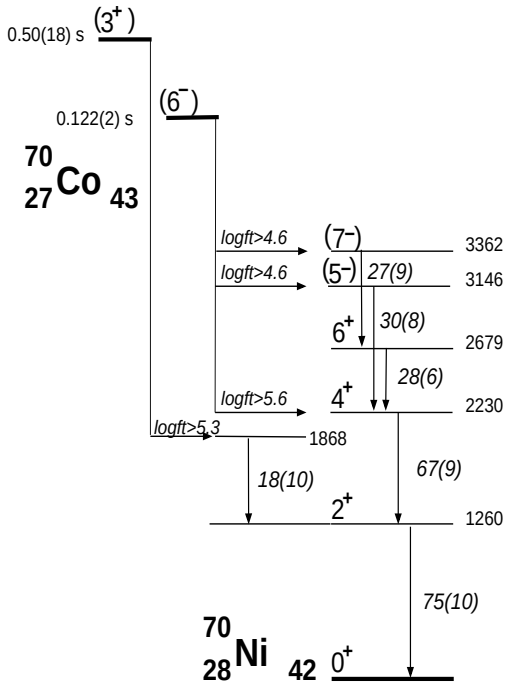

FIGURE 3. The decay scheme of ^{70}Ni

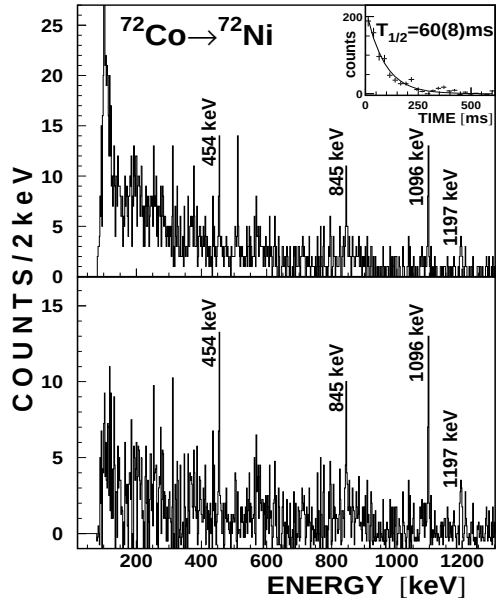

FIGURE 4. Beta delayed gamma spectrum of ^{72}Co Top spectrum: gammas observed within 300 ms after ion implantation. Bottom spectrum: top spectrum with subtracted background from gammas observed from 500ms to 5 s after ion implantation. Normalization factor set to 0.25. In the inset, the decay curve of the beta delayed gammas within 200 and 2000 keV energy range.

ion identification and validated the data analysis technique. The half life determined for the beta delayed gammas was determined to be 150(10) ms, which is compatible with the half life observed for the 7^- state in [25] $T_{1/2}$=120(30)ms. Previous measurements using similar correlation techniques resulted in measured half lives of $T_{1/2}$=150(20)ms [11] and $T_{1/2}$=92(25) ms [27]. In addition to the strong 448, 683, 970 and 1260 keV lines observed in beta decay studies by Mueller et al [25], we also identified an additional line at 916 keV. We tentatively place it at 3146 keV to feed the 4^+ state at 2230 keV (fig. 3). We were able also to identify the decay of the 3^+ state which appears to be populated weakly in this reaction. The 608 keV line can be seen in the gamma ray spectrum but with a very small statistics, and is approximately 5 times weaker then the 448 keV line. We could not observe the 1868 keV line from the decay of the second 2^+ state to the ground state, identified in ref [25], which is consistent with the weak population of the 3^+ isomer in the present reaction.

