Proposal to the ISOLDE and Neutron Time-of-Flight Committee

The neutron capture cross section of the *s*-process branch point isotope ^{63}Ni

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Neutron capture nucleosynthesis in massive stars plays an important role in Galactic chemical evolution as well as for the analysis of abundance patterns in very old metal-poor halo stars. The so-called weak *s*-process component, which is responsible for most of the *s* abundances between Fe and Sr, turned out to be very sensitive to the stellar neutron capture cross sections in this mass region and, in particular, of isotopes near the seed distribution around Fe. In this context, the unstable isotope ^{63}Ni is of particular interest because it represents the first branching point in the reaction path of the s-process. We propose to measure this cross section at n_TOF from thermal energies up to 500 keV, covering the entire range of astrophysical interest. These data are needed to replace uncertain theoretical predictions by first experimental information to understand the consequences of the ^{63}Ni branching for the abundance pattern of the subsequent isotopes, especially for ^{63}Cu and ^{65}Cu. The measurement will be carried out under the same conditions as for the ^{62}Ni experiment that was successfully completed at n_TOF during the summer of 2009. The results are important for a comprehensive discussion of the s-process abundances in massive stars.

PACS numbers:

I. INTRODUCTION AND PHYSICS MOTIVATIONS

The phenomenology of the s-process implies that the solar abundance distribution is composed of two parts, a *main* component, which is responsible for the mass region from Y to Bi, and a *weak* component, which contributes to the region from Fe to Sr. The main and weak component can be assigned to low mass stars with $1 \leq M/M_{\odot} \leq 3$ and to massive stars with $M \geq 8M_{\odot}$, respectively ($M_{\odot}$ stands for the mass of the sun). Accordingly, the Galactic enrichment with s-process material starts with the lighter s elements, because massive stars evolve much quicker.

The s-process in massive stars with $M \geq 8M_{\odot}$ operates in two major evolutionary stages, first during convective core He burning and subsequently during convective shell carbon burning. Another non negligible contribution to the final s yields may come from a partial tiny convective He burning shell at the outer border of the C shell, whose existence depends on the adopted stellar model [1, 2]. Neutrons are mainly produced by the ^{22}Ne$(\alpha, n)^{25}$Mg reaction in both cases, but at rather different temperatures and neutron densities. During core He burning, neutrons are produced near core He exhaustion at temperatures of T=(2.5 - 3.5)$\times 10^8$ K for about 10^4 years with neutron densities $\lesssim 10^6$ cm^{-3}, whereas the higher temperatures of T=(1.0 - 1.4)$\times 10^9$ K during the subsequent carbon shell burning phase give rise to peak values of about 10^{12} cm^{-3} [3, 4, 5].

Contrary to the conditions of the main component, the neutron exposure in massive stars is too small to achieve flow equilibrium, and this means that the uncertainty in the cross section of a particular isotope does not only imply a corresponding uncertainty of its abundance, but that it propagates to the abundances of subsequent isotopes in the s-process chain. This propagation effect was first noticed at the example of the ^{62}Ni$(n,\gamma)^{63}$Ni reaction [6]. Computations with different choices for the Maxwellian averaged cross section (MACS), which characterize the range of experimental data, are illustrated in Fig. 1. In particular the result of stellar-evolution calculations, when different values for the MACS of ^{62}Ni are used, is reported for a $15M_{\odot}$ and a $25M_{\odot}$ star, respectively. The results demonstrate that the neutron capture rate of a single nucleus has a significant impact on the abundances of many subsequent isotopes in the reaction chain. This propagation problem is particularly crucial for ^{63}Ni , because experimental cross section information for this unstable isotope is completely missing above thermal, so far [8].

A second reason why ^{63}Ni plays a crucial role for the weak s-process follows from the fact that its terrestrial half life of 100 years is reduced up to a factor of 200 under stellar conditions [9]. This implies that neutron capture and β decay rates become comparable and consequently ^{63}Ni represents the first branching point in the reaction path of the s-process as sketched in Fig. 2.

