Investigation of double beta decay of ^{58}Ni at the Modane Underground Laboratory

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Abstract. Investigation of double beta decay processes (β^+EC, EC/EC) of ^{58}Ni was performed at the Modane underground laboratory (LSM, France, 4800 m w.e.). A sample of natural nickel, containing ~68% of ^{58}Ni and a mass of ~21.7 kg, was measured using ultra low-background HPGe detector Obelix (sensitive volume of 600 cm^3) during ~143.8 days. New experimental limits on $2\nu\beta^+$EC decay of ^{58}Ni to the ground 0^+ and 2^+_1, 811 keV excited state of ^{58}Fe, and 2νEC/EC decay of ^{58}Ni to 2^+_1, 811 keV and 2^+_2, 1 675 keV excited states of ^{58}Fe were obtained in this measurement. There are -$T_{1/2}(\beta^+EC, 0^+ \rightarrow 0^+) > 1.7$ $\times 10^{22}$ y; $T_{1/2}$ $(\beta^+EC, 0^+ \rightarrow 2^+_1) > 2.3$ $\times 10^{22}$ y, $T_{1/2}$ (EC/EC, $0^+ \rightarrow 2^+_1$) > 3.3 $\times 10^{22}$ y, $T_{1/2}$ (EC/EC,$0^+ \rightarrow 2^+_2$) $> 3.4 \times 10^{22}$ y. For resonant neutrino-less radiative EC/EC decay with energy of 1 918.3 keV a new experimental limit of $T_{1/2}$ $(0\nu EC/EC - res, 1918 keV) > 4.1$ $\times 10^{22}$ y was also obtained. All limits are at 90 % CL.

1. Introduction

The nuclear double beta decay ($\beta^-\beta^-, \beta^+\beta^+, \beta^+EC$, EC/EC) is a good probe to investigate neutrino masses and some basic properties of weak interaction [1] , [2]. The 0ν mode, if it exists, immediately indicates a defect of the standard model. On the other hand, double beta decay ($\beta\beta$) with the emission of two neutrinos ($2\nu\beta\beta$) is an allowed process of the second order in the Standard Model (SM). The $2\nu\beta\beta$ decay provides the possibility of an experimental determination of the nuclear matrix elements (NME) involved in the double beta decay processes. This leads to the development of theoretical schemes for NME calculations both in connection with the $2\nu\beta\beta$ decay as well as the $0\nu\beta\beta$ decay. The $\beta\beta$ decay can proceed through transitions to the ground state as well as to various excited states of the daughter nucleus. Studies of the latter transitions allow to obtain supplementary information about $\beta\beta$ decay. Because of the smaller transition energies, the probabilities for $\beta\beta$ decay to excited states are substantially suppressed in comparison with transitions to the ground state, but by using low-background high sensitive HPGe detectors, the $2\nu\beta\beta$ decay to the 0^+_1 level in the daughter nucleus may be detected for some nuclei (e.g. ^{100}Mo, ^{96}Zr, ^{150}Nd). $2\nu\beta^-\beta^-$ decay to excited states of daughter nuclei was already detected in ^{100}Mo -^{100}Ru (0^+_1, 1130.3 keV) decay (several experiments, including measurements performed at LSM, Modane with the Obelix HPGe spectrometer [3]) and ^{150}Nd -^{150}Sm (0^+_1, 740.4 keV) decay. It should be noted that the energy spectrum obtained in the investigation of

$2\nu\beta\beta$ decay of ^{100}Mo to the excited states of ^{100}Ru using Obelix detector was measured with high level of sensitivity, allowed us to obtain the most precise value of the half-life of this rare process [3]. The present work is devoted to the investigation of β^+EC, and EC/EC decay of ^{58}Ni to excited states of ^{58}Fe (see Fig.1).

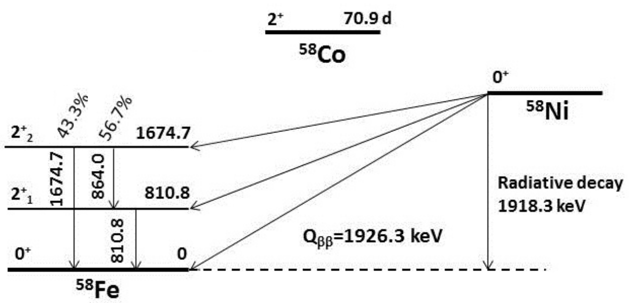

Figure 1. Decay scheme of ^{58}Ni→^{58}Fe.

