Measurement of ^{59}Ni(n , p)^{59}Co Reaction Cross-section through Surrogate Technique for Fusion Technology Applications

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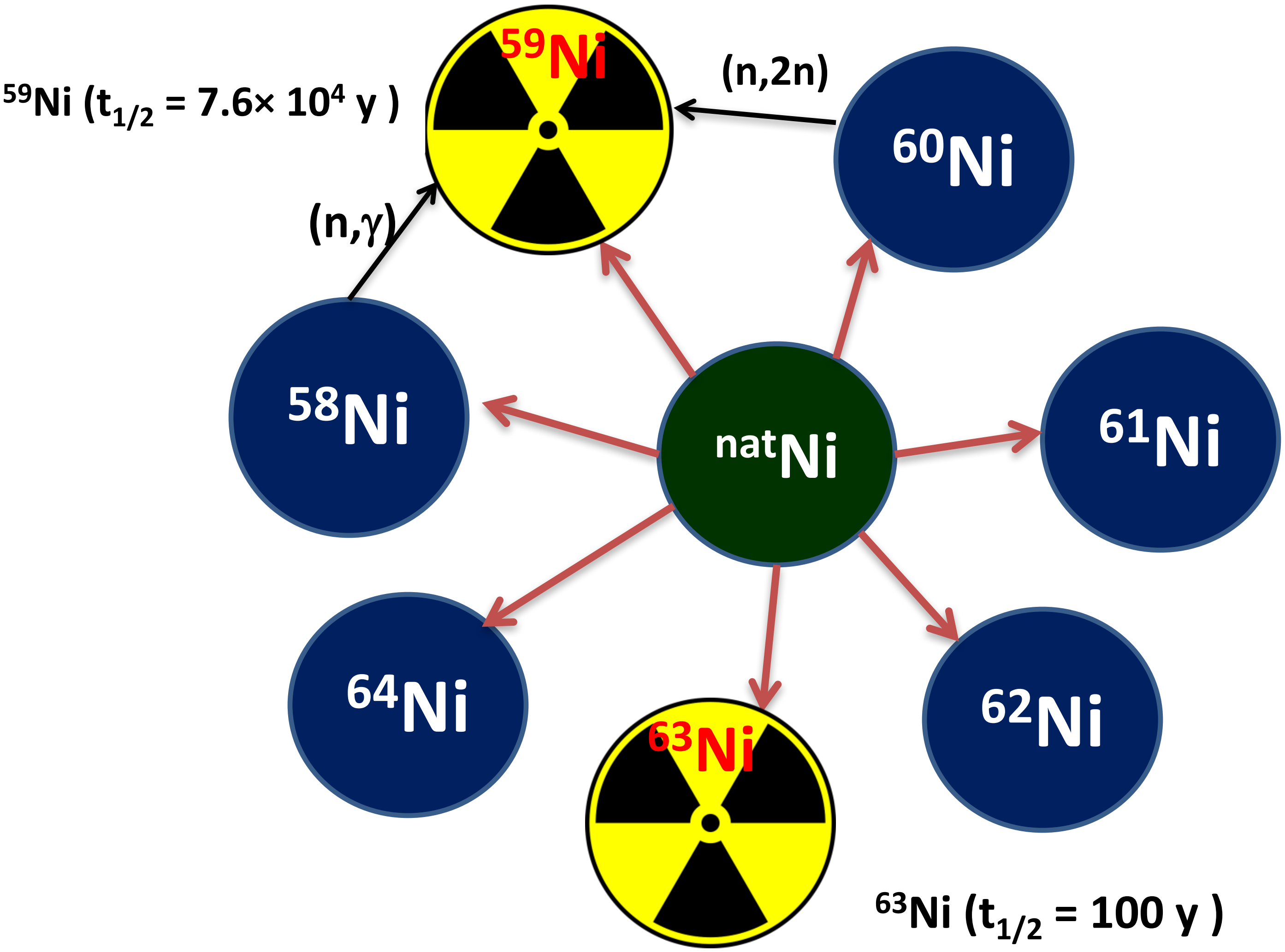
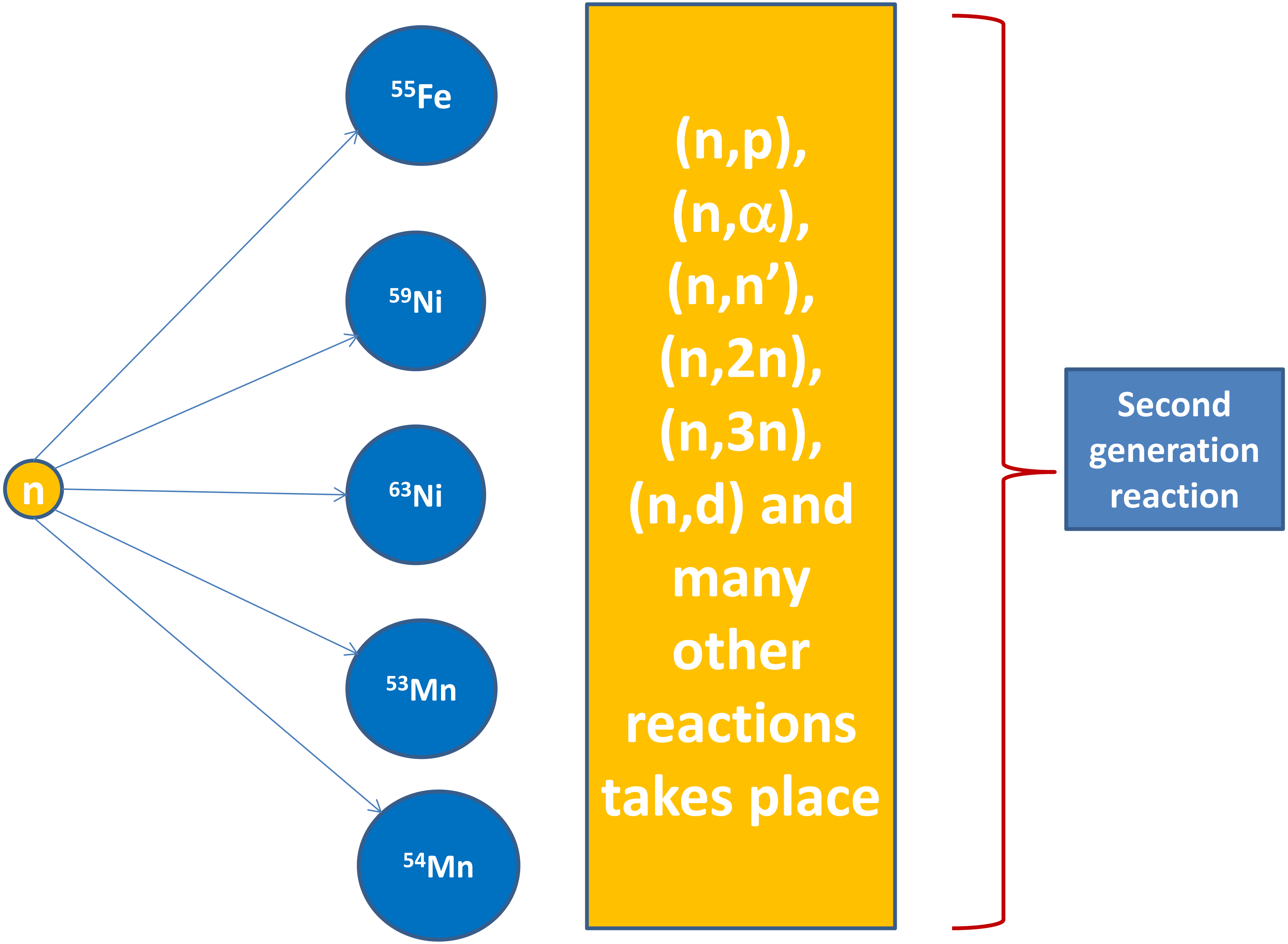
$^{59}Ni(n, p)^{59}Co$

- ☐ In the first generation fusion reactor thousands of tons stainless steel will be used for different components (structural materials) of a fusion reactor. Iron , nickel and chromium are the main constituents of stainless steel.

SUBSYSTEM	CANDIDATE MATERIAL
Plasma Facing Component	Cu-Cr-Zr, Be, SS316 LN
Divertor	W, Water, Inconel 718
Shielding Blanket	SS316LN & H_2O
Breeding Blanket	Li, LiPb (^{83}Pb ^{17}Li)
Vacuum Vessel	SS304, Borated steel
Magnets	NbSn, NbTi
Cryostat	SS304

- ☐ Natural Nickel (Ni) [^{58}Ni(68.077%),^{60}Ni(26.223%),^{61}Ni(1.140%),^{62}Ni (3.635%),^{64}Ni(0.926%)].
- ☐ ^{59}Ni ($t_{1/2} = 7.6\times10^4$ years) is one of the radio-nuclide which is produced in large quantities inside the fusion reactor.