In the low neutron density regime of core He burning, the branching is characterized by a significant production of ^{63}Cu by β decays from ^{63}Ni. At the much higher neutron density during C shell burning, however, the branching is closed and ^{63}Cu is completely bypassed by the reaction flow. In this phase, some ^{63}Cu is only produced by the subsequent decay of the surviving ^{63}Ni abundance. In summary, the neutron capture cross section of ^{63}Ni is crucial for determining the ^{63}Cu/^{65}Cu ratio, which in turn represents a sensitive constraint for stellar model calculations, because the propagation waves of these isotopes affect the entire abundance distribution of the weak s-process [11].

The proposed measurement will cover the full neutron energy range of astrophysical interest from thermal to about 500 keV. This will allow us to obtain reliable Maxwellian averaged cross sections (MACS)

$$< \sigma >_{kT} = \frac{< \sigma v >}{v_T} = \frac{2}{\sqrt{\pi}} \frac{\int_0^{\infty} \sigma(E_n) \cdot E_n \cdot \exp(-E_n/kT) \cdot dE_n}{\int_0^{\infty} E_n \cdot \exp(-E_n/kT) \cdot dE_n} \tag{1}$$

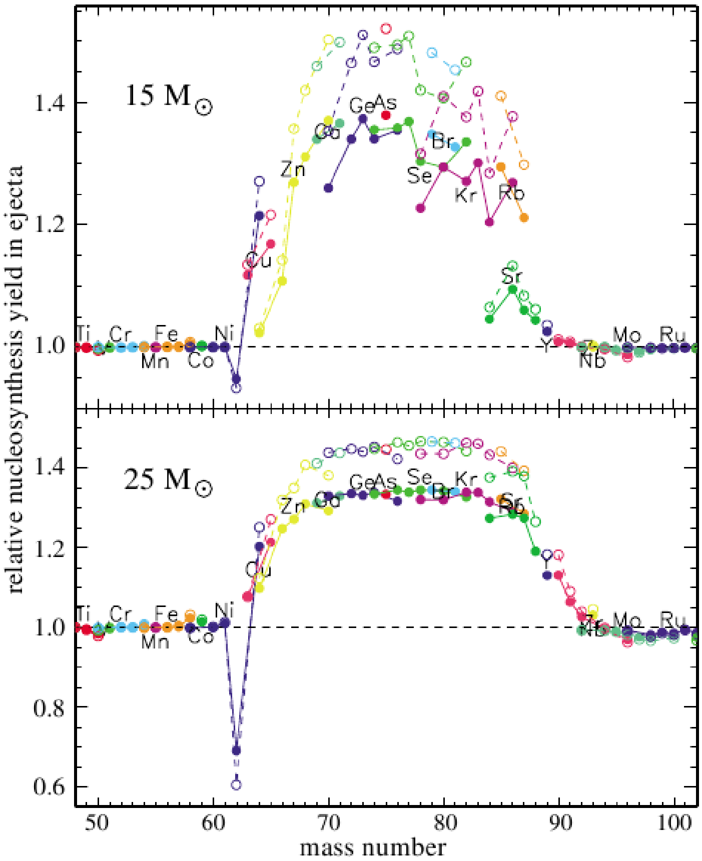

Figure 1: The effect of cross section uncertainties on the s-process efficiency in massive stars illustrated at the example of ^{62}Ni: the nucleosynthesis yield is displayed as a function of mass number calculated for different values of the ^{62}Ni$(n,\gamma)^{63}$Ni reaction cross section (solid dots 26.1 mb [6] and open dots 35.5 mb [7]) and normalized to the yield at a cross section of 12.5 mb [8] for a $15M_\odot$ (top) and a $25M_\odot$ (bottom) star. Figure from [6].

for both s-process episodes in massive stars, i.e. for $kT = 25$ as well as for $kT = 90$ keV.

II. MEASUREMENTS

Even though the interest in the neutron capture cross section of ^{63}Ni is evident, measurements have been performed so far only at thermal energy [12, 13, 14]. Therefore, stellar model calculations must rely on estimates for the MACS based on theoretical assumptions that could be affected by large uncertainties, in particular in view of the expected resonance structure in the keV region.

