Measurement of ^{64}Ni(n,γ) cross section at CERN n_TOF

Michele Spelta

GIANTS XI Workshop
Caserta, 20th – 21st October 2022

Original Proposal

Some Extremely-Metal Poor stars were found to show abundance patterns that scale as the solar r-component

$$N_r = N_{sun} - N_s$$

«Massive stars contribute significantly to the abundances between Fe and Zr»
(**Weak s-process**)

CERN-INTC-2006-012
INTC/P-208

The role of Fe and Ni for *s*-process nucleosynthesis in the early Universe and for innovative nuclear technologies

J.L. Tain*,[1] C. Domingo-Pardo,[1] F. Bečvář,[2] E. Berthoumieux,[3] F. Calviño,[4] D. Cano-Ott,[5] P. Cennini,[6] N. Colonna,[7] G. Cortes,[4] I. Dillmann,[8,9] W. Dridi,[3] E. González,[5] A. Guerra,[5] C. Guerrero,[5] F. Gunsing,[3] M. Heil†,[9] F. Käppeler,[9] D. Karadimos,[10] P. Koehler,[11] C. Lamboudis,[12] H. Leeb,[13] S. Marrone,[7] T. Martinez,[5] C. Massimi,[14] A. Mengoni,[15] P.M. Milazzo,[16] R. Plag,[9] G. Tagliente,[7] P. Vaz,[17] V. Vlachoudis‡,[6] and The n_TOF Collaboration

Abstract

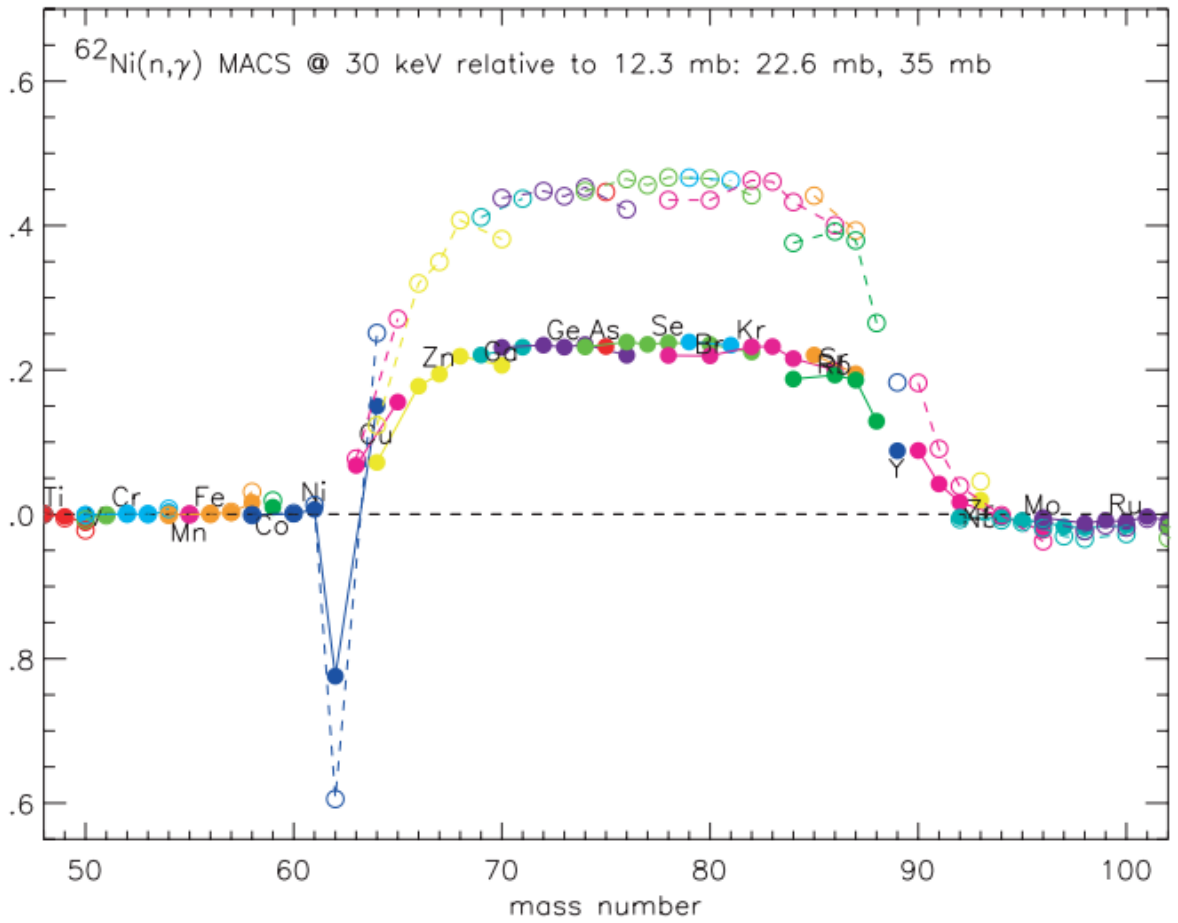
The early universe was enriched in heavy elements by massive stars via their *s*- and *r*-process contributions. Ultra metal-poor stars were found to show abundance patterns that scale exactly with the solar *r* component. While this holds exactly for elements heavier than barium, there is still confusion about significant discrepancies in the mass region below $A \leq 120$. It is known that massive stars contribute significantly to the abundances between Fe and Zr. This so-called weak *s*-process component was found to exhibit large uncertainties due to the poorly known cross sections, especially in the Fe-Ni region. In view of this problem it is proposed to perform accurate state-of-the art measurements on highly enriched samples of the stable Fe and Ni isotopes at the n_TOF facility. Transformation of these results into significantly improved stellar cross section rates will allow to disentangle the *s* and *r* contributions observed in the oldest stars for a reliable comparison with galactic chemical evolution models. These results are also very important for the design of advanced reactor concepts.