n

$^{55}\mathrm{Fe}$

$^{59}\mathrm{Ni}$

$^{63}\mathrm{Ni}$

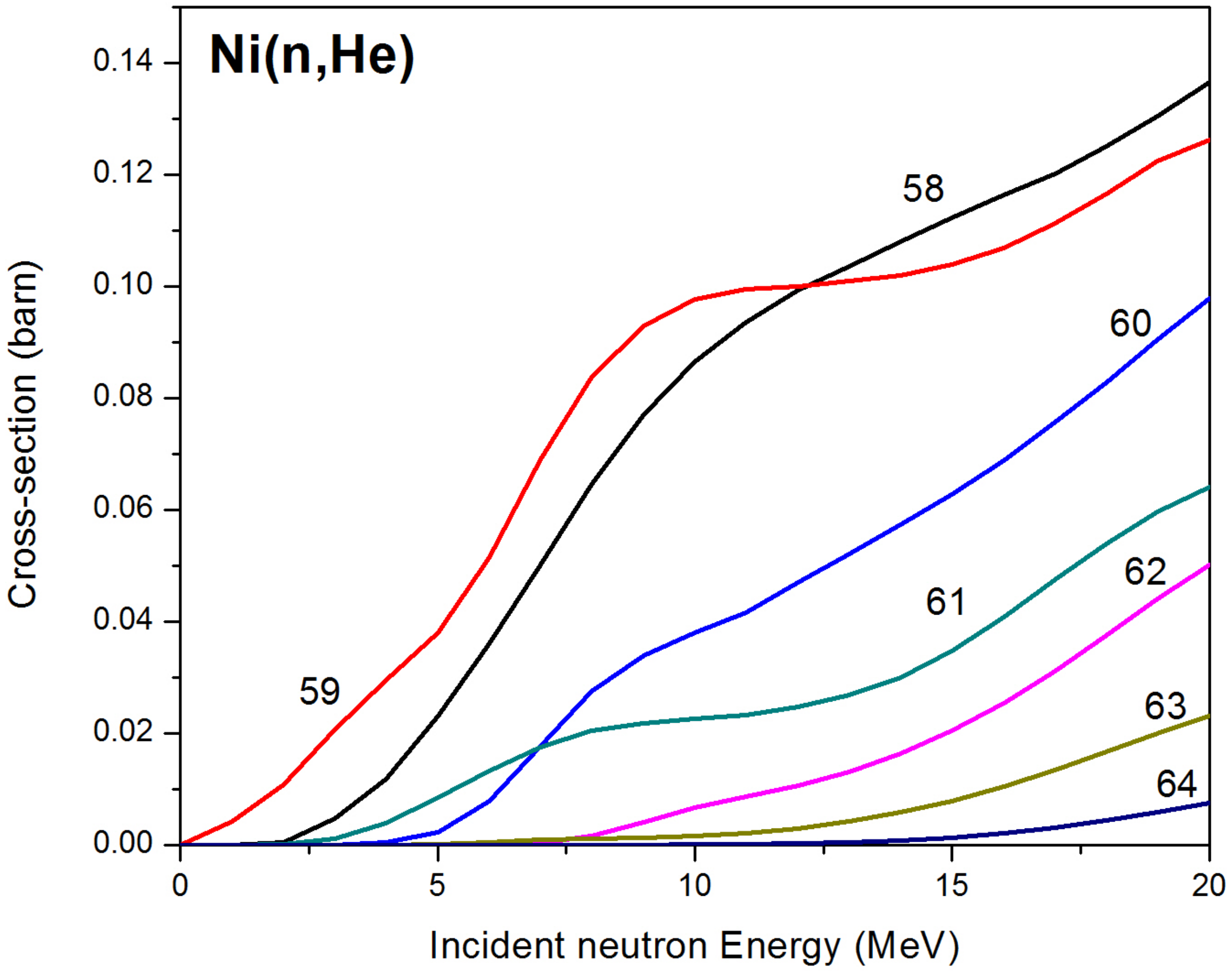
$^{53}\mathrm{Mn}$

$^{54}\mathrm{Mn}$

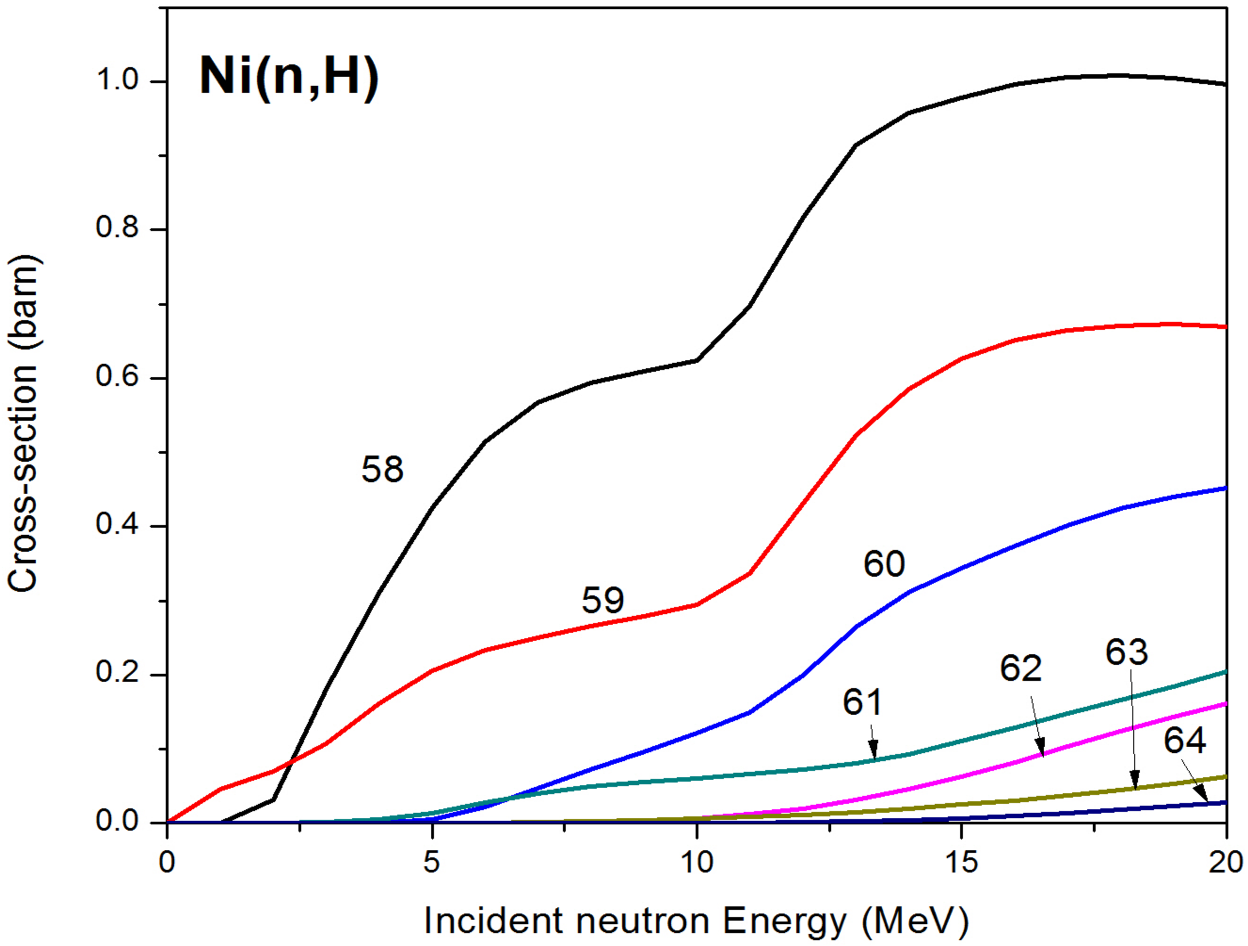
(n,p), (n,α), (n,n’), (n,2n), (n,3n), (n,d) and many other reactions takes place

Second generation reaction

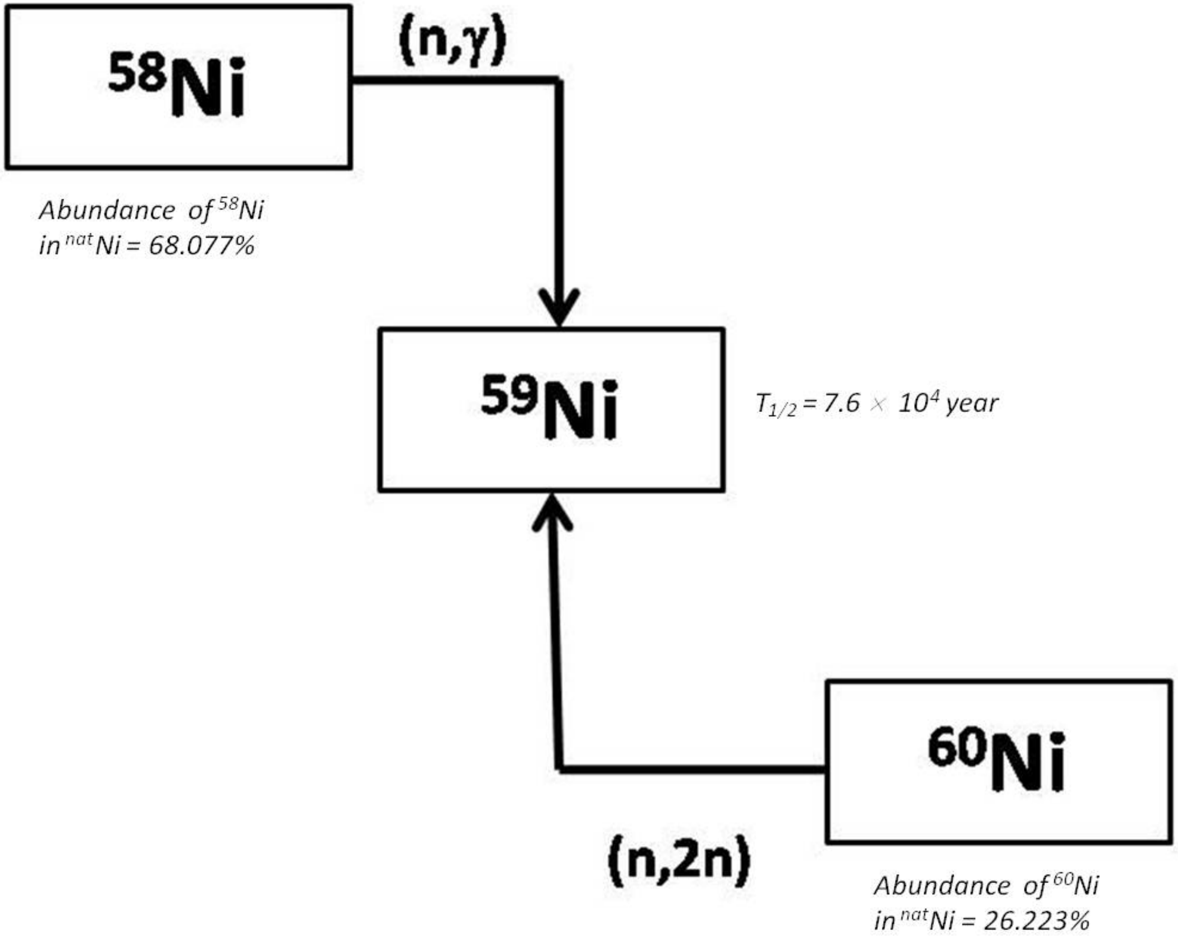
Helium Generation due to the different isotopes of Nickel (Preliminary calculation with TALYS-1.8)



