Nuclear Data and Neutronics Study for Long-lived Radionuclides (A ~ 50-60) in Fusion Reactor Technology

By - Jyoti Pandey

ITER-India, Institute For Plasma Research, DAE, Government of India, Bhat, Gandhinagar-382428, Gujarat, India.

Contents

- Motivation of the present research work
- Nuclear Data Studied In Present Research Work
- Surrogate technique
- Experimental results of $^{59}Ni(n,xp)$ reaction
- Summary & Conclusions

Motivation of the present research work

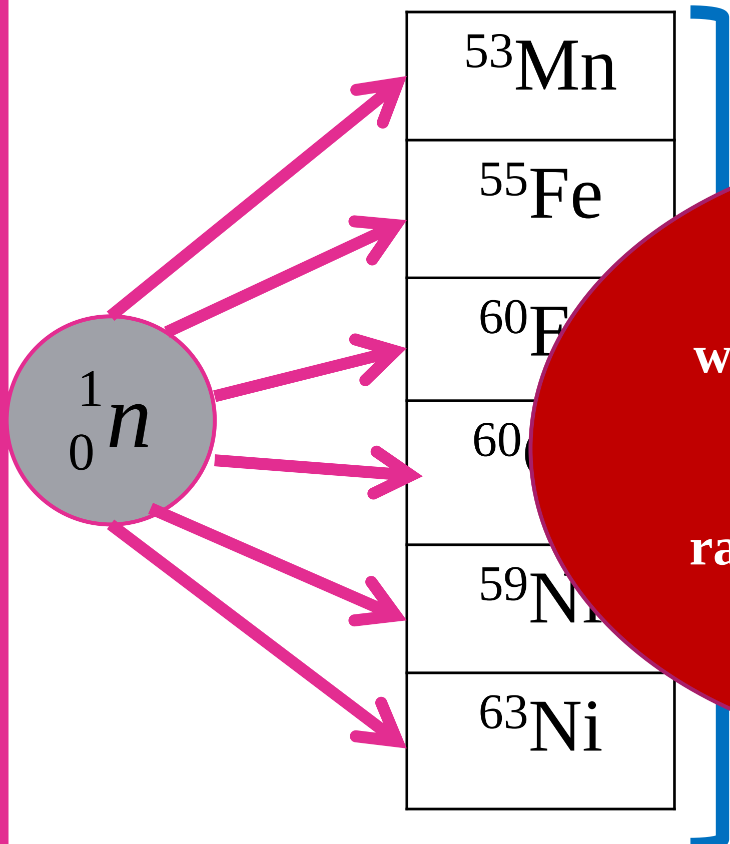
At present stainless steel (SS) is the prominent candidate as structural material for upcoming experimental fusion reactor.

K	Ti	V	Cr	Mn
0.005 %	0.15 %	0.004 %	17.50 %	1.80 %

Main Element	% in SS
Cr	16-18%
Fe	65-72%
Ni	10-14 %
Mo	2-3 %

SUBSYSTEM	CANDIDATE MATERIAL
Plasma Facing Component	Cu-Cr-Zr, Be, SS316 LN
Shielding Blanket	SS316LN & H_2O
Vacuum Vessel	SS304, Borated steel
Cryostat	SS304

- Neutron induced cross-section for long-lived activation products produced in fusion reactor are very important since they could pose a **serious radiation damage & waste disposal problem.**



In present research work, we try to fullfill a gap in nuclear data library, for various radionuclides present in A~50-60.

These radionuclides are dominant inside the Fusion Reactor for a long decay time

...on of hydrogen and ... in the reactor at ...cations.

... displacements and ...ismutations, etc., can produce structural defects in the material.

Microstructure and property changes over long time.

Neutron cross section on long-lived radionuclides are required to be included in nuclear data libraries.

^{59}Ni(n,xp)

- 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.

- 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 ($t_{1/2}$ = 7.6×10^{4} years) is one of the radio-nuclide which is produced in large quantities inside the fusion reactor during its operation. **[Wallner et al. , 2011 R.A. Forrest, 2006].**

- Neutron induced reaction on the generated ^{59}Ni is required for design of a fusion reactor components.

- No experimental data in IAEA-EXFOR database.

- No evaluated data in major ENDF libraries.