CERN-INTC-2006-012
INTC/P-208

Original Proposal

The role of Fe and Ni
for *s*-process nucleosynthesis in the early Universe
and for innovative nuclear technologies

«The abundances in the mass region of the weak s-component [...] exhibit a **pronounced propagation effect**»



Important role of **Fe** and **Ni**

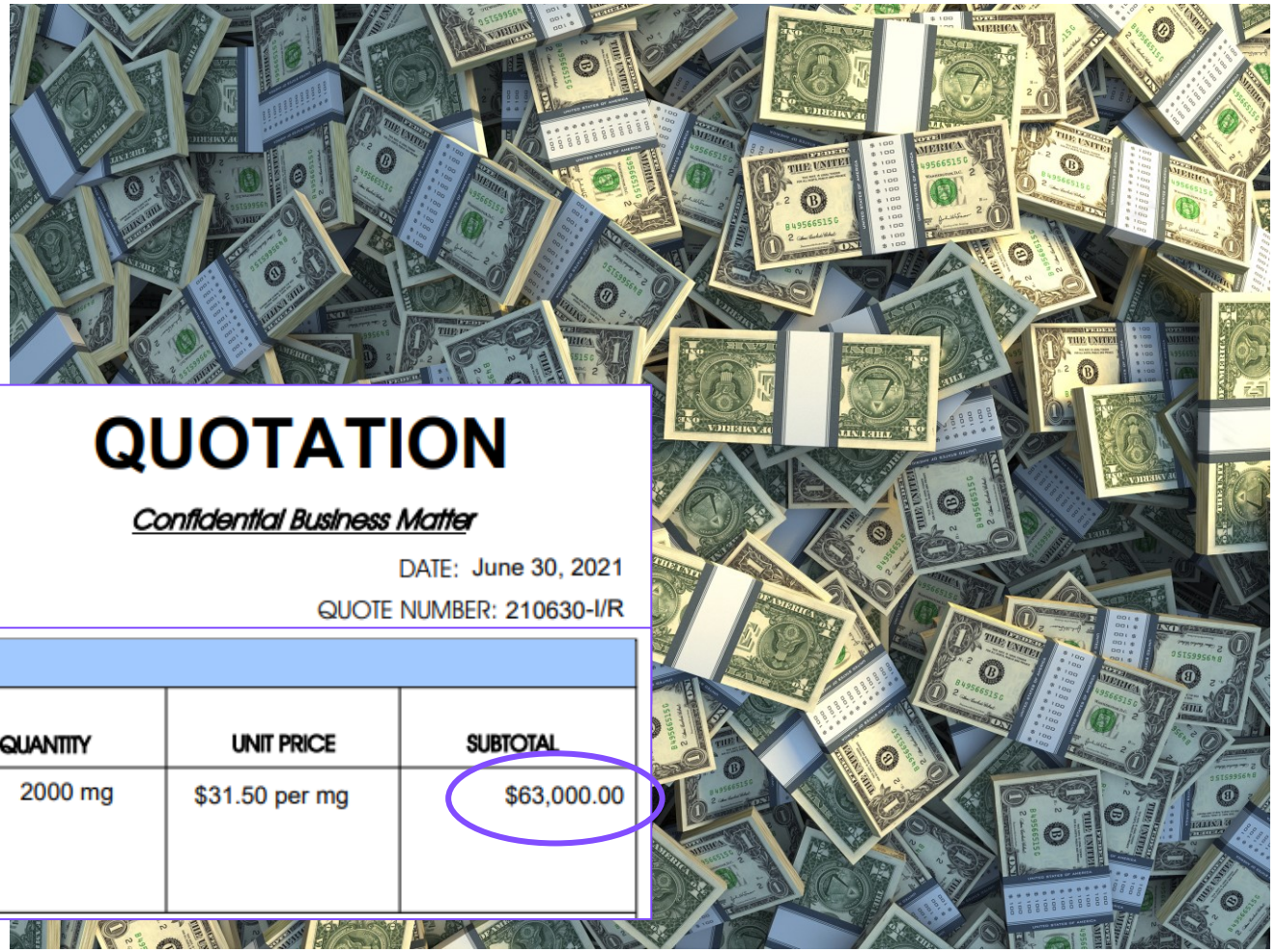
CERN-INTC-2006-012
INTC/P-208

Original Proposal

✓ ✓
54, 56, 57, ^{58}**Fe**

✓ ✓ ✓
58, 60, 61, 62, 63, ^{64}**Ni**

The role of Fe and Ni
for *s*-process nucleosynthesis in the early Universe
and for innovative nuclear technologies