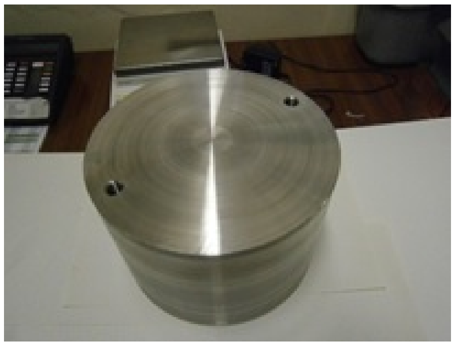

Figure 2. View of nickel sample.

2. Experimental setup

The measurement was performed at the Modane underground laboratory (LSM, France, 4800 m w.e.) using the ultra low-background HPGe detector Obelix with sensitive volume of 600 cm^3 and efficiency of 160% [4]. The energy resolution of the Obelix detector is ~1.2 keV at 122 keV(^{57}Co) and ~2 keV at 1332 keV (^{60}Co). The detector part of the cryostat is encircled by the passive shielding of several layers of roman lead with a total thickness of ~12 cm (activity of < 60 mBq/kg) and low active lead (activity of ~ 5 - 20 Bq/kg) with a total thickness of ~20 cm, and placed inside a tightly closed stainless steel cover. To decrease the concentration of ^{222}Rn gas near the detector the passive shielding of the spectrometer is flushed with radon-depleted air (concentration of ^{222}Rn is ~ 15 mBq/m^3) from a radon trapping facility installed in LSM. We measured the sample of natural nickel, containing ~68% of ^{58}Ni. This is one of the largest natural abundance among all double beta decay emitters, which makes it one of the favorable candidates for investigation of double beta decay. The sample of nickel with a total mass of ~21.7 kg was produced in a shape of a Marinelli beaker in 2014. To install the sample on the Obelix detector the first internal layer of the lead shielding of the Obelix detector was removed [4]. The photo of the sample is shown on the Fig.2.

3. Analysis and results

Three experimental runs were performed with the sample of nickel from 2014 till 2017 years. Such types of the low-background measurements are based on the comparison of the measurements of samples and the background of the spectrometer. The background of spectrometer was measured and analyzed before starting of each experimental run. The integral count rate of the spectrometer was changed from 73 counts/kg·d in the energy region of 40-3000 keV in 2014 to 95 counts/kg·d in 2017. Increasing of the background was caused by cosmogenic isotopes produced in a germanium crystal during location of the detector on the Earth's surface (detector was repaired by Canberra at the end of 2016). Because of the high Q-value of ^{58}Ni - 1926.3±0.7 keV, several transitions to the excited states of daughter nuclear ^{58}Fe are possible. The objects of analysis in the measurement of ^{58}Ni were γ-rays with energies of 511, 811, 864, 1675 and 1918.3 keV. The β^+EC decay of ^{58}Ni will be accompanied by emission of positron, which creates two correlated annihilation γ-quanta with energies of 511 keV. The β^+EC decay of ^{58}Ni to the first 2^+_1,811 keV excited state of ^{58}Fe will be accompanied by emitting of additional γ-quantum with energy of 811 keV. EC/EC decay of ^{58}Ni to the first 2_1^+,811 keV and second 2_2^+,1675 keV excited states of ^{58}Fe will be accompanied by γ-rays with energies of 811 keV and 1675 keV, or 811+864 keV respectively. The investigation of resonant neutrino-less radiative EC/EC decay of ^{58}Ni $\rightarrow$ ^{58}Fe is based on the search for γ-quanta with energy of 1918.3 keV in the measured spectrum.

All these γ-quanta can be detected by the Obelix detector with high efficiency. Test measurements of the sample were performed in 2014 (T_{mes}=47.5 d) and 2015 (T_{mes}=19 d). The main goal of these measurements was to obtain radioactive contaminations of the investigated sample. They showed an increased level of short-living cosmogenic isotopes in the sample of nickel, mainly of ^{57}Co and ^{58}Co. The average activities of cosmogenic isotopes in 2014 were - ^{57}Co($T_{1/2}$=271.8 d)=5.0 mBq/kg, ^{58}Co($T_{1/2}$=70.9 d)=3.8 mBq/kg, ^{56}Co($T_{1/2}$=77.3 d)=2.3 mBq/kg, ^{54}Mn($T_{1/2}$=312.3d)=0.7 mBq/kg. To decrease the level of this additional activity, the sample was stored underground till 2017 when the level of already mentioned activities became negligible. The main experimental run was started in April 2017. The total exposition of the measurement is - 143.8 days. Total spectrum of this run is shown on Fig.3. There are no events from ^{58}Co in the region of interest. The decreasing of this cosmogenic isotope in the sample of nickel during 2014-2017 is shown on Fig.4. Green line in the Fig.4 shows spectrum of nickel in the region of interest measured in 2017.