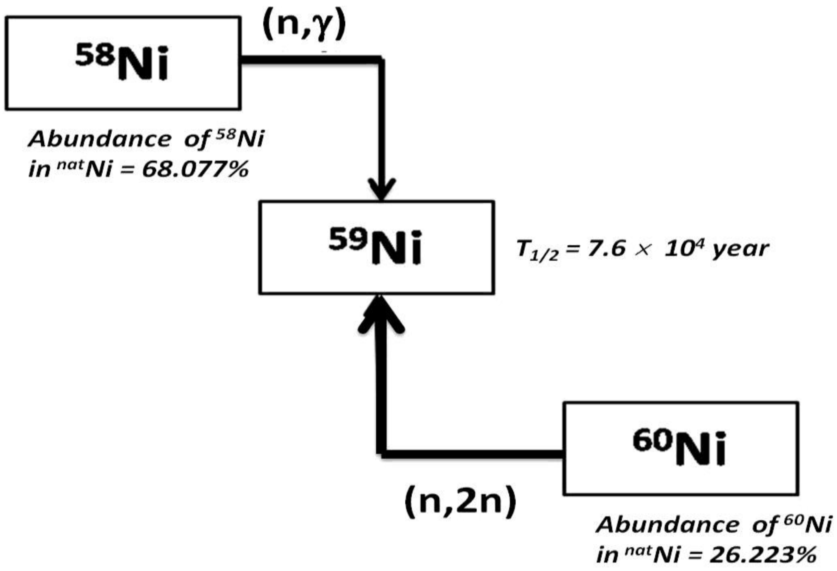
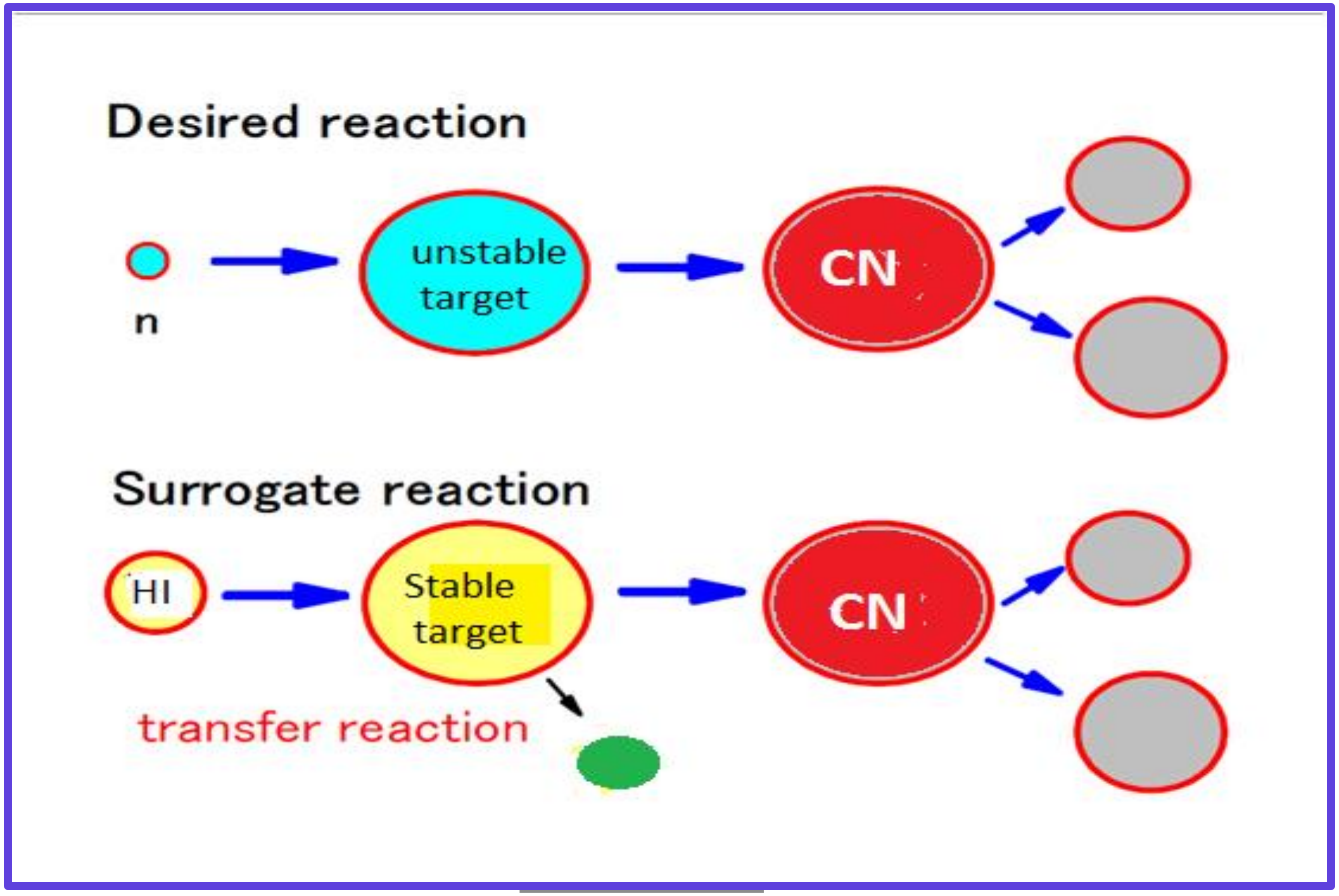