ISOFLEX USA
Isotopes for Science, Medicine and Industry

P.O. Box 29475
San Francisco CA 94129 USA
Tel: 415-440-4433 Fax: 415-563-4433

QUOTATION

Confidential Business Matter

DATE: June 30, 2021

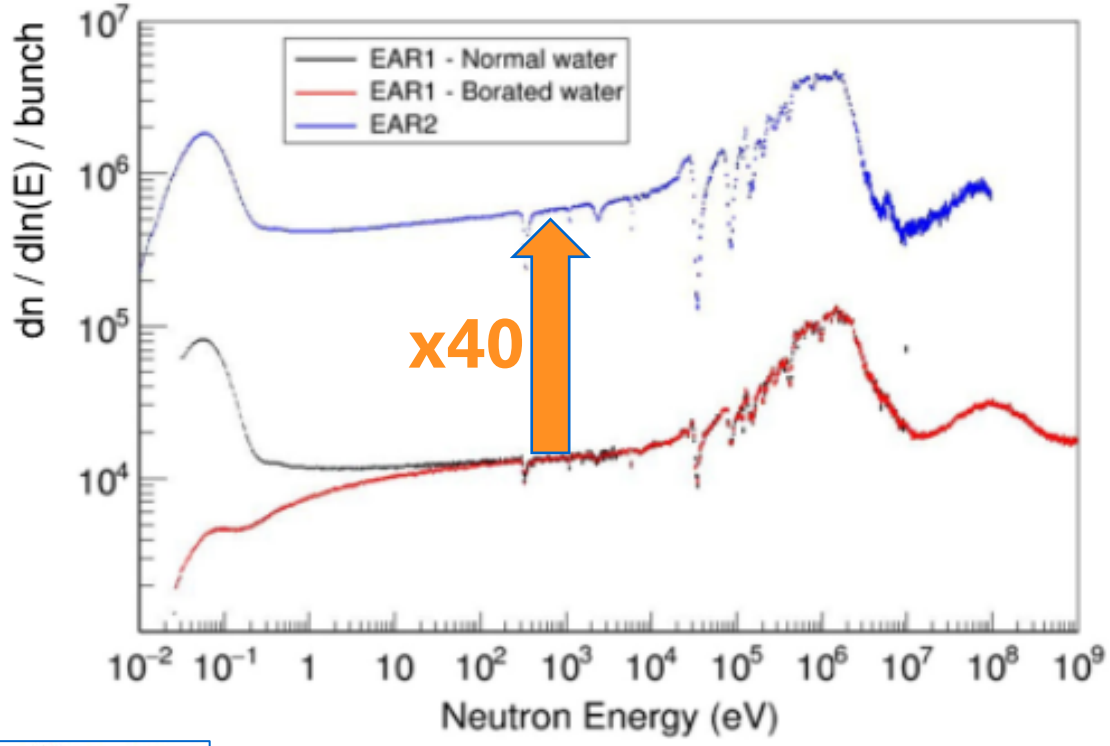
QUOTE NUMBER: 210630-I/R

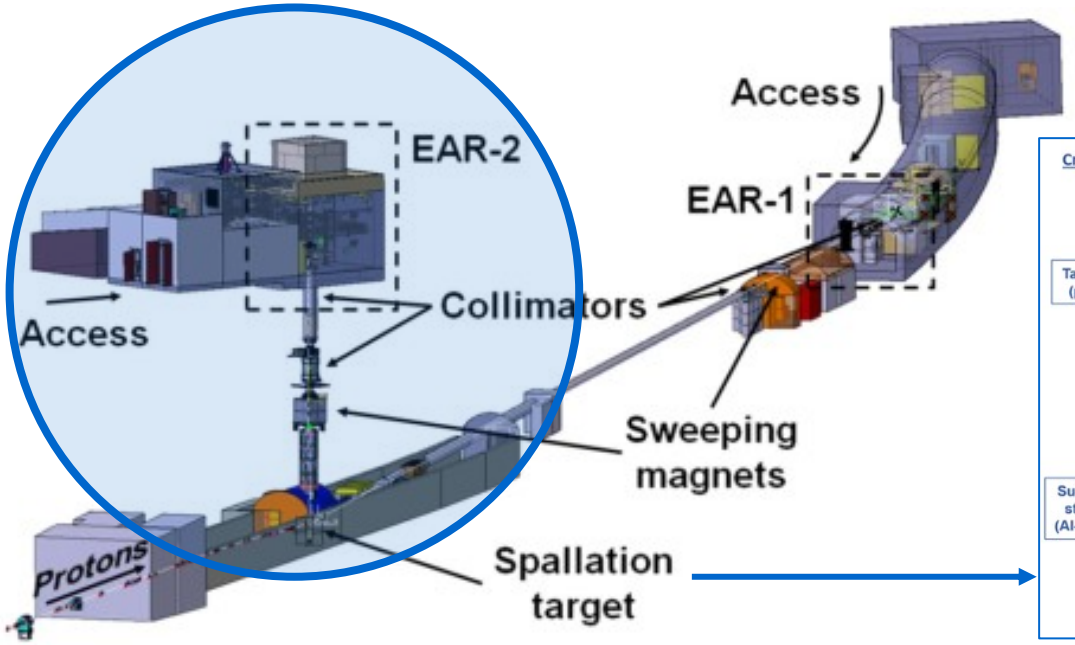
QUOTATION SUMMARY

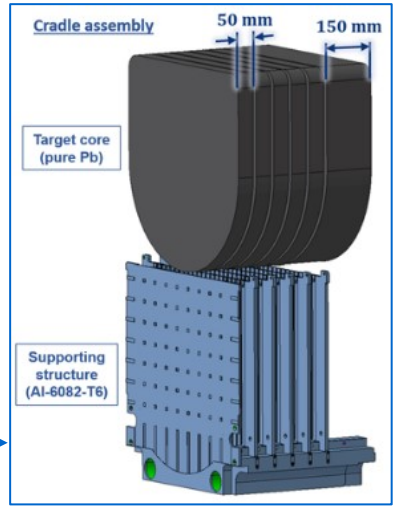
DESCRIPTION	PROPOSED DELIVERY	QUANTITY	UNIT PRICE	SUBTOTAL
Nickel-64 (Ni-64), metal powder **Isotopic Enrichment:** 99,33atom% **Harmonized Code:** - 2845.90.0000 (USA)	~4 weeks ARO	2000 mg	$31.50 per mg	$63,000.00

What has changed?

«The measurement [...] can be performed using small quantities of ^{64}Ni, taking advantage of the **higher neutron flux in the n_TOF EAR2**.»







Third-generation n_TOF spallation target (2021)

Motivation (1)

«The cross sections of the stable isotopes of Fe and Ni are important for the **quantitative description of the s process in massive stars**»

CERN-INTC-2006-012
INTC/P-208

The role of Fe and Ni
for *s*-process nucleosynthesis in the early Universe
and for innovative nuclear technologies

J.L. Tain*,[1] C. Domingo-Pardo,[1] F. Bečvář,[2] E. Berthoumieux,[3] F. Calviño,[4] D. Cano-Ott,[5] P. Cennini,[6] N. Colonna,[7] G. Cortes,[4] I. Dillmann,[8,9] W. Dridi,[3] E. González,[5] A. Guerra,[5] C. Guerrero,[5] F. Gunsing,[3] M. Heil†,[9] F. Käppeler,[9] D. Karadimos,[10] P. Koehler,[11] C. Lamboudis,[12] H. Leeb,[13] S. Marrone,[7] T. Martinez,[5] C. Massimi,[14] A. Mengoni,[15] P.M. Milazzo,[16] R. Plag,[9] G. Tagliente,[7] P. Vaz,[17] V. Vlachoudis‡,[6] and The n_TOF Collaboration

Abstract

The early universe was enriched in heavy elements by massive stars via their *s*- and *r*-process contributions. Ultra metal-poor stars were found to show abundance patterns that scale exactly with the solar *r* component. While this holds exactly for elements heavier than barium, there is still confusion about significant discrepancies in the mass region below $A \leq 120$. It is known that massive stars contribute significantly to the abundances between Fe and Zr. This so-called weak *s*-process component was found to exhibit large uncertainties due to the poorly known cross sections, especially in the Fe-Ni region. In view of this problem it is proposed to perform accurate state-of-the art measurements on highly enriched samples of the stable Fe and Ni isotopes at the n_TOF facility. Transformation of these results into significantly improved stellar cross section rates will allow to disentangle the *s* and *r* contributions observed in the oldest stars for a reliable comparison with galactic chemical evolution models. These results are also very important for the design of advanced reactor concepts.

Motivation (2)

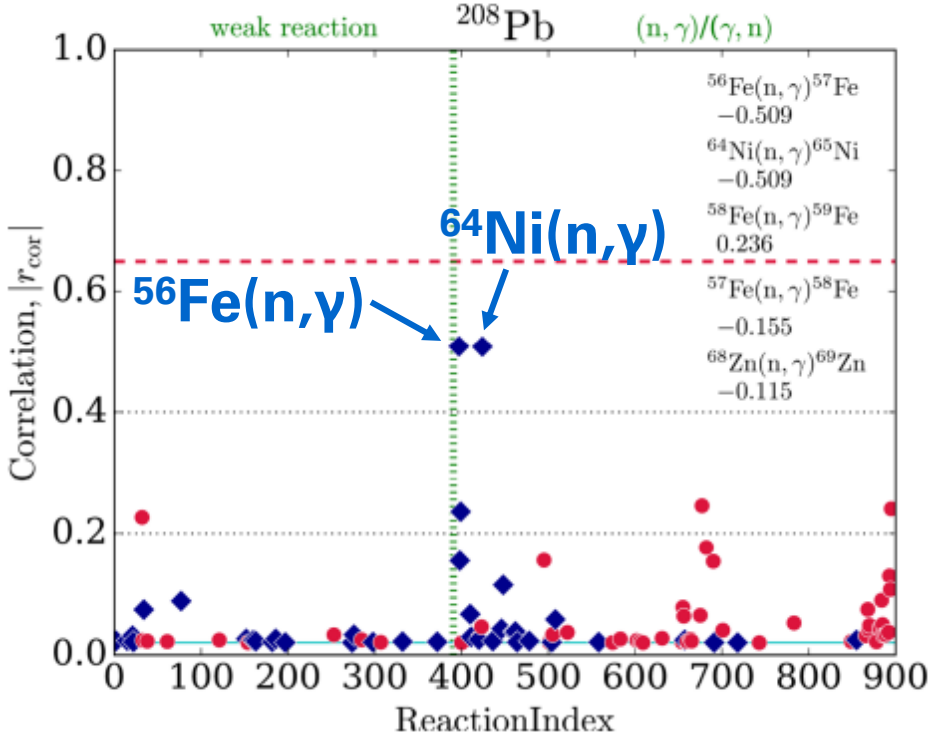
^{56}Fe(n,γ), **^{64}Ni(n,γ)** and ^{138}Ba(n,γ) reactions significantly **affect the uncertainty in the abundances of a large number of nuclides produced in low-mass AGB stars.**