Hydrogen Generation due to the different isotopes of Nickel (Preliminary calculation with TALYS-1.8)



Major Pathways of the production of ^{59}Ni in the fusion reactor environment

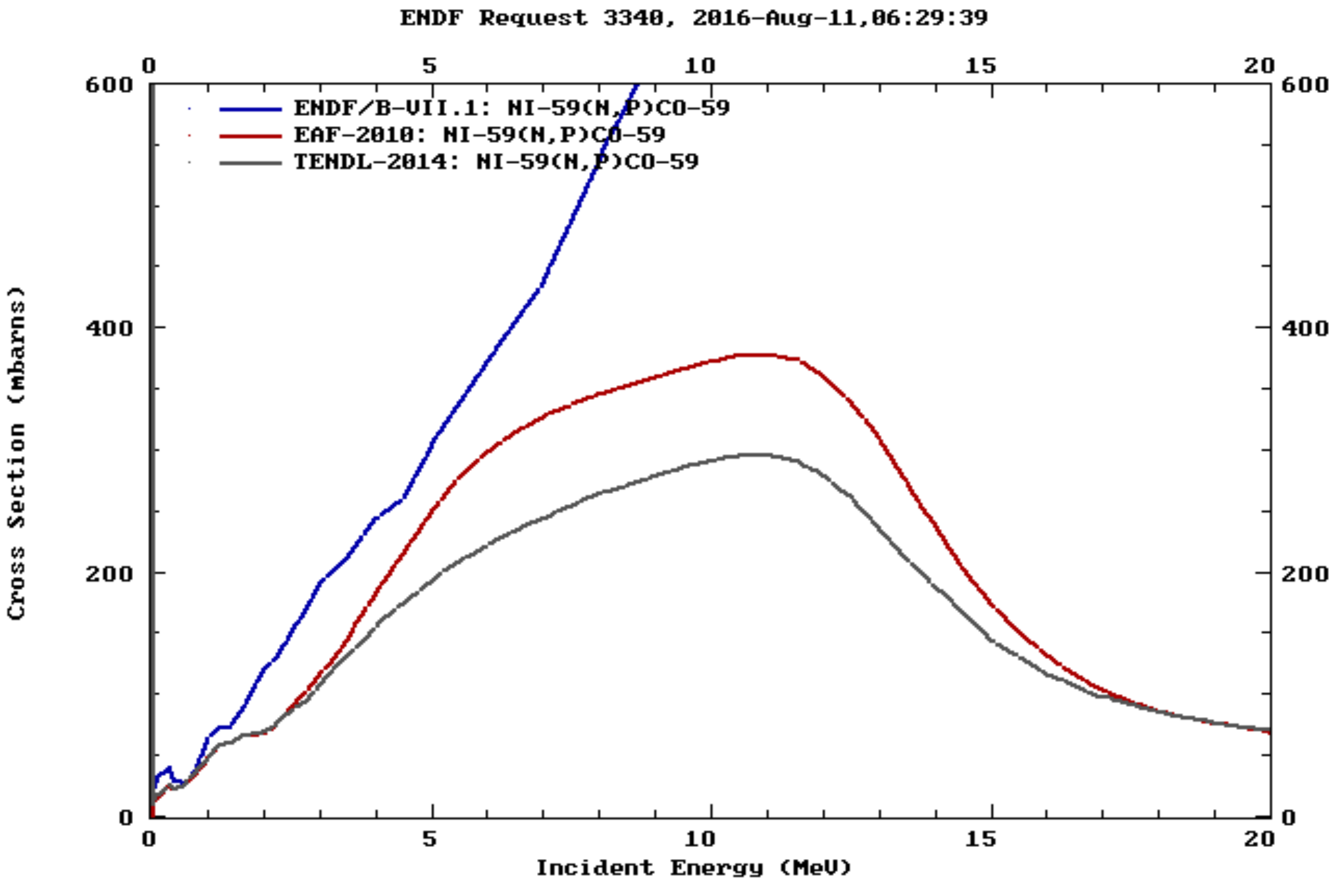


Abundance of ^{58}Ni in ^{nat}Ni = 68.077%

$T_{1/2} = 7.6 \times 10^4$ year

Abundance of ^{60}Ni in ^{nat}Ni = 26.223%

Present status of ^{59}Ni(n,p)



- Large discrepancy in the data libraries
- Not based on measured data
- No experimental data is available for this reaction in IAEA EXFOR databse

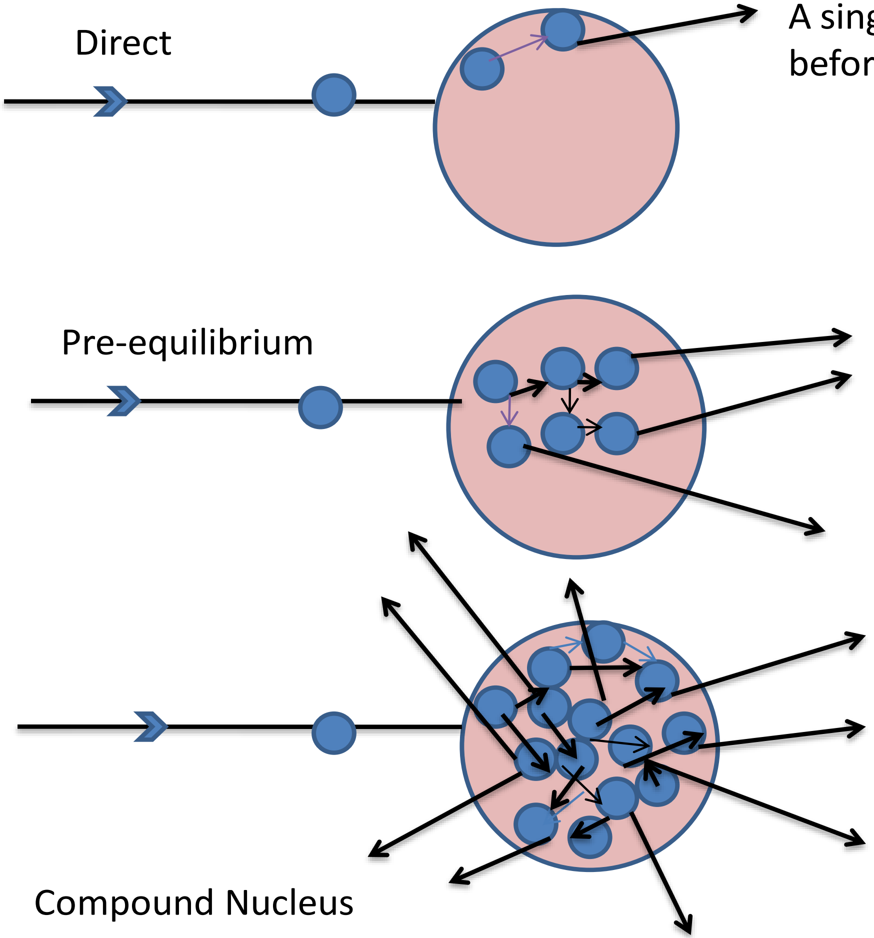
FOCUSED OBJECTIVES

- To measure the cross-section of $^{59}\mathbf{Ni(n,\ p)}^{59}\ \mathbf{Co}$ from $E_n = 9 - 20$ MeV .

- Cross-section measurement is not possible directly for this reaction due to non-existence of this isotope in nature.

- This is the main reason for using surrogate method for the measurement of this cross-section.

Different Types of Nuclear Reaction Mechanism



Direct

A single interaction
before emission

Pre-equilibrium

A small number of interaction
before emission

A large number of interaction
before emission

Compound Nucleus

Bohr's Compound Nucleus Theory

According to Bohr Compound Nucleus Theory –

1. The formation of the compound nucleus and it's break up are independent of each other. This is known as the independence hypothesis.

2. The compound nucleus forgets it's mode of formation. The decay of compound nucleus depends only on the properties of compound nucleus and not upon how it was formed. The life time of compound nucleus is around 10^{-15} seconds.