Fig: Different Pathways of Production of ^{59}Ni in fusion reactor environment

Surrogate technique



Experiment impossible

Experiment possible

The surrogate method is an indirect method to measure reaction cross-section.

Central assumption: Both reactions form the same compound nucleus

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 forn ... leus is –

E_{exc} = K.E. of the ir ... he particle in ... d nucleus

Importannce of Surrogate Technique : With a fixed beam energy, the surrogate method allows us to detemine the cross-sectio n over a wide range of neutron energies.

Cross-section, differential and double differential cross-section of the stable and unstable nuclides of Ni, Fe, Cr, Mn for fusion applications

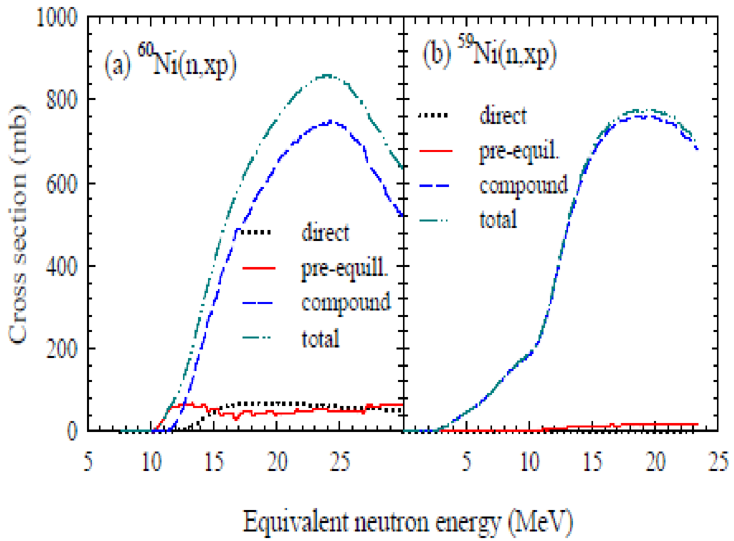


Fig. The excitation function of ^{59}Ni(n,xp), ^{60}Ni(n,xp) reaction in the neutron energy range from 1-25 MeV along with different reaction mechanisms (direct+pre-equilibrium+compound) calculated from TALYS-1.8.

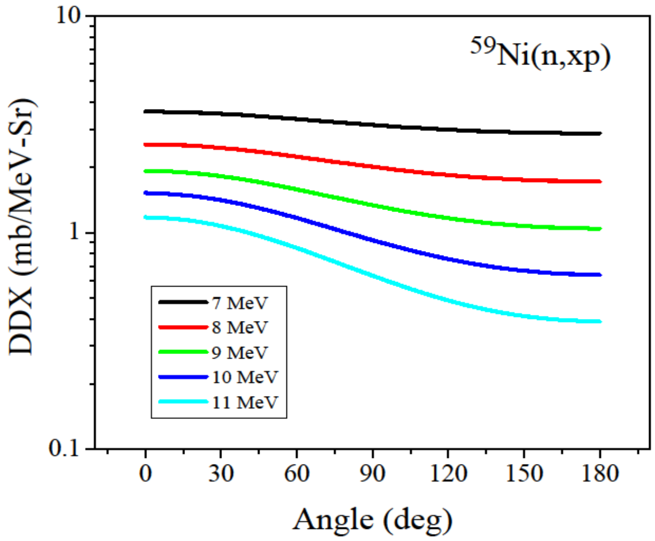


Fig. Theoretical variations in DDXs with angle of emission for 7-11 MeV protons emitted through ^{59}Ni(n,xp) reaction at 14 MeV neutron energy.