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 478, 4101–4127 (2018) doi:10.1093/mnras/sty1185
Advance Access publication 2018 May 5

Uncertainties in s-process nucleosynthesis in low-mass stars determined from Monte Carlo variations

G. Cescutti,[1★†] R. Hirschi,[2,3†] N. Nishimura,[4†] J. W. den Hartogh,[2,5†] T. Rauscher,[6,7†] A. St. J. Murphy[8†] and S. Cristallo[9,10]

[1]*INAF, Osservatorio Astronomico di Trieste, I-34131 Trieste, Italy*
[2]*Astrophysics group, Lennard-Jones Laboratories, Keele University, ST5 5BG Staffordshire, UK*
[3]*Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa 277-8583, Japan*
[4]*Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*
[5]*Konkoly Observatory, Konkoly Thege Miklós út 15-17, H-1121 Budapest, Hungary*
[6]*Department of Physics, University of Basel, Klingelbergstr. 82, CH-4056 Basel, Switzerland*
[7]*Centre for Astrophysics Research, University of Hertfordshire, College Lane, Hatfield AL10 9AB, UK*
[8]*SUPA, School of Physics and Astronomy, University of Edinburgh, Edinburgh EH9 3FD, UK*
[9]*INAF, Osservatorio Astronomico d'Abruzzo, I-64100 Teramo, Italy*
[10]*INFN-Sezione di Perugia, I-06123 Perugia, Italy*



Motivation (3)

«Recent magnetic AGB models were found to **disagree with respect to ^{64}Ni isotopic ratios measurements in presolar SiC grains**. The other Ni isotopic ratios well match the theoretical models.»

The Astrophysical Journal Letters, 897:L25 (8pp), 2020 July 10 https://doi.org/10.3847/2041-8213/ab9fa1

Magnetic-buoyancy-induced Mixing in AGB Stars: Presolar SiC Grains

Diego Vescovi[1,2,3], Sergio Cristallo[2,3], Maurizio Busso[2,4], and Nan Liu[5,6]
[1] Gran Sasso Science Institute, Viale Francesco Crispi, 7, I-67100 L'Aquila, Italy; diego.vescovi@gssi.it
[2] INFN, Section of Perugia, Via A. Pascoli snc, I-06123 Perugia, Italy
[3] INAF, Observatory of Abruzzo, Via Mentore Maggini snc, I-64100 Teramo, Italy
[4] University of Perugia, Department of Physics and Geology, Via A. Pascoli snc, I-06123 Perugia, Italy
[5] Laboratory for Space Sciences and Physics Department, Washington University in St. Louis, St. Louis, MO 63130, USA
[6] McDonnell Center for the Space Sciences, Washington University in St. Louis, St. Louis, MO 63130, USA
Received 2020 May 25; revised 2020 June 18; accepted 2020 June 24; published 2020 July 9

Abstract

Isotope ratios can be measured in presolar SiC grains from ancient asymptotic giant branch (AGB) stars at permil-level (0.1%) precision. Such precise grain data permit derivation of more stringent constraints and calibrations on mixing efficiency in AGB models than traditional spectroscopic observations. In this paper we compare SiC heavy-element isotope ratios to a new series of FRUITY models that include the effects of mixing triggered by magnetic fields. Based on 2D and 3D simulations available in the literature, we propose a new formulation, upon which the general features of mixing induced by magnetic fields can be derived. The efficiency of such a mixing, on the other hand, relies on physical quantities whose values are poorly constrained. We present here our calibration by comparing our model results with the heavy-element isotope data of presolar SiC grains from AGB stars. We demonstrate that the isotopic compositions of all measured elements (Ni, Sr, Zr, Mo, Ba) can be simultaneously fitted by adopting a single magnetic field configuration in our new FRUITY models.

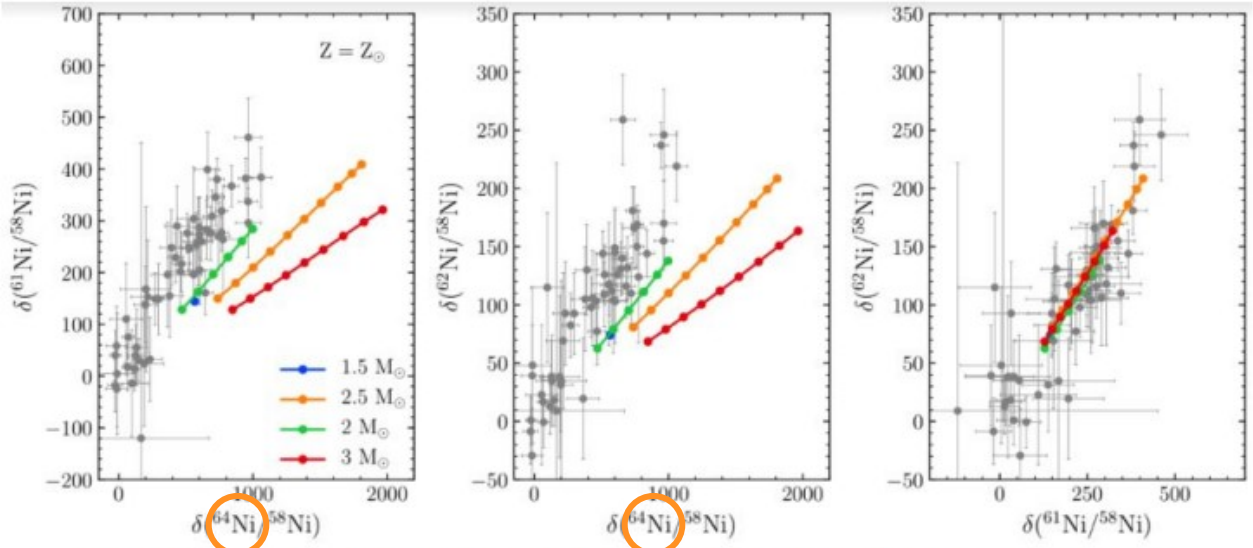


Figure 2 Comparison between theoretical AGB models and presolar grain measurements.