Calculations of the measured spectrum were based on the search for the possible peaks in the regions of interest (ROI) 511, 811, 864, 1675 and 1918.3 keV. The main ROI and results of searching for mentioned peaks are shown on the Fig 5. Efficiency of the Obelix detector for registration of γ-rays emitting from the sample of nickel was calculated using ROOT-VMC-GEANT4 DPGE package simulations in the energy region of 0.05- 5 MeV. Then the calculated efficiency was tested by the measurement of low-active sample prepared in Marinelli beaker on the base of La_2O_3 powder. This method of efficiency calibration was described in details in [4]. Basing on the calculation of experimental data, obtained after 143.8 days of measurement of nickel sample with the Obelix spectrometer new limits on β^+EC, EC/EC decay of ^{58}Ni (at 90% CL) were obtained -Table.1. These new results improve already existing experimental limits (last column in Table.1) by more than one order of magnitude. Theoretical predictions for $T_{1/2}$ of $2\nu\beta^+$EC, 2νEC/EC and 0νEC/EC radiative decays of ^{58}Ni are in the ranges of - $T_{1/2}(2\nu\beta^+\text{EC},0^+ \rightarrow 0^+)=1.9\times10^{24}$-$8.6\times10^{25}$ y [5],[6], $T_{1/2}(2\nu\text{EC/EC},0^+ \rightarrow 0^+)=3.9\times10^{23}$-$2.8\times10^{25}$y [5],[6], $T_{1/2}(0\nu\text{EC/EC-radiative})=2\times10^{35}$-$3\times10^{36}$y [7].

Table 1. New limits on double beta decay of ^{58}Ni obtained from the measurement of natural nickel with a mass of ~21.7 kg with the Obelix detector during 143.8 d.

Decay mode $T_{1/2}$ years	Final state or decay energy	New Limits, $T_{1/2}$, years	Previous Limits,
β^+EC	g.s.	1.7×10^{22} (90% CL)	7.0×10^{20} (68% CL) [8]
β^+EC	811 keV	2.3×10^{22} (90% CL)	4.0×10^{20} (68% CL) [8]
EC/EC	811 keV	3.3×10^{22} (90% CL)	4.0×10^{19} (90% CL) [9]
EC/EC	1675 keV	3.4×10^{22} (90% CL)	4.0×10^{19} (90% CL) [9]
0νEC/EC-res	1918 keV	4.1×10^{22} (90% CL)	2.1×10^{21} (90% CL) [7]

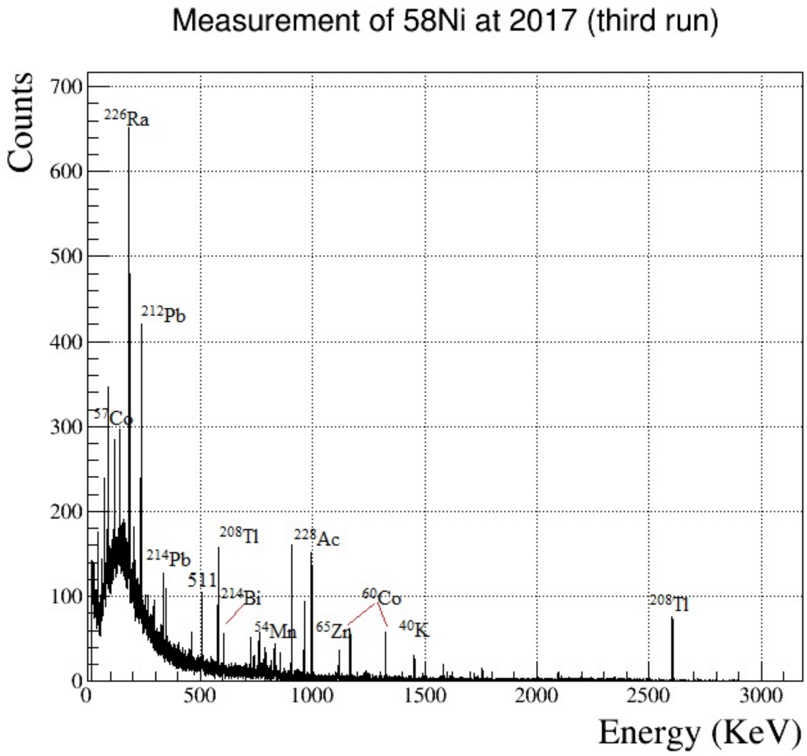

Figure 3. Total spectrum of the third run of the measurement of nickel sample.