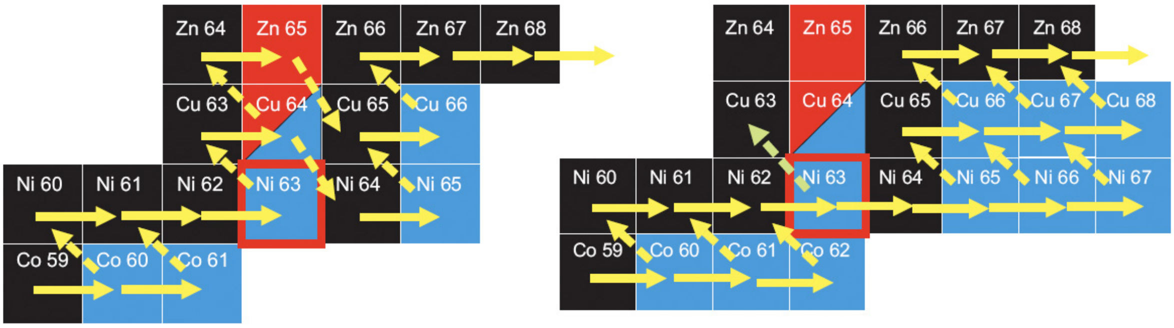

Figure 2: The *s*-process path in the vicinity of Cu. The main reaction flows during core-He burning (left) and shell-C burning (right). Figure from [10].

The relatively short half-life of 100 yr makes the preparation of a highly enriched ^{63}Ni sample very difficult. The material to be used in the proposed measurement has been produced by breeding of a pure ^{62}Ni sample in a thermal reactor yielding a final enrichment in ^{63}Ni of 12.7%. The ^{63}Ni sample consists of three cylindrical metal discs, 10 mm in diameter and with a total mass of 995 mg, which corresponds to 112 mg of ^{63}Ni. Two of these discs, 210 mg and 130 mg in mass respectively, had an initial enrichment of 11.9% in ^{63}Ni right after irradiation [15], while the third 665 mg disc had an initial enrichment of 13.7% ^{63}Ni [16, 17]. Over the last 25 years, 18.3 mg of ^{63}Cu have been produced by decay of ^{63}Ni, corresponding to 16.3% relative to ^{63}Ni. This sizable content of Cu can be removed by chemical purification. Furthermore, the ^{63}Ni capture cross section can be determined only with reasonable accuracy if the ^{62}Ni(n,γ) cross section is very well defined.

The n_TOF facility is the ideal place for this important measurement. The high instantanenous neutron flux minimizes the background uncorrelated with the neutron beam, while the low neutron sensitivity of the apparatus minimizes the neutron background, which would otherwise heavily affect the measurement, given the presumably large elastic-to-capture cross section ratio of this isotope as demonstrated by several successful measurements, which have been performed in the past [18]. A further advantage is that the n_TOF Collaboration has already determined the capture cross section of ^{62}Ni with the same setup in 2009, and these data can be used to correct for the large ^{62}Ni component of the sample.

The measurement will be performed with the well established C_6D_6 detector setup, which is optimized for very low neutron sensitivity. Although accurate ^{62}Ni data are at hand, we propose to take also some new data with the ^{62}Ni sample to verify and to possibly improve the results by taking advantage of the much reduced background related to in-beam γ-rays, which has been obtained in 2010 with the new ^{10}B-loaded water moderator [19]. In particular, in the keV region, the background induced by the 2.2 MeV γ-rays, originating from neutron capture on hydrogen inside the water moderator of the target, is approximately a factor 10 lower. This improvement of the n_TOF facility was achieved only after the ^{62}Ni measurement. Finally, thanks to a recent upgrade of the data acquisition system, we will be able to extend the measurements down to thermal neutron energy for comparison of our results with existing thermal cross sections.

III. BEAM TIME REQUEST

The request for the number of protons is based on the experience of previous measurements with C_6D_6 scintillation detectors. Together with ^{62}Ni and ^{63}Ni samples, we plan to measure the yield for Au and C samples as well. Au is used for normalizing the yield, the carbon sample serves for determining the background due to neutrons scattered by the sample. Although the neutron sensitivity of the apparatus is very small, the large elastic-to-capture cross section ratio in some of the resonances may result in a non-negligible neutron background, as already observed in the case of ^{62}Ni.