State of the art

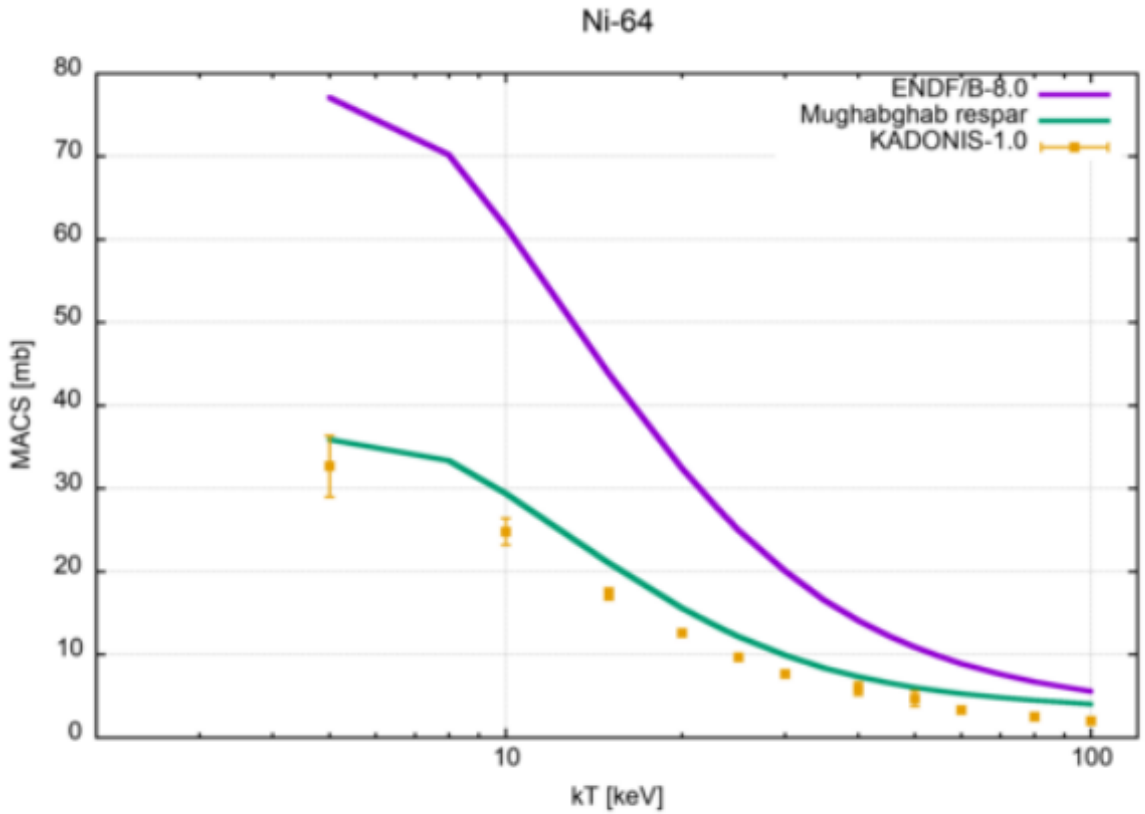


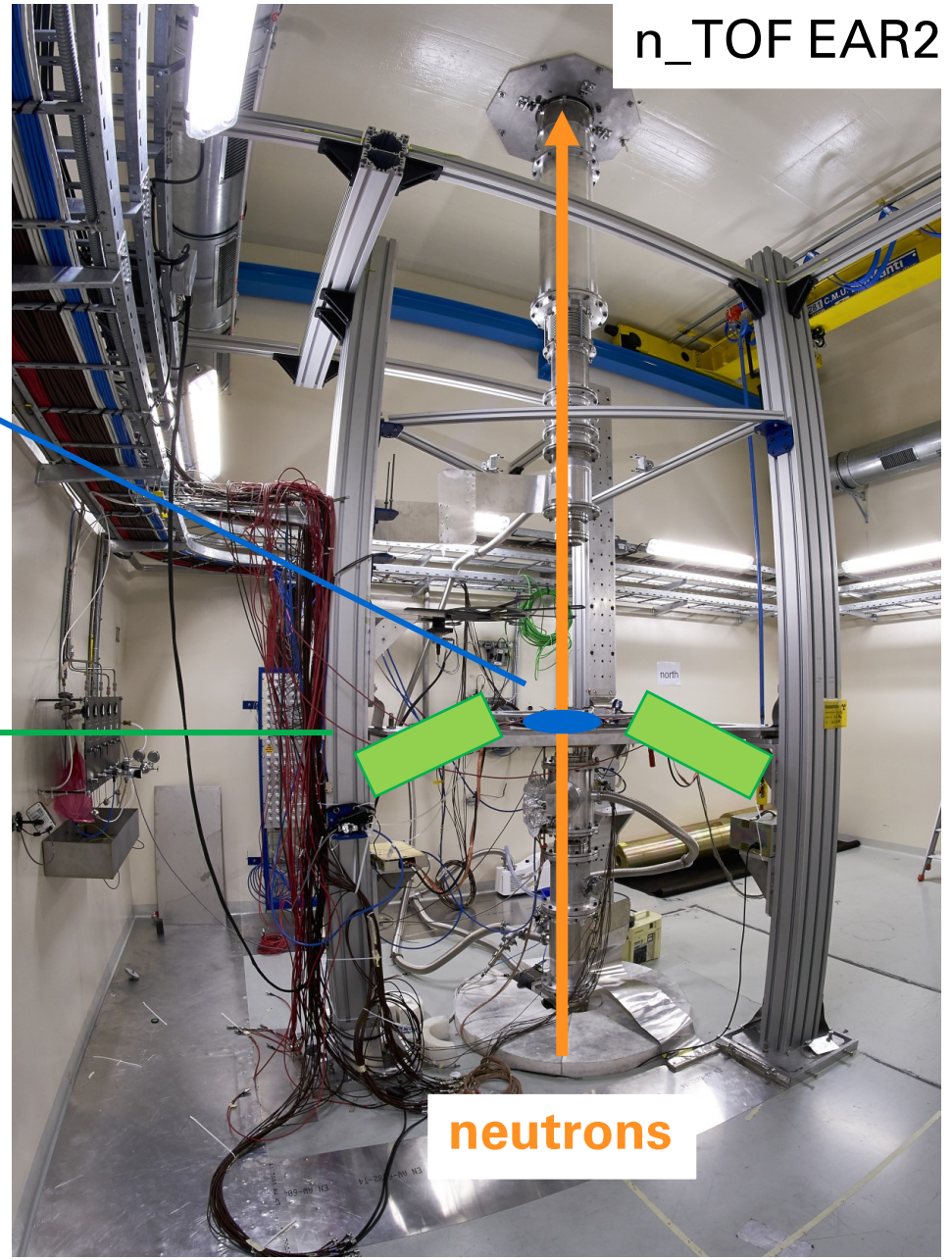
Figure 1 Comparison of the MACS calculated with different libraries.