3. The cross section for the compound nucleus is defined as the product of formation of compound nucleus and it's decay probability.

$$\begin{tikzcd} & & Y + y \\ X + x \arrow[r] & C^* \arrow[ur] \arrow[dr] & \\ & & Z + z \end{tikzcd}$$

$$\sigma(x, y) = \sigma_x \frac{\Gamma_y}{\Gamma}$$

According to H-F theory the compound nuclear cross-section is given by

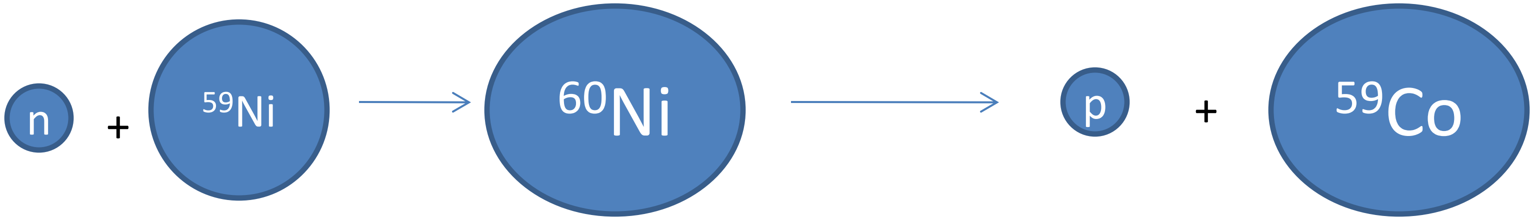
$$\sigma_{\alpha\chi}(E_a) = \sum_{J,\pi} \sigma_{\alpha}^{CN}(E_{ex}, J, \pi)\; G_{\chi}^{CN}(E_{ex}, J, \pi)$$

Applying W-E Approximation , the formula for desired cross-section is simplified as (Applicable only at High Excitation Energy)

$$\sigma_{\alpha\chi}(E^*) = \underbrace{\sigma_{\alpha}^{CN}(E^*)}_{\textbf{Calculated}}\,\underbrace{G_{\chi}^{CN}(E^*)}_{\textbf{Measured}}$$

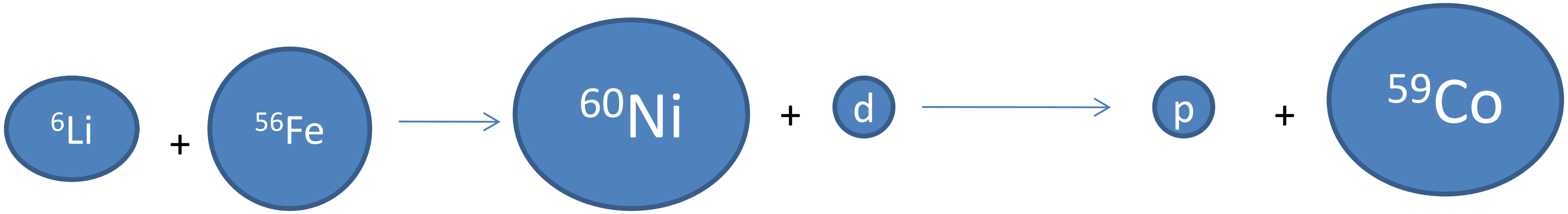
SURROGATE TECHNIQUE

Desired Reaction



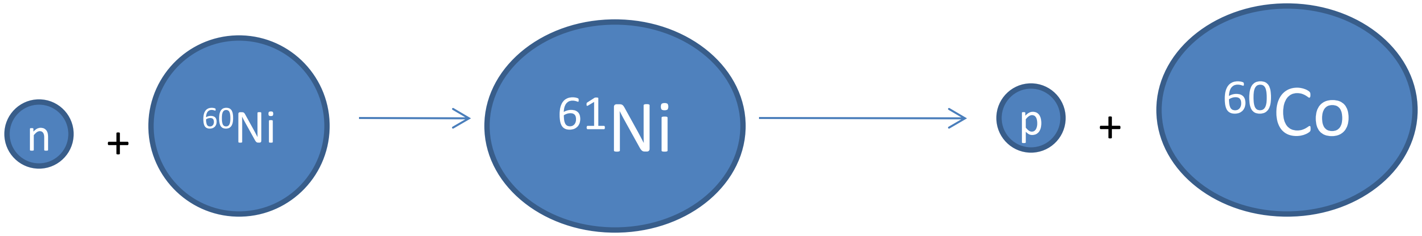
$n + {}^{59}\mathrm{Ni} \rightarrow {}^{60}\mathrm{Ni} \rightarrow p + {}^{59}\mathrm{Co}$

Surrogate Reaction



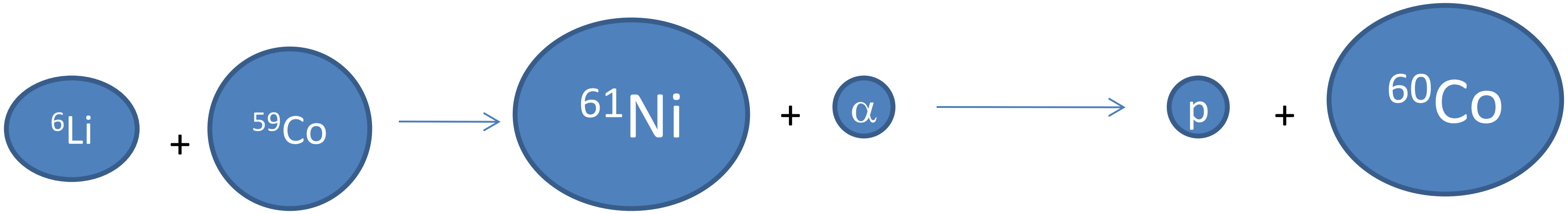
${}^{6}\mathrm{Li} + {}^{56}\mathrm{Fe} \rightarrow {}^{60}\mathrm{Ni} + d \rightarrow p + {}^{59}\mathrm{Co}$

Reference Reaction



$$n + {}^{60}\mathrm{Ni} \rightarrow {}^{61}\mathrm{Ni} \rightarrow p + {}^{60}\mathrm{Co}$$

Surrogate Reaction



$${}^{6}\mathrm{Li} + {}^{59}\mathrm{Co} \rightarrow {}^{61}\mathrm{Ni} + \alpha \rightarrow p + {}^{60}\mathrm{Co}$$

Condition for using the surrogate technique

- The Surrogate method is limited to Compound nuclear reactions.
- Same Compound Nucleus should be formed through Desired and Surrogate reaction channels.
- Compound Nucleus Excitation Energy should be same in both desired reaction and surrogate reaction.
- Excitation energy formula of the compound nucleus is –

E_{exc} = K.E. of the incident particle in CM frame + B.E. of the particle in compound nucleus

THEORETICAL STUDY OF THE PROPOSED EXPERIMENT

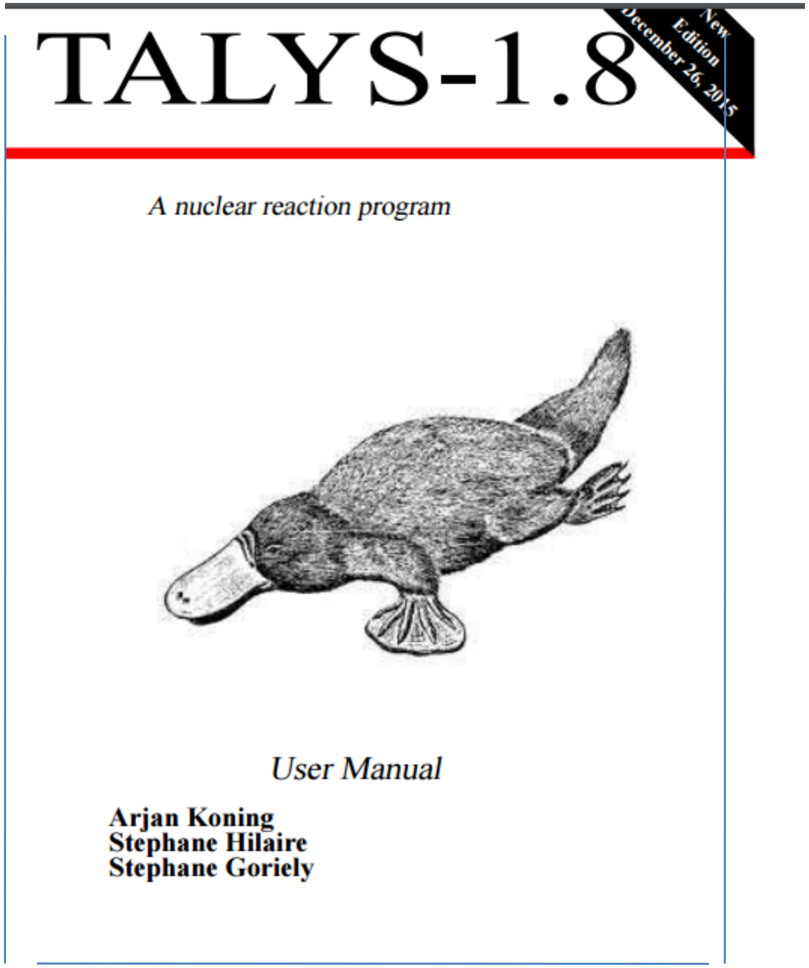
TALYS -1.8
(Nuclear Reaction Modular Code)

- Software for the simulation of nuclear reactions in the energy range 1 keV – 200 MeV

- User-friendly Code containing an optimal combination of reliable nuclear models .

- Developed by – Arjan Koning , Stephane Hilarie , Stephane Goriely Created at NRG in Petten , the Netherlands, and is available free of charge.