Because experimental capture data are not available in the resonance region, the ^{63}Ni(n, γ) rates were calculated by using theoretical guesses from the evaluated cross section libraries shown in Fig. 3.

Moreover, we tried to predict a realistic capture cross section for ^{63}Ni. The estimation was done by generating a random set of resonances with fixed statistical properties [20, 21]. In particular, these are: i) Wigner distribution of level spacing; ii) Porter-Thomas distribution of the neutron widths; iii) Gaussian distribution of the γ-ray widths. The procedure was tested on the neighbouring stable isotopes ^{60}Ni and ^{62}Ni. The parameters used in this calculation are listed in table I. All the calculations were performed using neutron strength functions of $S_0 = 3\times10^{-4}$ and $S_1 = 0.5\times10^{-4}$, and a reaction-width of $\Gamma_\gamma = 1.0\pm0.3$ eV (the uncertainty is assumed as standard deviation of the reaction-width gaussian distribution). These values are close to the experimental values for ^{62}Ni and do not vary much for different nickel isotopes.

The expected capture yields obtained on the basis of these estimated cross sections are

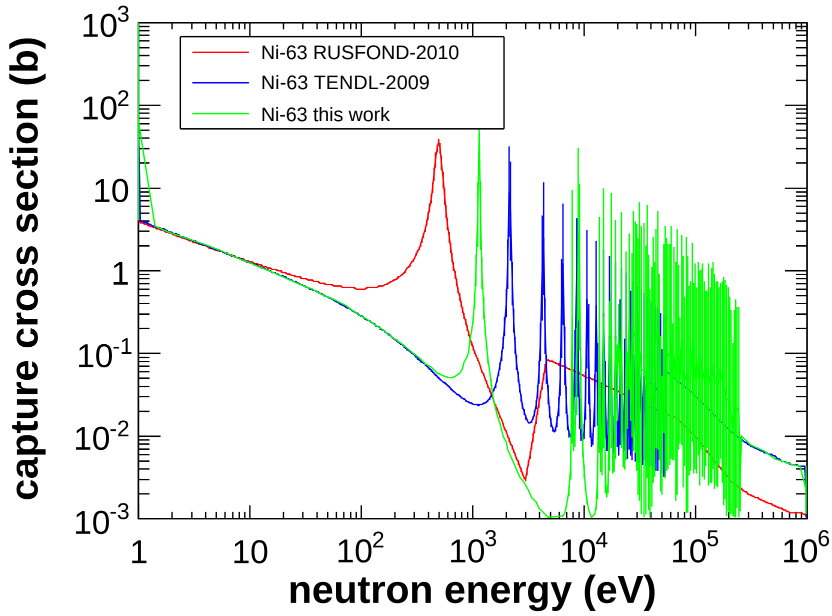

Figure 3: Evaluated capture cross section of ^{63}Ni, according to the libraries TENDL (2009), RUSFOND (2010) and the present theoretical calculation.

	Spin	S_n	R'	<D(ℓ=0)>	<D(ℓ=1)>
		MeV	fm	keV	keV
^{63}Ni	$\frac{1}{2}^-$	9.657	5.36	2.1	1.0
				7.9 (J=0)	7.9 (J=0)
				2.8 (J=1)	2.8 (J=1)
					1.97 (J=2)

Table I: Statistical properties of ^{63}Ni, where S_n is the neutron separation energy, R' the radius, $< D(\ell = 0) >$ the s-wave level spacing and $< D(\ell = 1) >$ the p-wave level spacing.

plotted in Fig. 4. The calculation was performed for a disc sample 10 mm in diameter with ^{62}Ni and ^{63}Ni components corresponding to 1.070×10^{-2} and 1.364×10^{-3} atoms/barn according to the sample composition.

Comparing the isotopic yields in Fig. 4 one finds that ^{63}Ni resonances can be safely identified in the keV region, thanks to the excellent energy resolution at n_TOF, which allows resolution of single resonances up to several hundred keV.