The Maxwellian Averaged Cross Section (MACS) suffers for **severe discrepancies** amongst the databases available in literature.

Experimental setup

Sample of **500 mg** Ni metal powder with enrichment **99.33% of ^{64}Ni**, 1 cm radius

C_6D_6 liquid scintillators (TED)
(Low sensitivity to scattered n)

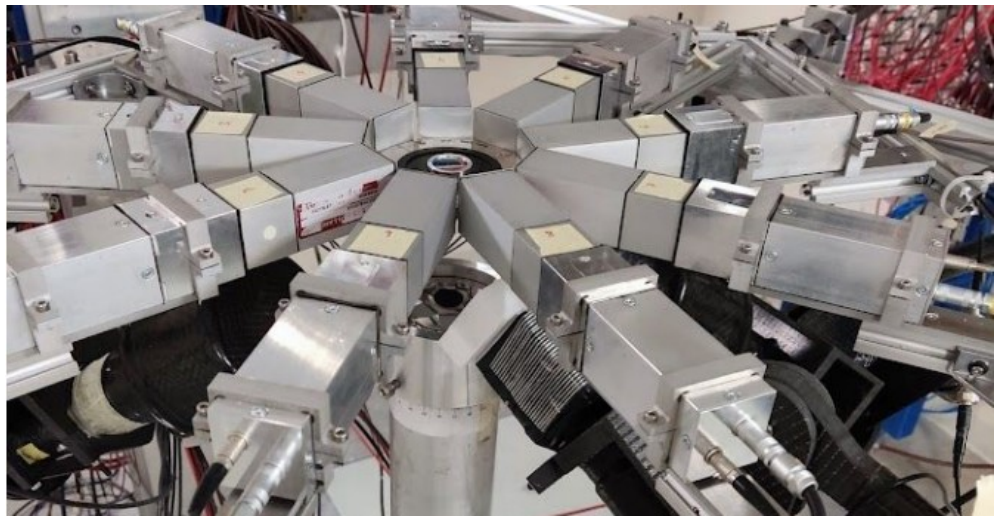


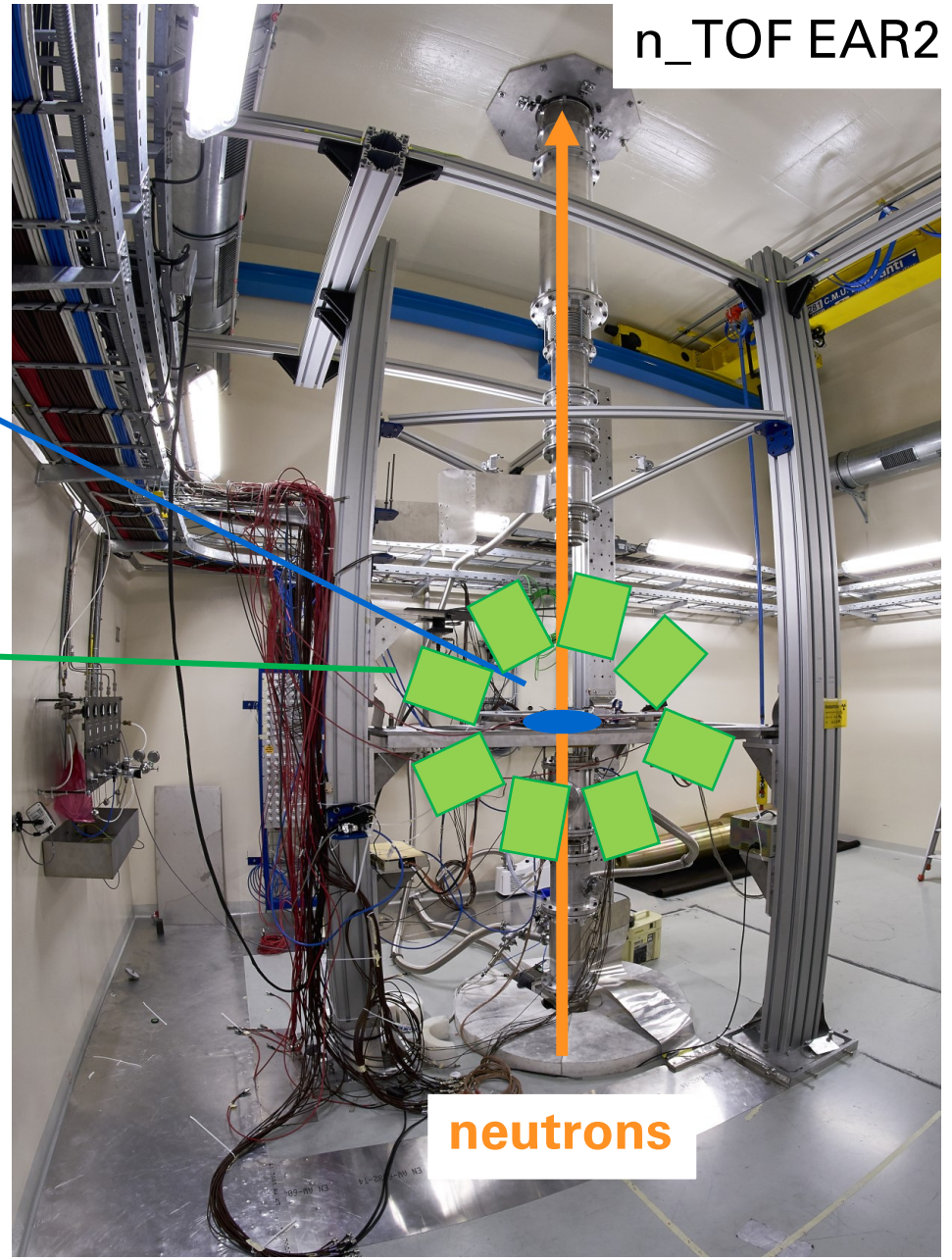
Experimental setup

Sample of **500 mg** Ni metal powder with enrichment **99.33% of ^{64}Ni**, 1 cm radius