- Versatile tool to analyse basic microscopic experiments and to generate nuclear data for its use and



TALYS-1.8

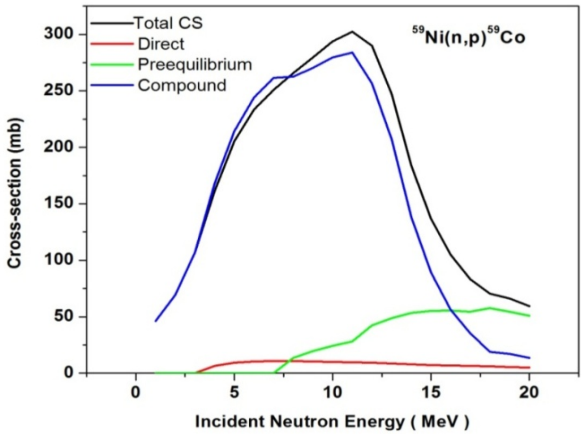
New Edition December 26, 2015

A nuclear reaction program

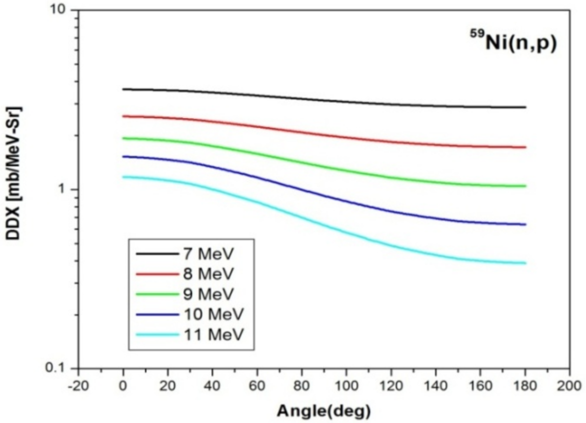
User Manual

Arjan Koning
Stephane Hilaire
Stephane Goriely

THEORETICAL STUDY



Excitation function of ^{59}Ni(n,p) reaction along with the contribution from the different reaction mechanism (Direct + Pre-equilibrium +Compound) [Using TALYS – 1.8]



Theoretical variations in DDX with angle of emission for 7-8-9-10-11 energy proton emitted through ^{59}Ni(n,p) reaction at 14 MeV neutrons [Using TALYS – 1.8]

- TALYS-1.8 is used to check the different nuclear reaction mechanism contribution

- From 2-14 MeV the reaction mainly goes through compound nucleus process

- Angular Distribution of outgoing protons is symmetric .

Selection of Li-6 beam energy

Main Condition - Compound Nucleus Excitation Energy should be same in both desired reaction and surrogate reaction.

- Excitation Energy of (^{60}Ni*) in the Desired Reaction

  $n + {}^{59}Ni \rightarrow ({}^{60}Ni)^* \rightarrow p + {}^{59}Co.$

  at neutron energy 14 MeV ~ E*(25) MeV.

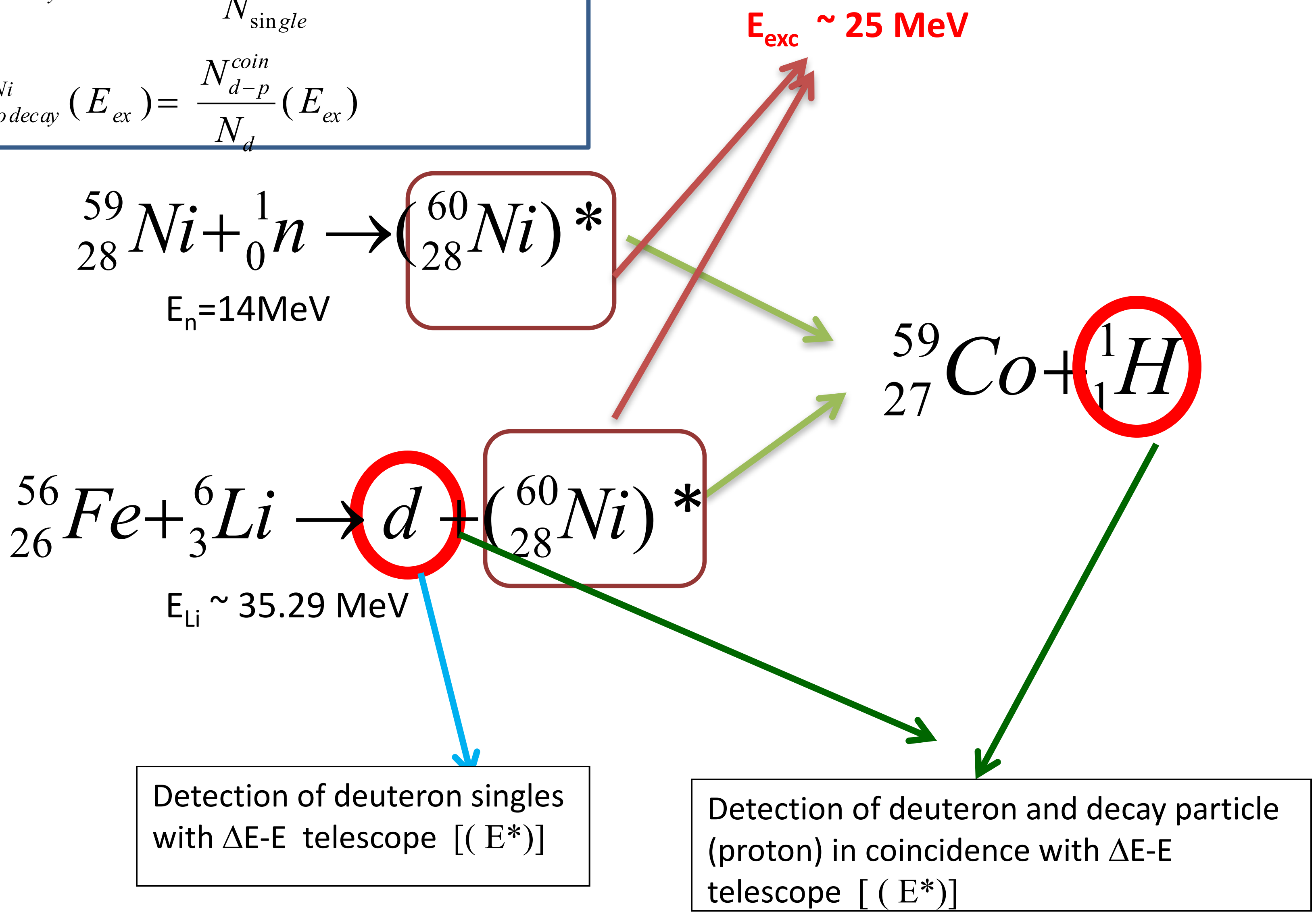
- Excitation Energy of (^{60}Ni*) in the Surrogate Reaction

  $^{6}Li + {}^{56}Fe \rightarrow d + ({}^{60}Ni)^*$

  at lithium energy 35 MeV ~ E*(25) MeV.

$$P^{CN}_{surro\,decay}(E_{ex}) = \frac{N^{coin}_{ejec-decay}}{N_{single}}(E_{ex})$$

$$P^{60Ni}_{surro\,decay}(E_{ex}) = \frac{N^{coin}_{d-p}}{N_d}(E_{ex})$$



E_{exc} ~ 25 MeV

$${}^{59}_{28}Ni + {}^{1}_{0}n \rightarrow ({}^{60}_{28}Ni)^*$$

E_n=14MeV

$${}^{59}_{27}Co + {}^{1}_{1}H$$

$${}^{56}_{26}Fe + {}^{6}_{3}Li \rightarrow d + ({}^{60}_{28}Ni)^*$$

E_{Li} ~ 35.29 MeV

Detection of deuteron singles with ΔE-E telescope [(E*)]

Detection of deuteron and decay particle (proton) in coincidence with ΔE-E telescope [(E*)]

EXPERIMENTAL HALL

(At TIFR)

EXPERIMENTAL DETAILS

Beam Requirments ---

- Beam and it’s energy --- Lithium -6 and 35.89 MeV

Targets and Detectors used

Targets-

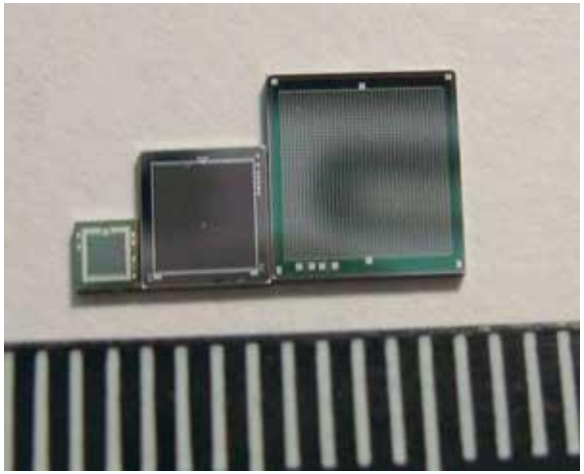
^{56}Fe(~700µg/cm^2),^{59}Co(~600µg/cm^2)

Detector-

- Two ΔE-E telescope detectors for PLFs
- A Large Area Solid State (16 Strip Detector) for Decay particle from compound nucleus – 2 detectors