β^- decay of ^{72}Co

A similar data analysis was performed for the 3290 ions of ^{72}Co which were identified and implanted. The beta delayed gamma spectrum is shown in fig. 4 revealing gamma lines of 454, 845, 1096 and 1197 keV. The excess of counts in the 511 keV line has not been understood. Based on the intensity of gamma lines and expected similarities between ^{70}Co and ^{72}Co beta decays, the level scheme for ^{72}Ni has been constructed. The decay has been attributed to originate the (6^-,7^-) state. The half life of these decay was determined to be 60(8) ms. The previously measured [11] value was 90(20) ms. We could not find conclusive evidence for the decay of the 3^+ state, possibly because of the low population of this non-yrast state. We have attributed the strongest 1096 keV line to be a transition between the first excited 2^+ state in ^{72}Ni and its 0^+ ground state. The observed level scheme (fig. 5) does not reveal signatures of collective excitations. The previously used shell model calculation with the S3V realistic interaction predicts an energy spectrum similar to the experimentally observed spectrum, see fig. 6.

The important question arises whether these experimental findings can help resolve the question of the disappearing 8^+ isomer in ^{72,74}Ni. Unfortunately the 8^+ states seem not to be significantly populated in the ^{70}Co decay and probably also not in the ^{72}Co decay. One can try to reproduce the observed level scheme with shell model calculations and from these calculations try

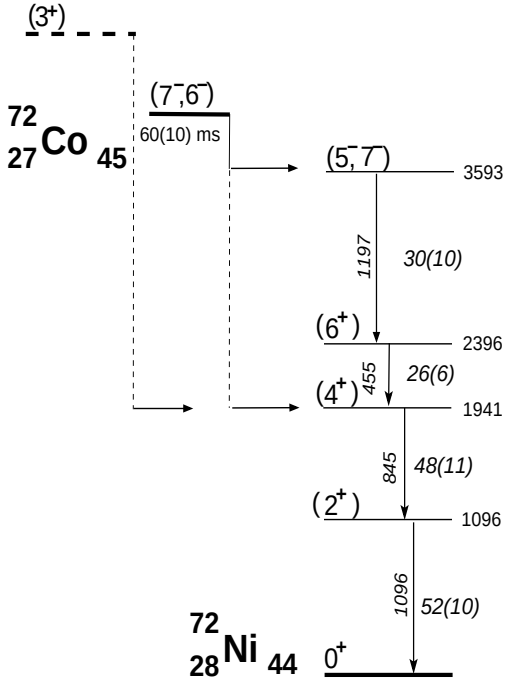

FIGURE 5. The decay scheme of ^{72}Ni

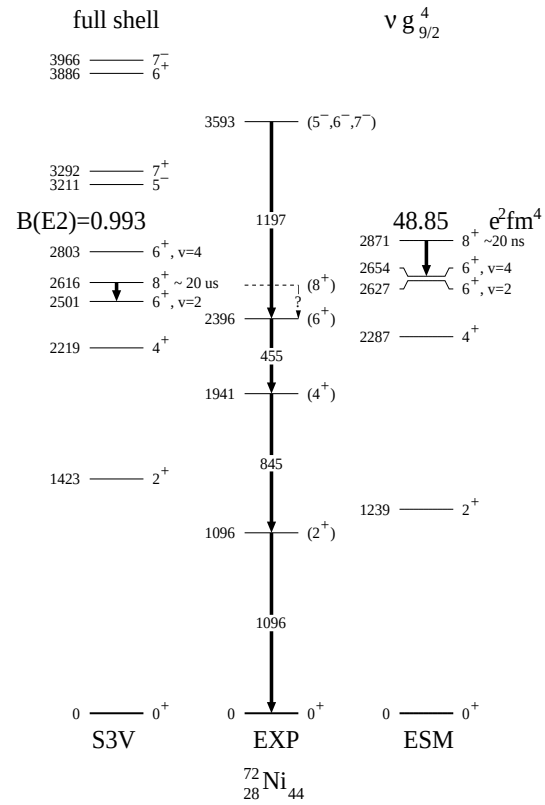

FIGURE 6. Comparison of the measured energy levels in ^{72}Ni with shell model calculations using S3V and full fpg model space and empirical ESM residual interactions and restricted to the $g_{9/2}$ shell.