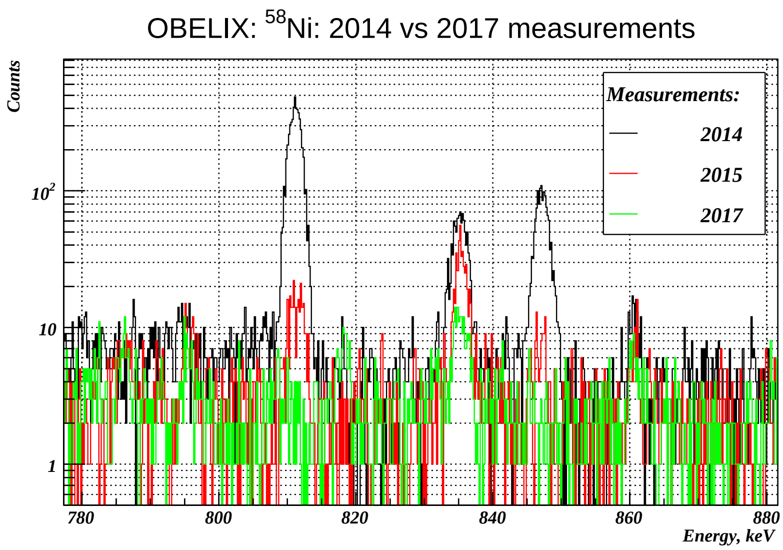

Figure 4. Changing level of ^{58}Co in the region of interest.

4. Summary

The double beta decay (β^+EC, EC/EC) processes were investigated in ^{58}Ni. No signals were observed in regions of the interest. Nevertheless, experimental limits on $2\nu\beta^+$EC, 2νEC/EC

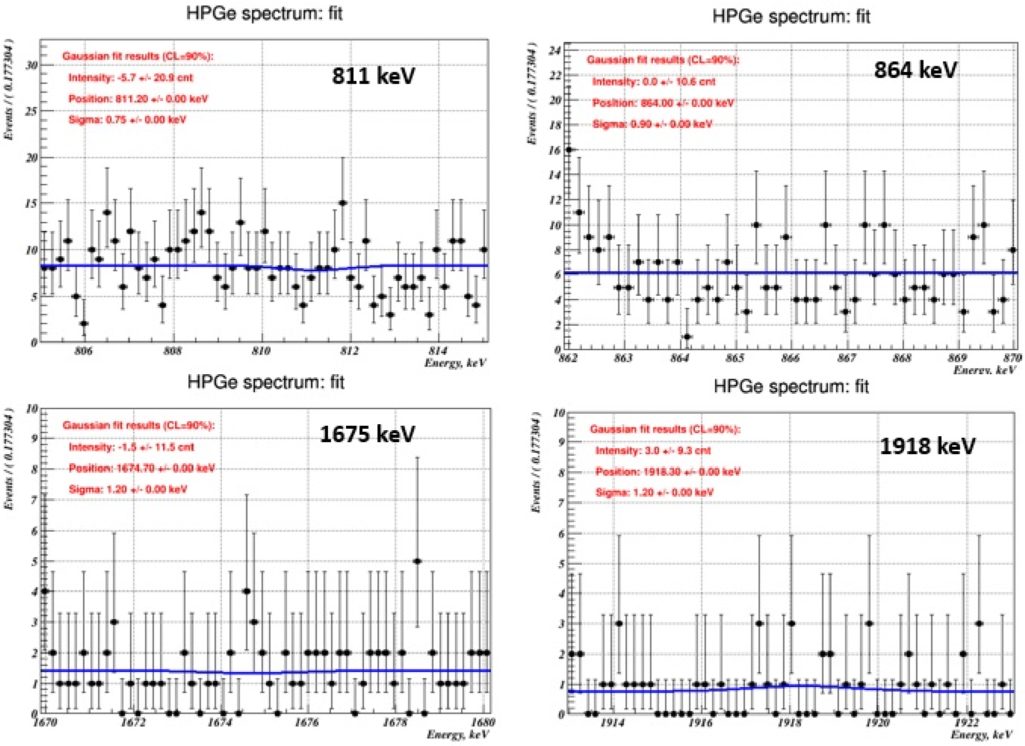

Figure 5. Regions of interest in 811, 864, 1675, 1918 keV of the spectrum of nickel sample measured by Obelix spectrometer during 143.8 days.

and 0νEC/EC radiative decays of ^{58}Ni were determined (see Table. 1). Measurement of nickel sample is still in progress and we hope to improve our experimental limits which are now the best.

4.1. Acknowledgments

The authors would like to thank the LSM staff for their technical assistance. This work was performed within LEA-JOULE agreement and IN2P3-JINR collaboration agreements No.15-93 and was partly supported by grants from European Regional Development Fund (cz.02.1.01/0.0/0.0/16_013/0001733) and RFBR No.18-02-00732.

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