- the reaction mainly goes through compound nuclear process. Its cross-section can be found by surrogate technique.

- the angular distribution of ^{59}Ni(n,xp) reaction is isotropic in nature for 7-11 MeV protons emitted through reaction at 14 MeV neutron energy.

Selection of Li-6 beam energy

Desired reaction: $^{59}Ni(n, xp)$, E_n = 11.9-15.8 MeV

Surrogate Reaction : $^{56}Fe(^{6}Li, d)^{60}Ni^{*}$, E_{Li} = 33-40 MeV

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

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

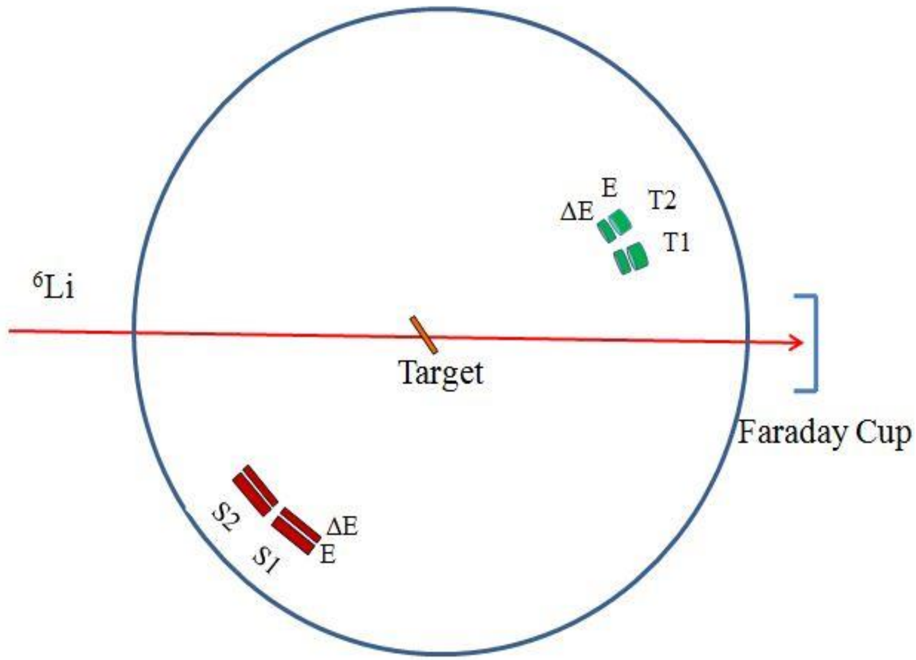
  at neutron energy 14 MeV ~ E*(25) MeV.

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

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

  at lithium energy 35.89 MeV ~ E*(25) MeV.

Similarly, we have done calculation for our reference reaction.



Schematic diagram of experimental setup inside scattering chamber

Journal of Material Science and Surface Engineering **7(1): 909-912** ISSN (Online): 2348-8956; 10.jmsse/2348-8956/7-1.1 (2020).

Beam Requirments ---

Beam and it's energy --- Lithium -6
35.89 and 40MeV

Targets and Detectors used

Targets- ^{56}Fe(~700μg/cm²),^{59}Co(~600μg/cm²) using thermal evaporation method.

Detector

- Two ΔE-E telescope detectors for PLFs, evaporated particle.
- Two Large Area Solid State (16 Strip Detector) for Decay particle from compound nucleus detectors
- 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

Measurement of ^{59}Ni(n,xp) cross-section by surrogate technique

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

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

E_{exc} ~ 25 MeV

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

E_n=14MeV

$$X + {}^{1}_{1}H$$

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

E_{Li} ~ 35.89 MeV

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

Detection of deuteron and decay particle (proton) in coincidence by using16 strip ΔE-E telescope [(E*)]

Similarly, we have done measurement for our reference reaction.