to infer the position of 8^+ level. Such an attempt has been made [21] using the two body interactions derived from ^{70}Ni data. Only the excitation involving $g_{9/2}$ neutrons was allowed. The empirical two body matrix elements were used to calculate the ^{72}Ni level scheme, fig. 6 (ESM). This figure shows the expected similarity of ^{70}Ni and ^{72}Ni predicted by S3V and ESM calculations. The striking difference is, however, the presence of a low lying seniority $v = 4$ $J^\pi = 6^+$ state which is predicted by ESM to be below the seniority $v = 2$ $J^\pi = 8^+$ state, opening another deexcitation branch for the isomer with a larger B(E2)=2.7 W.u. The lifetime predicted by these calculations is about 10-20 ns, which is just at the limits of the previous experiment sensitivity. This level is placed well above the $J^\pi = 8^+$ state by the S3V calculations. Microscopically the lowering of the $v = 4$ $J^\pi = 6^+$ state is related to the low $J^\pi = 2^+$ excitation energies in ^{70,72}Ni. Therefore, the present experimental results supports the above mentioned ESM scenario for non-observation of the 8^+ isomerism.

The 8^+ isomer in ^{76}Ni

In this experiment a simultaneous search for the isomer in ^{76}Ni was performed. The ^{76}Ni ions were transmitted through the spectrometer with similar efficiency as ^{72}Co. The test of the electronics, acquisition system and data analysis was done with the known simultaneously observed ^{67}Ni isomer [5, 29]. We have identified 269 of the ^{76}Ni ions. These ions have been correlated with 44 gammas detected in the clover detectors within 1 μs after implantation. This gives a ratio of F=0.16(4) gammas per ion. The comparison with other ions of Ni (e.g. F=0.021(5) for ^{75}Ni) shows that this ratio is very high and strongly suggests the presence of an isomer. The ratio of F=0.2 has been obtained for q=+27 ions of ^{70}Ni with a known 8^+ isomer. The details of this finding will be published separately [20].

SUMMARY

In conclusion, in an experiment performed using fragmentation of a ^{86}Kr beam the spectroscopy of excited levels in ^{70,72}Ni populated in the decays of ^{70,72}Co isotopes was performed. For the first time the excited levels

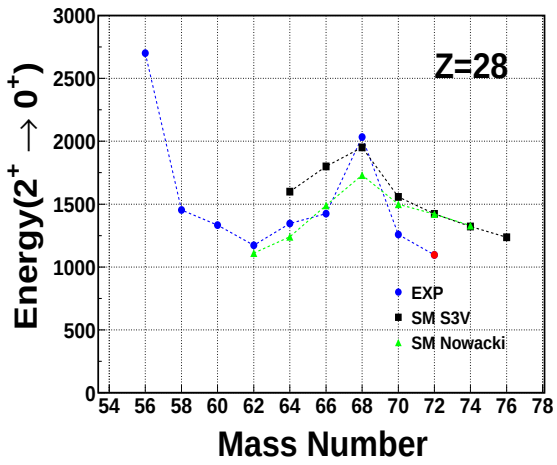

FIGURE 7. Systematic trend of the 2^+ levels. Experimental points are compared with full fpg shell model calculations using realistic TBME:S3V see. ref. [21] and Nowacki see ref. [9]

in ^{72}Ni have been identified and the spin and parities have been postulated, based on the comparison with ^{70}Co decays. The 2^+ level energy of 1096 keV in ^{72}Ni shows a systematic drop and is not explained by the shell model calculations based on the realistic interactions, see fig. 7. A possible explanation for the disappearance of 8^+ isomers has been provided based on the experimental data. The calculations with ESM parameters predict near degeneracy of the $J^\pi = 6^+$ states with seniority $v = 2$ and $v = 4$. There is no supporting evidence for effects of deformation. The first evidence for the isomerism in ^{76}Ni has been obtained, thus confirming the persistence of the N=50 shell closure in ^{78}Ni.

ACKNOWLEDGMENTS

This work has been supported by Polish Committee of Scientific Research under Grant No. KBN 2 P03B 036 15 and the EU Access to Large Scale Facilities Program. EXOGAM is a joint project, funded by CEA (France), ESPRC (UK), GSI (Germany) and NBI (Denmark). ORNL is managed by UT-Battelle, LLC, for the U.S. Department of Energy under Contract DE-AC05-00OR22725.

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