sTED

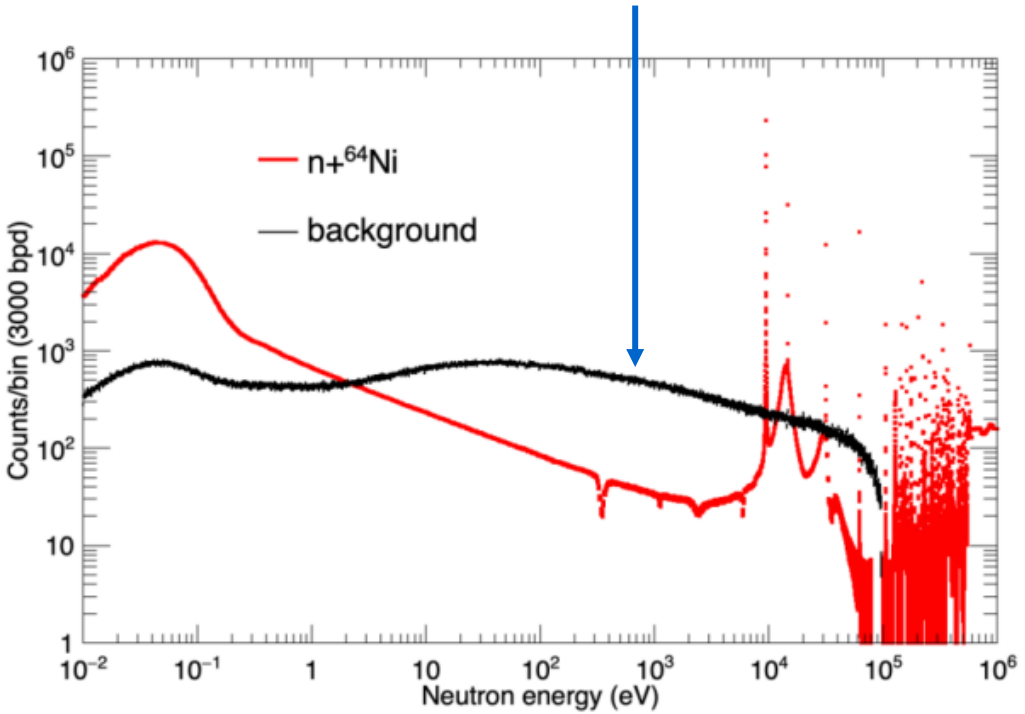
(Low sensitivity to scattered n, higher neutron energies detectable)