Experimental results of ^{59}Ni(n,xp) reaction

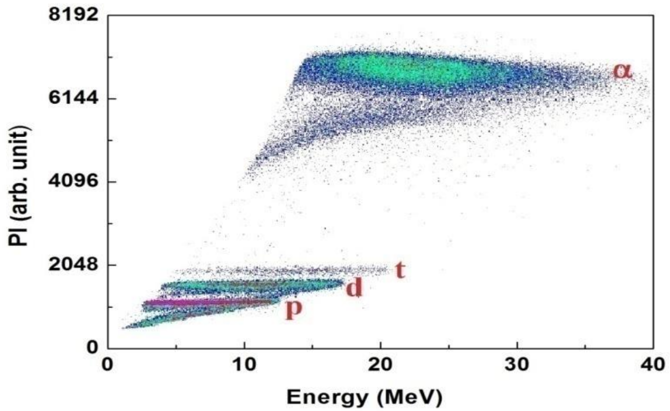


Fig. A typical plot of particle identification (PI) versus total energy (E_{total}) of the PLFs produced in ^{6}Li+^{56}Fe reaction at E_{lab}=35.89 MeV.

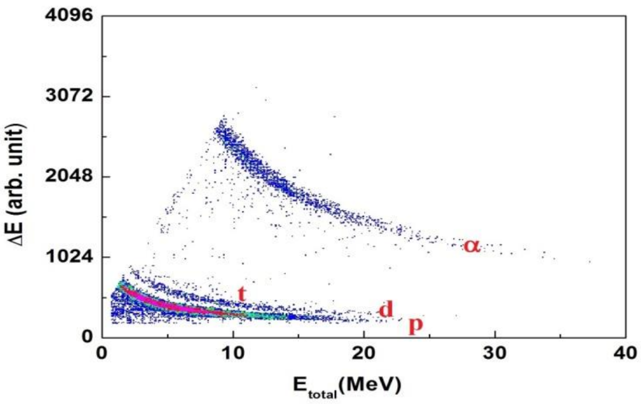


Fig. A two dimensional ΔE versus E spectrum obtained from one of the 32 ΔE-E strip combinations placed at backward angles, for ^{6}Li+^{56}Fe reaction at E_{lab} =35.89 MeV.

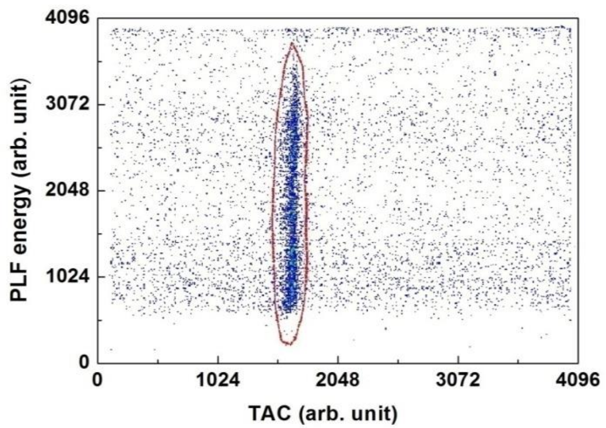


Fig. A typical PLF-proton TAC versus deuteron (PLF) energy plot in the ^{6}Li+^{56}Fe reactions at E_{lab} = 35.89 MeV.

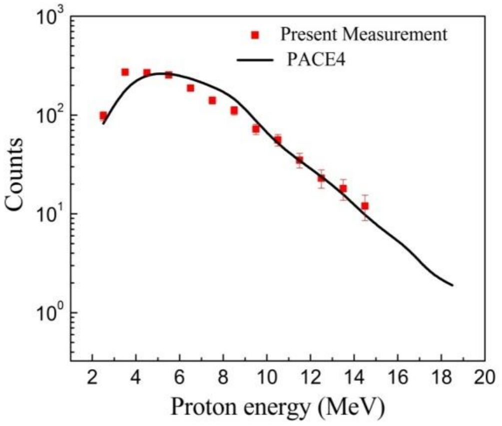


Fig. Measured proton energy spectra in coincidence with deuteron PLFs for the ^{6}Li+^{56}Fe reaction at 35.89 MeV corresponding to a compound nucleus excitation energy of ~ 25 MeV. The statistical model prediction iby PACE4 normalised to the data is shown as a continuous line.