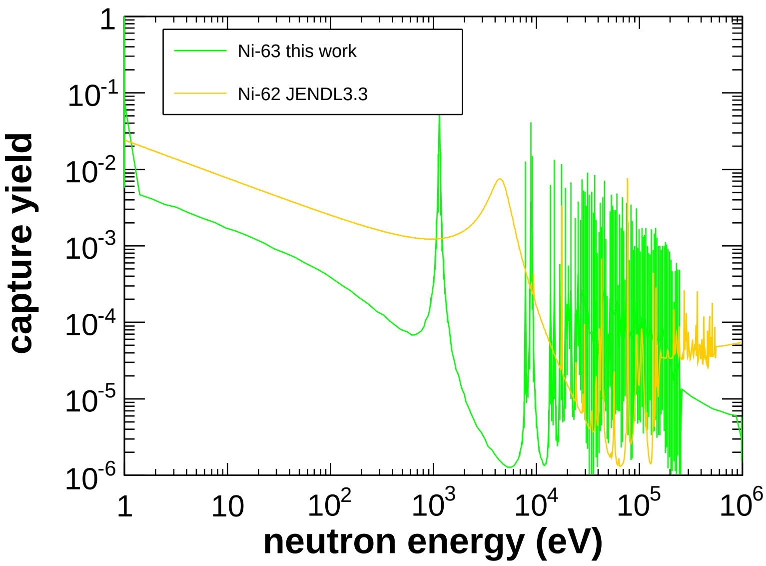

Figure 4: Calculated capture yield for ^{62}Ni and ^{63}Ni, according to the composition of the sample to be measured. A total mass of 112 mg has been assumed for ^{63}Ni.

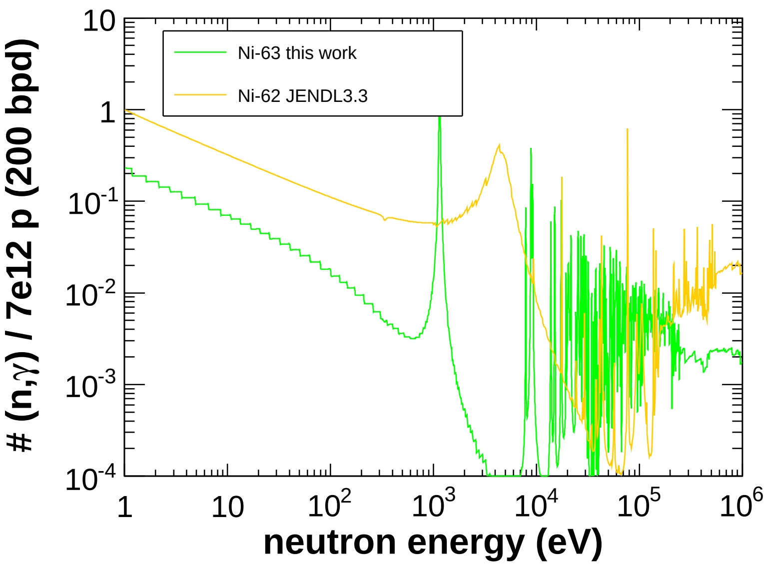

Figure 5: Reaction rates (for the nominal proton bunch of 7×10^{12} protons) estimated for the sample considered in the present proposal on the basis of Fig. 4. The resolution in the plot is 200 bins/neutron energy decade.

The resulting number of capture reactions per standard proton pulse is shown in Fig. 5 for a resolution of 200 bins per neutron energy decade. Since the dimension of the available sample (1 cm in diameter) is smaller that that of the neutron beam, a beam interception factor of 0.23 has been properly taken into account in the calculation. The expected count rate in Fig. 5 was obtained with the established overall 20% efficiency for detecting a capture event with the C_6D_6 setup. According to these count-rate estimates we request a total of 5×10^{18} protons for the present measurement.

IV. CONCLUSIONS

Experimental cross section information on ^{63}Ni is completely missing above thermal so far, despite of its role as an important branching point in the weak *s*-process. The present proposal aims at a first measurement of the neutron-induced capture cross section of ^{63}Ni in the resonance region in the full energy range from thermal to about 500 keV with good accuracy. The measurement will be performed with a well known capture setup (C_6D_6 liquid scintillators) that has been used successfully in previous measurement campaigns at n_TOF. The requested beam time for the measurement corresponds to the neutron fluence produced with 5×10^{18} protons.

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