Telescope Detector

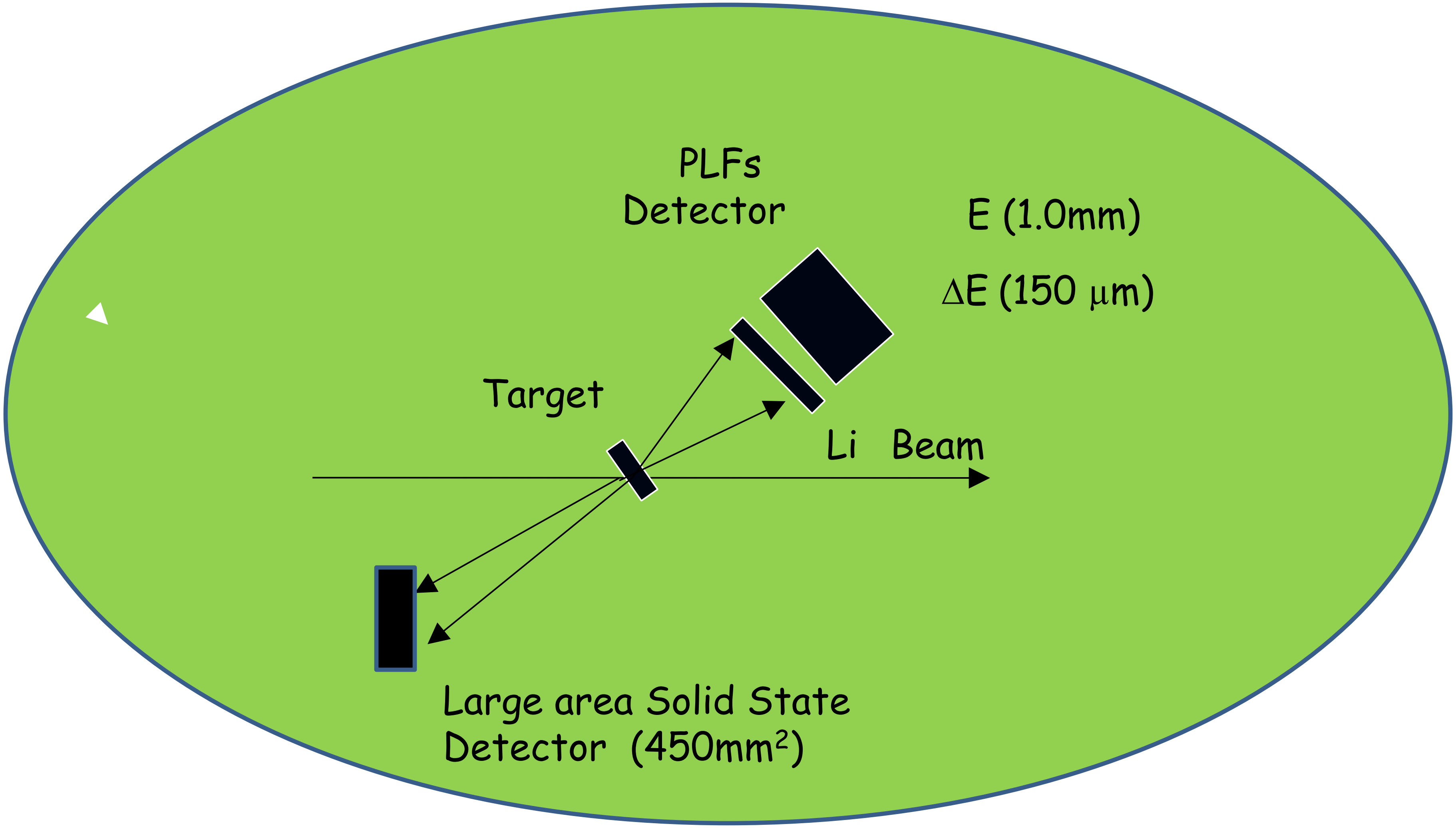
- Both are SSB (Silicon Surface Barrier) Detector Used for Charged particle detection .
- Detectors are useful for measuring the energy deposition of passing charged particles , i.e. dE/dx .
- ΔE - Particle identification by mass
  E - Particle will go further and will completely stop there and convert it’s Kinetic Energy into Current Energy



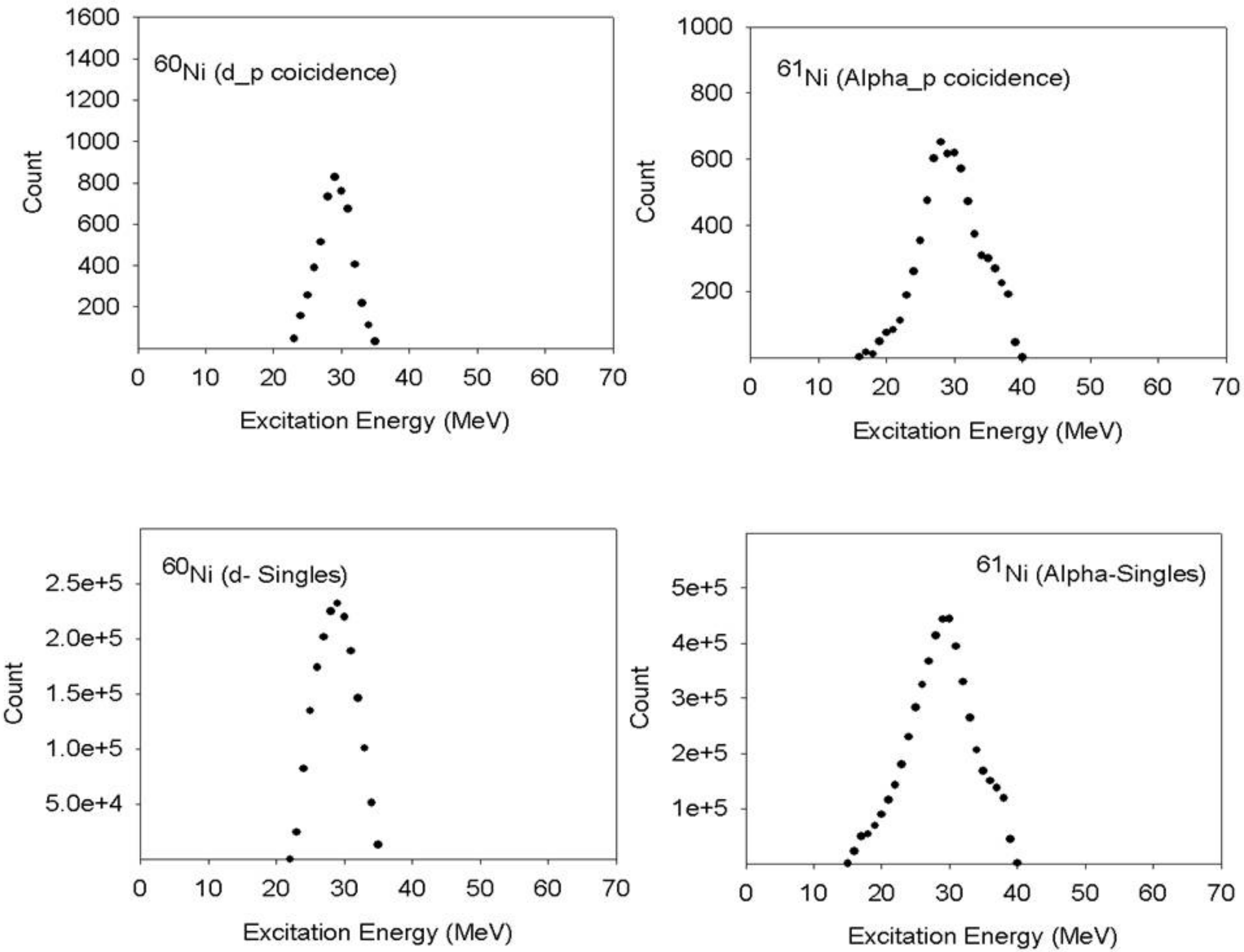
16-Strip Detector

EXPERIMENTAL SETUP

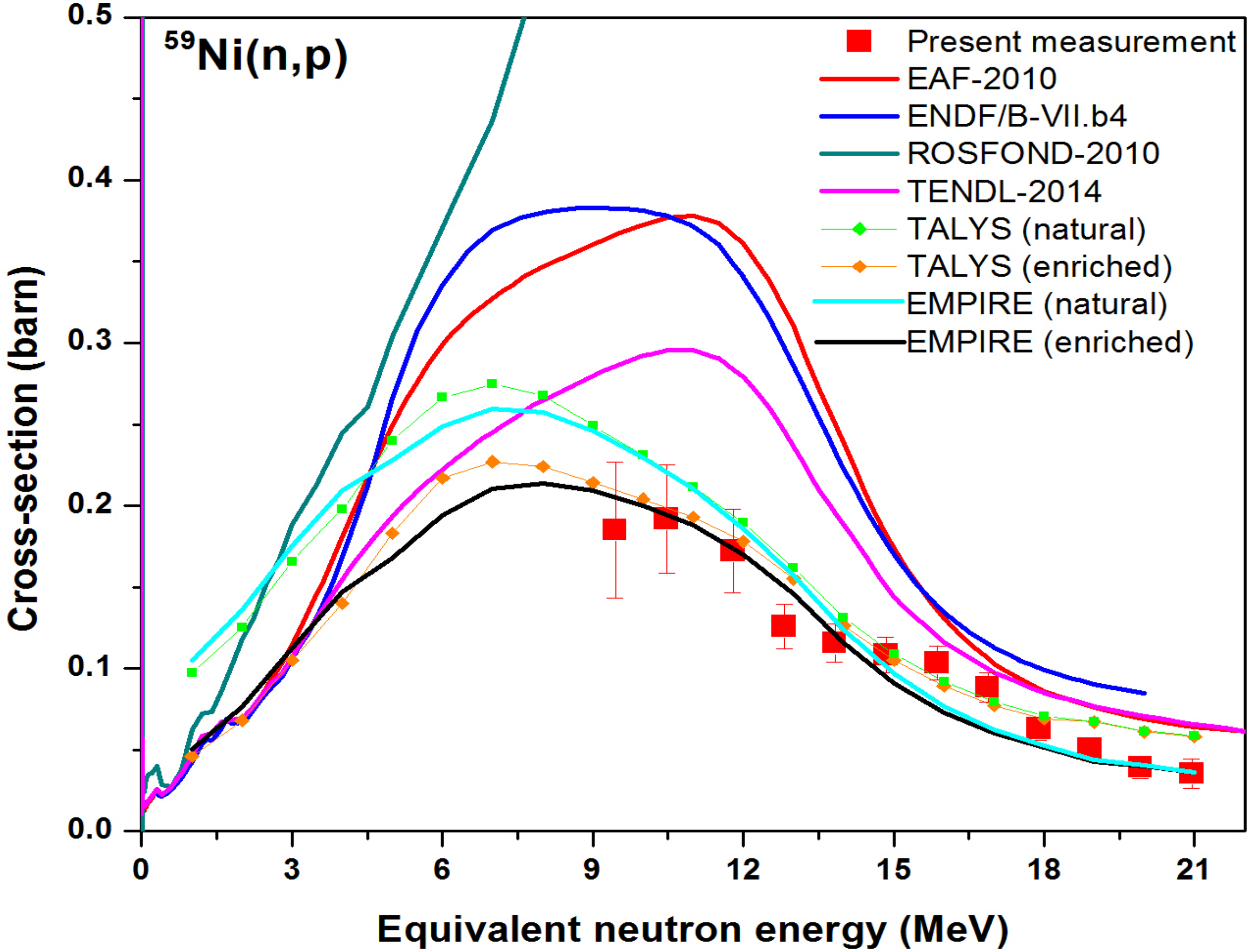
(INSIDE OF SCATTERING CHAMBER)



Excitation energy spectra of the target like fragments produced $^{6}Li+^{56}Fe$ and $^{6}Li+^{59}Co$ reactions corresponding to PLF deuteron and alpha with and without coincidence with evaporated spectra



RESULTS


^{59}Ni(n,p)
Present measurement
EAF-2010
ENDF/B-VII.b4
ROSFOND-2010
TENDL-2014
TALYS (natural)
TALYS (enriched)
EMPIRE (natural)
EMPIRE (enriched)
Cross-section (barn)
0.0
0.1
0.2
0.3
0.4
0.5
0
3
6
9
12
15
18
21
Equivalent neutron energy (MeV)

Conclusion

- Scientists are becoming increasingly excited about the successful completion of the fusion reactor work. A reactor which can replicate the sun’s energy source on Earth through scientific and technological innovation which are earlier unimagined.