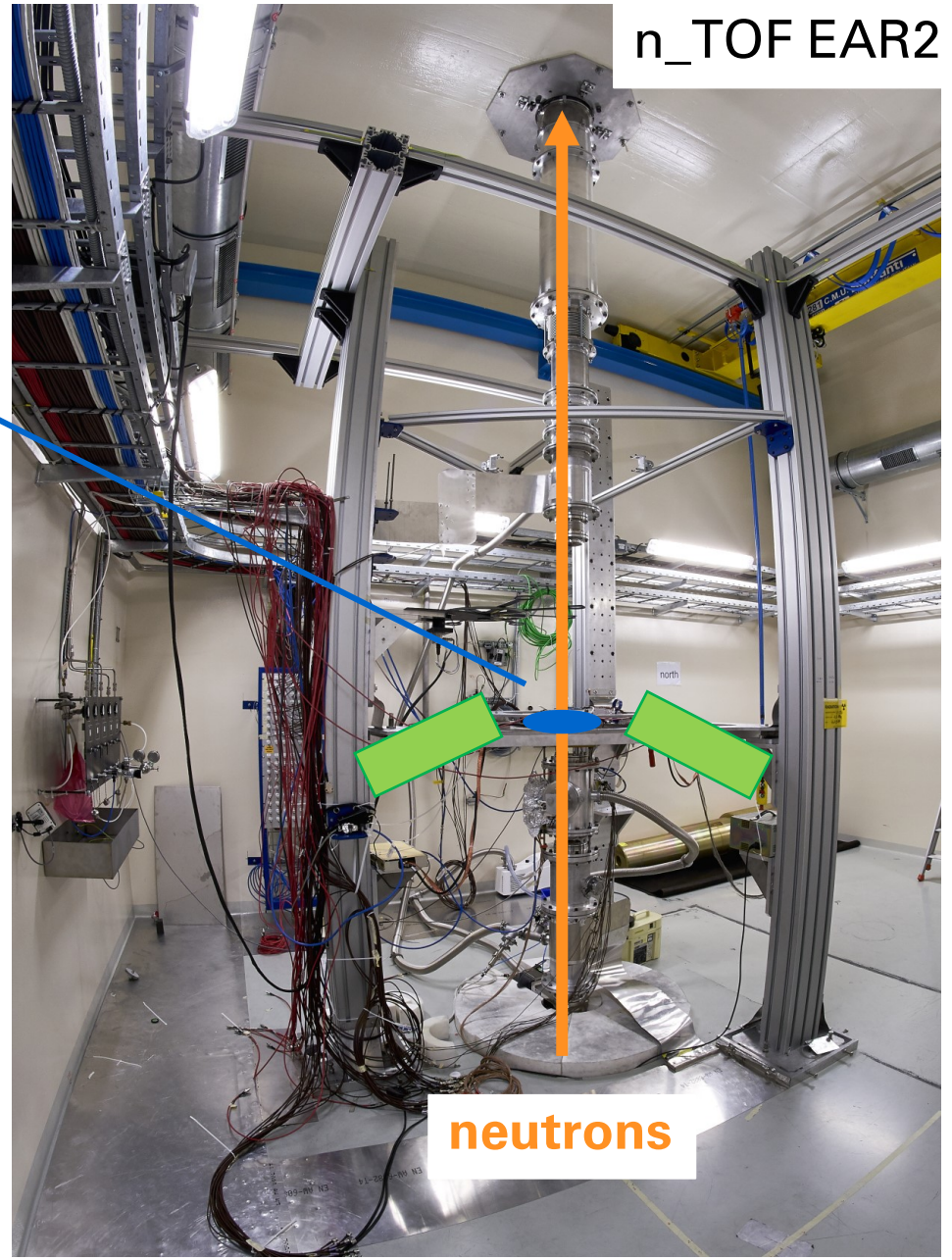




Experimental setup

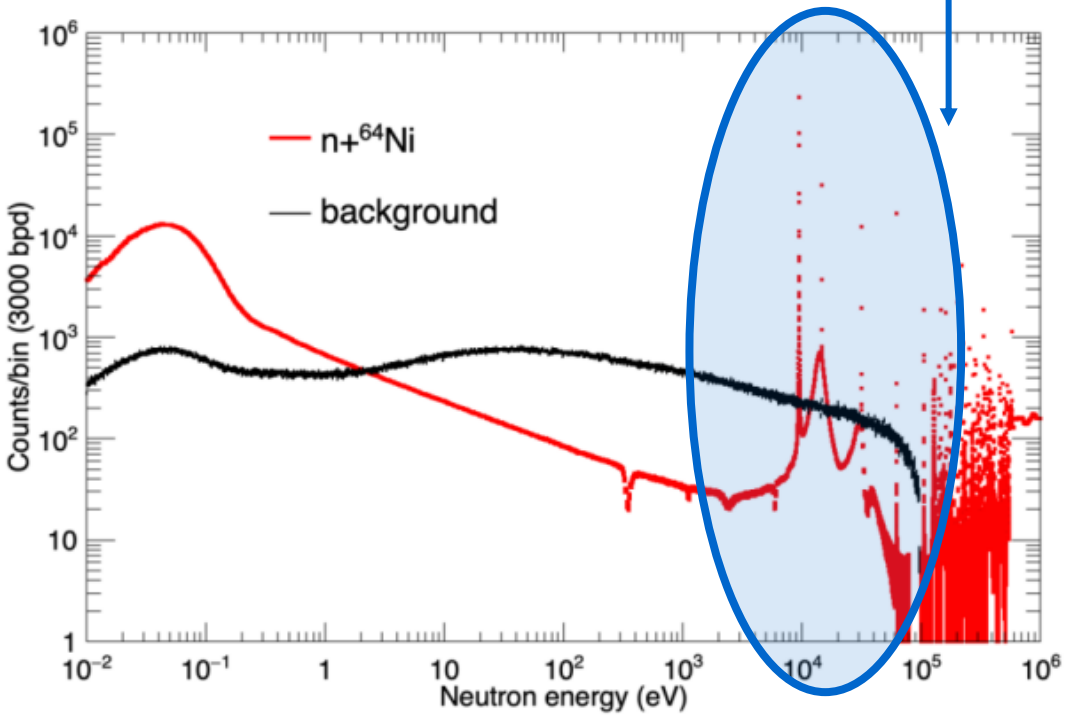
Measurements with different samples and without sample for background evaluation and normalization

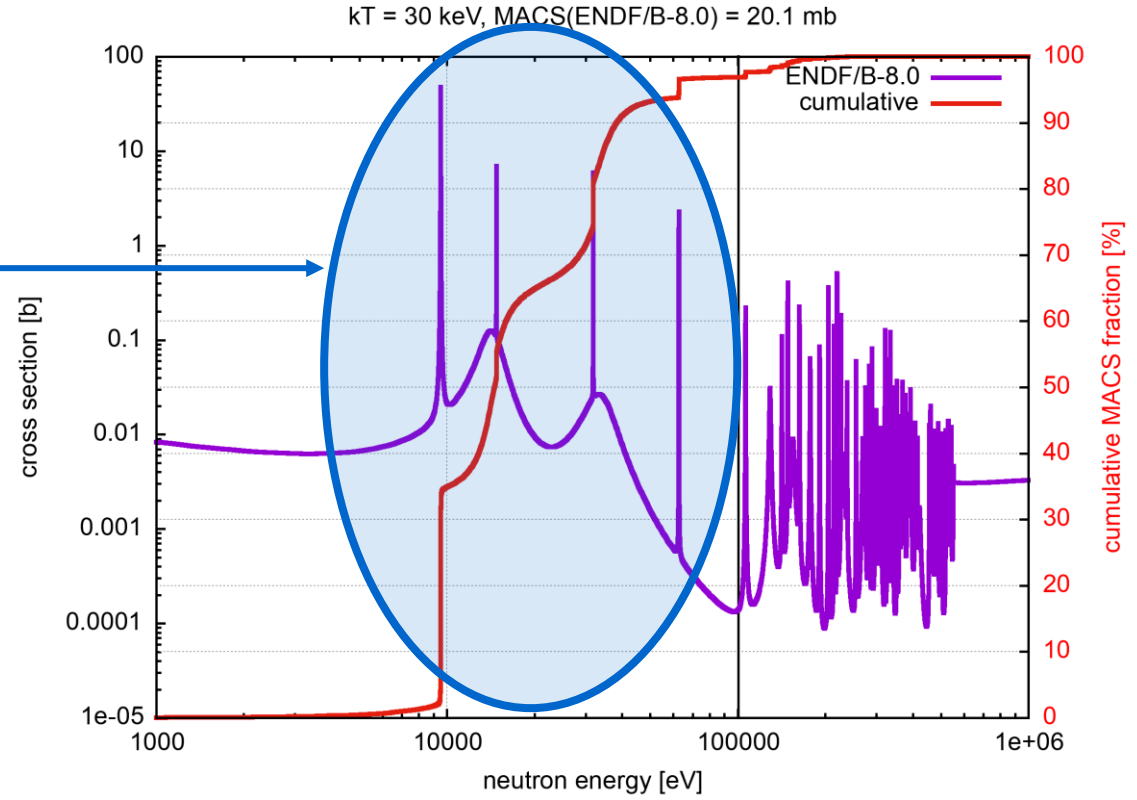




Goal

Accurate evaluation of the resonances
(**from thermal to 100 keV**)





3000 bins/decade
< 5% uncertainty

The end

Reference

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
Addendum of the Proposal INTC-P-208

Measurement of the neutron capture cross section of ^{64}Ni

G. Tagliente[1], G. Cescutti[2,3], N. Colonna[1], S. Cristallo[4,5], D. Diacono[1], C. Lederer-Wood[6], C. Massimi[7,8], M. Mastromarco[1,9], A.M. Mazzone[1,10], P.M. Milazzo[3], N. Sosnin[11], D. Vescovi[12]

1. Istituto Nazionale di Fisica Nucleare, Sez. di Bari, Italy
2. Università di Trieste, Dipartimento di Fisica, Trieste, Italy
3. Istituto Nazionale di Fisica Nucleare, Sez. Trieste, Italy
4. Istituto Nazionale di Astrofisica, Osservatorio Astronomico d'Abruzzo, Teramo, Italy
5. Istituto Nazionale di Fisica Nucleare, Sez. di Perugia, Italy
6. School of Physics and Astronomy, University of Edinburgh, United Kingdom
7. Istituto Nazionale di Fisica Nucleare, Sez. di Bologna, Italy
8. Università di Bologna, Dipartimento di Fisica e Astronomia, Bologna, Italy
9. Università degli Studi di Bari, Dipartimento Interateneo di Fisica, Bari, Italy
10. CNR, Istituto di Cristallografia, Bari, Italy
11. University of Manchester, United Kingdom
12. Goethe University Frankfurt, Max-von-Laue-Strasse 1, Frankfurt am Main 60438, Germany

The following document is an addendum to the proposal INTC-P-208 [1], approved in 2006, concerning the measurement of the neutron capture cross-section of highly enriched samples of the stable Fe and Ni isotopes. The proposed measurements aimed at improving the existing cross section data of interest for the *s*-process nucleosynthesis in *Massive* stars and for innovative nuclear technologies.
In the past years the neutron capture cross sections of the ^{54,57}Fe, ^{58,62,63}Ni isotopes has been successfully performed at the n_TOF experimental area 1 (EAR1), the results of this work together with the astrophysical implications are reported in several publications and conference proceedings [2,3,4].
The measurement of the ^{64}Ni(n,γ) has been postponed in the past due to the cost of the sample, while now it can be performed using small quantities of ^{64}Ni, taking advantage of the higher neutron flux available