- ^{59}Ni(n,p) reaction cross-section have been measured in the energy range 10-21 MeV by surrogate-reaction method.

- The present experimental data have been compared with evaluated data libraries TENDL,EMPIRE and TALYS.

- The experimental data is found to be reasonably consistent with TALYS .

- The present measurement will be useful to improve and update the different data libraries and opens up the possibility of measuring the compound nuclear reactions involving unstable targets with the relevance to fusion technology

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- B. PANDEY et al., "Measurement of ^{55}Fe(n,p) cross-section by the surrogate-reaction method for fusion technology applications", Physical Review C 93,021602(R) (2016).
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- R.A.FORREST, "Data Requirements for Neutron Activation Part I : Cross-Sections," Fusion Eng. Des.,81,2143(2006); http://dx.doi.org/10.1016/j.fusengdes.2006.01.001

List of publications

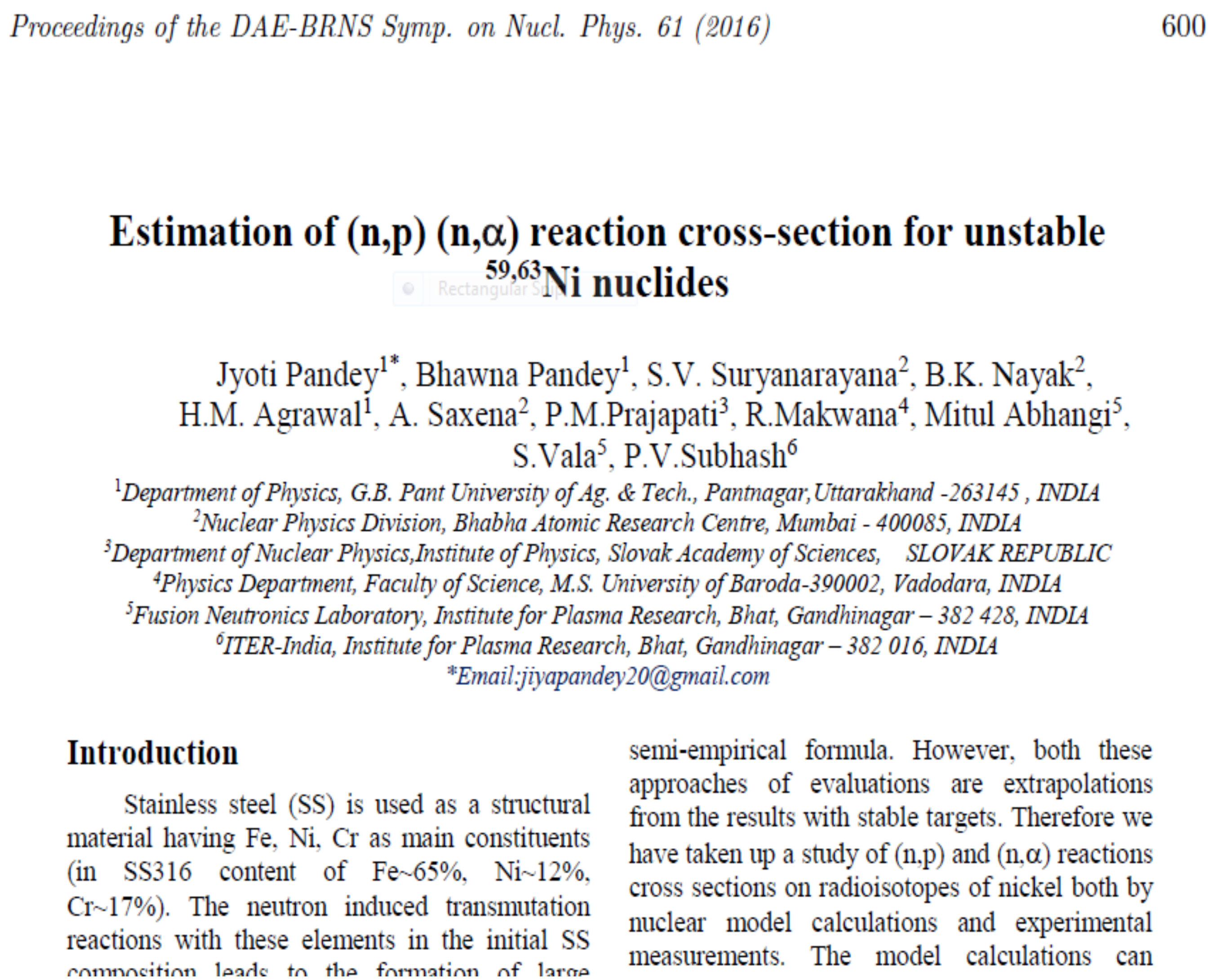
1. Jyoti Pandey, Bhawna Pandey, H.M. Agrawal "Estimation of (n,p) cross-section for radionuclide ^{60}Co", Proceeding at **DAE-BRNS "National Conference on Recent Trends in Nuclear Physics"** organized by Aligarh Muslim University, Aligarh , India, 75-76 (2016).

2. Jyoti Pandey,Bhawna Pandey,H.M. Agrawal "Estimation of (n,p) (n,α) reaction Cross-sections for unstable ^{59,63}Ni nuclides", **Proceeding at 61st DAE-BRNS Symposium on Nuclear Physics** December, Vol.61, 600-601 (2016).

3. Jyoti Pandey, Bhawna Pandey, H.M. Agrawal, P.V. Subhash , S.Vala , Akhil Sai Aiyyala Rajnikant Makwana, S.V. Suryanarayana, "Neutron induced Cross-section of radionuclide ^{60}Co for fusion technology application", **Fusion Science and Technology** (Under Communication).

4. Jyoti Pandey, Bhawna Pandey, P.V.Subhash, H.M. Agrawal "Helium and Hydrogen generation due to the presence of radionuclides (A~50-60) in fusion recator environment", **Proceedings of the International Conference on High Energy Radiation and Applications (ICHERA)**,during 10-13 October,2017 in the Physics Department, Faculty of Science , The Maharaja Sayajirao , University of Baroda (Under Communication).

Papers In Proceedings



Proceedings of the DAE-BRNS Symp. on Nucl. Phys. 61 (2016)

Estimation of (n,p) (n,α) reaction cross-section for unstable ^{59,63}Ni nuclides

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Introduction

Stainless steel (SS) is used as a structural material having Fe, Ni, Cr as main constituents (in SS316 content of Fe~65%, Ni~12%, Cr~17%). The neutron induced transmutation reactions with these elements in the initial SS composition leads to the formation of large

semi-empirical formula. However, both these approaches of evaluations are extrapolations from the results with stable targets. Therefore we have taken up a study of (n,p) and (n,α) reactions cross sections on radioisotopes of nickel both by nuclear model calculations and experimental measurements. The model calculations can

National Conference on Recent Trends in Nuclear Physics, 15-16 February, 2016 AMU, Aligarh

Estimation of (n,p) cross-section for radionuclide ^{60}Co

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Introduction

During the operation of reactors, various types of radionuclides are produced such as ^{60}Co, ^{60}Fe, ^{63}Ni, ^{55}Fe etc. These radionuclides with sufficiently long half-lives will remain in the reactor waste. High radioactive Cobalt (^{60}Co, ^{58}Co) has been recognized to found in waste disposal in the nuclear power plant during its operation. In the produced waste ^{60}Co ($t_{½} = 5.3$ yr) is of special concern. Radionuclide Co-60 plays a very important role during the storage and transportation phase of the waste management scenario and in some cases for safety and maintenance assessment [1].

The neutron induced cross-section of these radio nuclides has been identified to find the new needs of nuclear industry. The major challenge is to determine the neutron induced cross-section of these radionuclides (unavailable in nature) which will be very crucial to estimate the accurate amount of hydrogen and helium gases produced, nuclear heating, dose rate, radiation damage etc [2].

Estimation of ^{60}Co(n,p) reaction cross-section is one of the first priority reaction [3]. The winsomeness of the reaction ^{60}Co(n,p)^{60}Fe (present study) is that the target i.e. ^{60}Co and the

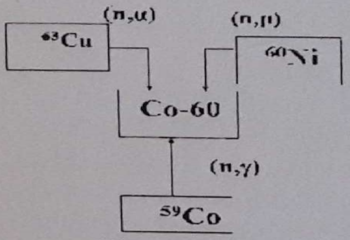


Figure 1

Present status of the neutron-induced cross-section of radio nuclide Co-60

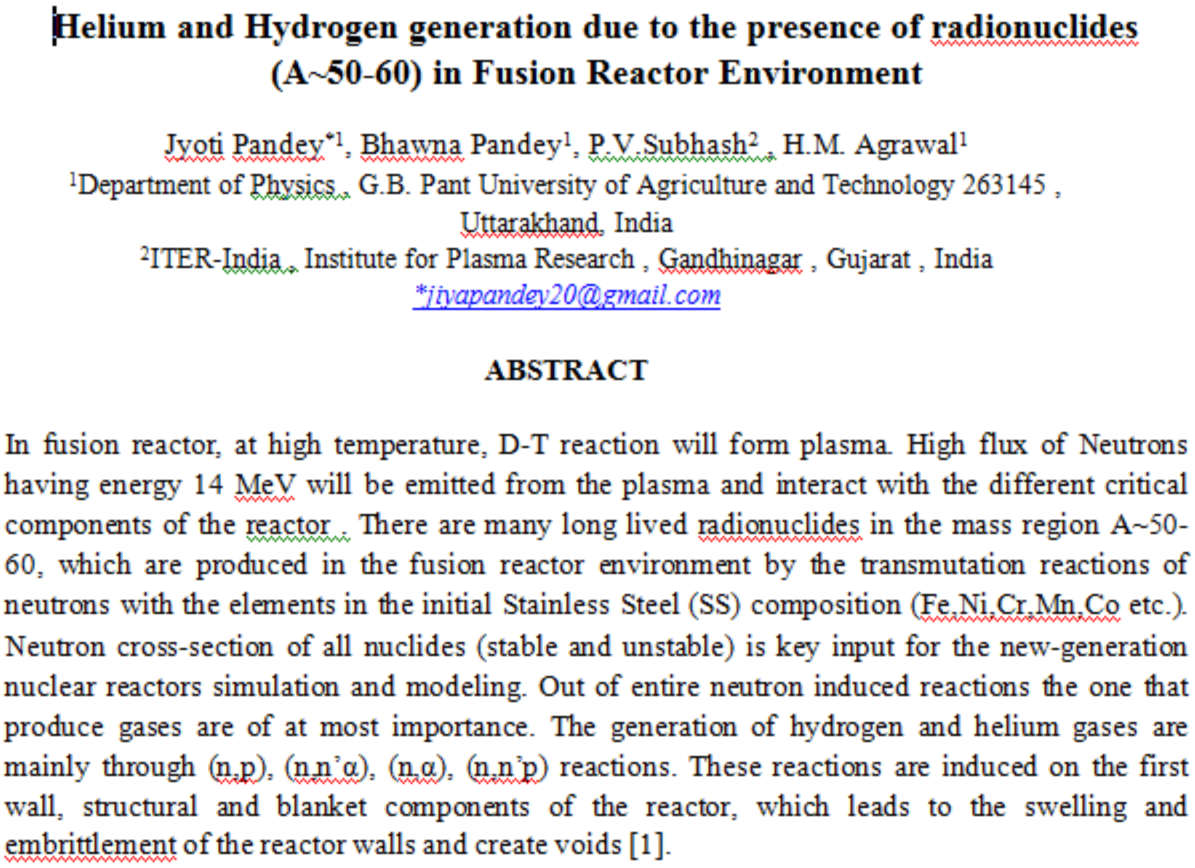
There is no experimental measurement for ^{60}Co(n,p)^{60}Fe in the EXFOR data library. From point of waste disposal, the secondary reaction on ^{60}Co, i.e ^{60}Co(n,p)^{60}Fe results in a very long lived product ^{60}Fe. Neutron induced cross–section measurement by neutron activation method is not possible because ^{60}Co is not present in nature. However the different data libraries are showing a large discrepancy itself.

Recently ^{55}Fe(n,p) reaction cross-section has been measured first time by Pandey et al. , by surrogate reaction method [4].

Nuclear Model Calculation

The cross-section of ^{60}Co(n,p)^{60}Fe reaction has been estimated by using the recent nuclear

Papers In Proceedings at International Conference on High Energy Radiation and Applications (ICHERA)



Helium and Hydrogen generation due to the presence of radionuclides (A~50-60) in Fusion Reactor Environment

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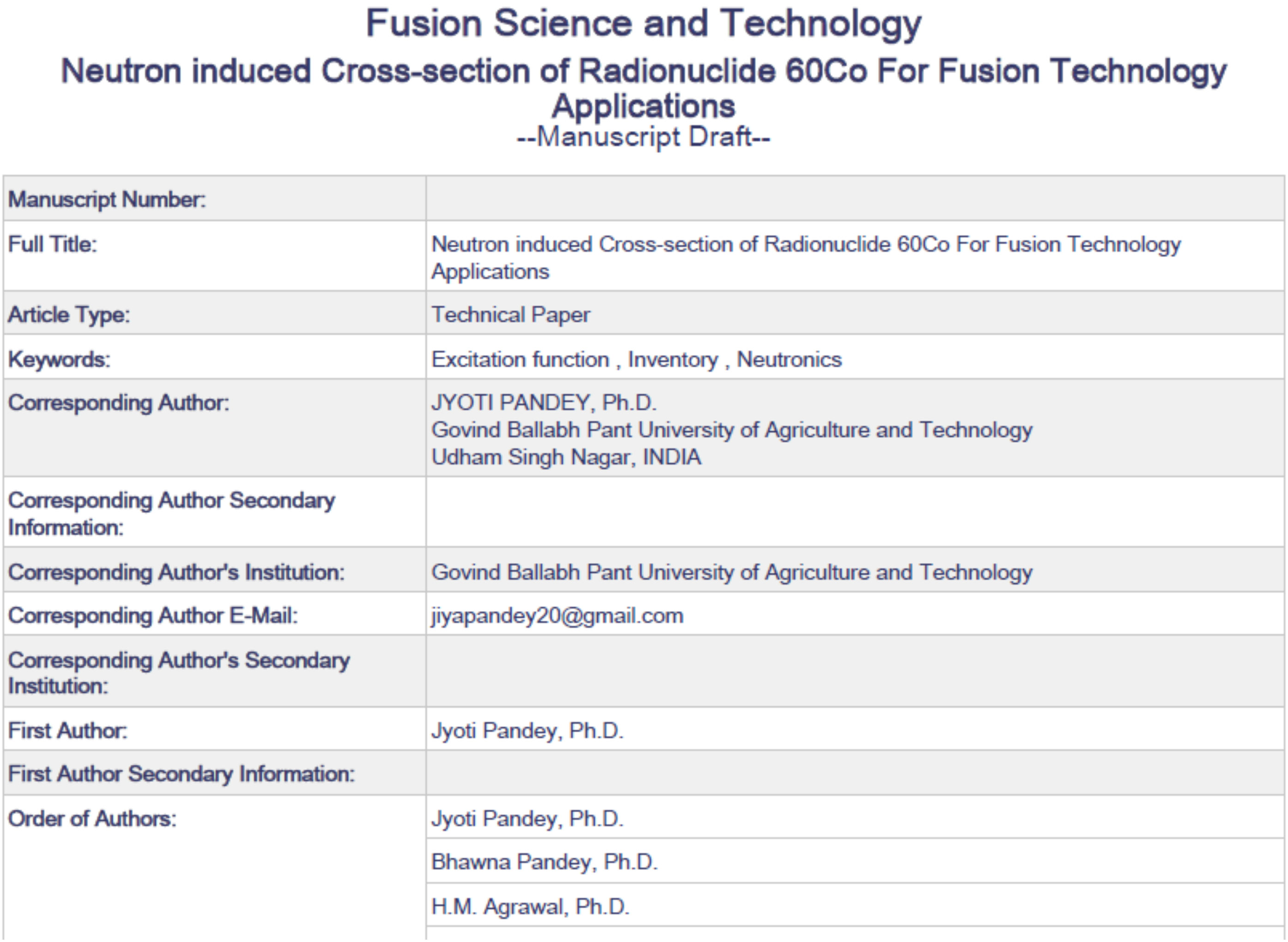
ABSTRACT

In fusion reactor, at high temperature, D-T reaction will form plasma. High flux of Neutrons having energy 14 MeV will be emitted from the plasma and interact with the different critical components of the reactor . There are many long lived radionuclides in the mass region A~50-60, which are produced in the fusion reactor environment by the transmutation reactions of neutrons with the elements in the initial Stainless Steel (SS) composition (Fe,Ni,Cr,Mn,Co etc.). Neutron cross-section of all nuclides (stable and unstable) is key input for the new-generation nuclear reactors simulation and modeling. Out of entire neutron induced reactions the one that produce gases are of at most importance. The generation of hydrogen and helium gases are mainly through (n,p), (n,n'α), (n,α), (n,n'p) reactions. These reactions are induced on the first wall, structural and blanket components of the reactor, which leads to the swelling and embrittlement of the reactor walls and create voids [1].

Papers In Fusion Science and Technology (Accepted)



Fusion Science and Technology

Neutron induced Cross-section of Radionuclide 60Co For Fusion Technology Applications

--Manuscript Draft--

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Neutron induced Cross-section of Radionuclide ^{60}Co For Fusion Technology Applications

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Abstract – *^{60}Co ($t_{1/2}$ = 5.3 years) is one of the radionuclides produced in large quantities inside a fusion reactor. The excitation function of ^{60}Co(n,p) and ^{60}Co(n,α) reaction from threshold to 20 MeV , proton and alpha particle emission spectra from the ^{60}Co target at 14-MeV neutron energy are calculated using optimized input parameters in nuclear reaction modular code TALYS-1.6 . The code account for the major nuclear reaction mechanism , including direct , preequilibrium and compound nucleus contributions . The prediction accuracy of the present calculation is considered to satisfy the requirement for fusion reactor applications. The theoretical nuclear model calculations with a reliable parameter set up to 20 MeV are recommended to estimate the cross section of radionuclides in the mass region A~50-60. Activation analysis has also been carried out for per kg of cobalt in Stainless Steel (SS316L(N)-IG) using FISPACT-2007.*

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