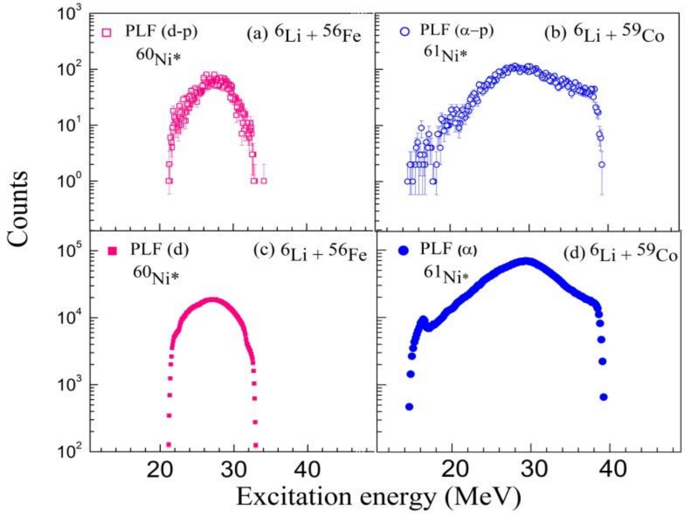


Fig. Excitation energy spectra of the target-like fragments produced in ^{6}Li+^{56}Fe and ^{6}Li+^{59}Co reaction corresponding to PLF deuteron and alpha respectively with [(a),(b)] and without [(c),(d)] coincidence with evaporated protons.

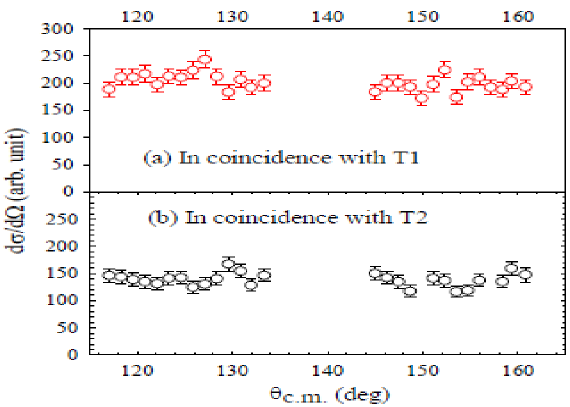


Fig. Angular distributions of proton induced in ^{6}Li+^{56}Fe system as a measured by strip telesope in coincidence with PLFs detected by (a) T1 (b)T2. Isotropic distribution of proton emission implies dominance of compound nuclear process.

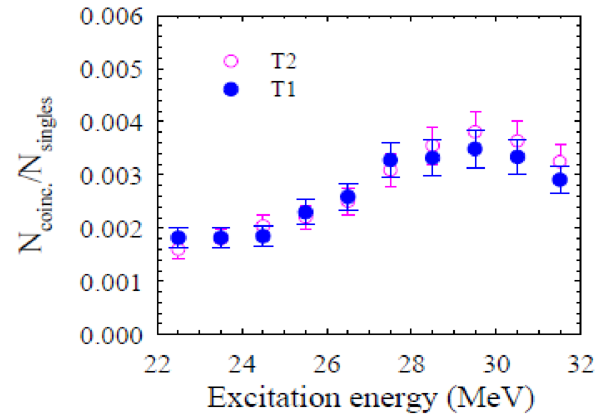


Fig. Ratio of proton counts in coincidence to singles as a function of excitation energy of the composite nucleus 60Ni* obtained using the gate of the PLF telescope (a) T1 and (b) T2. Data of both T1 and T2 provide same results.

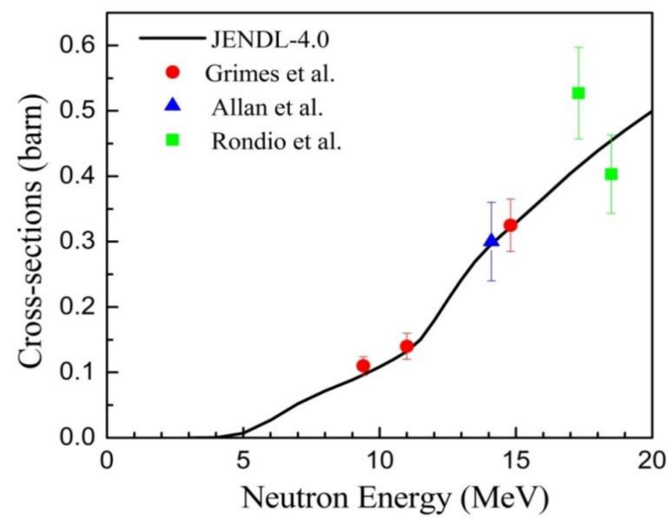
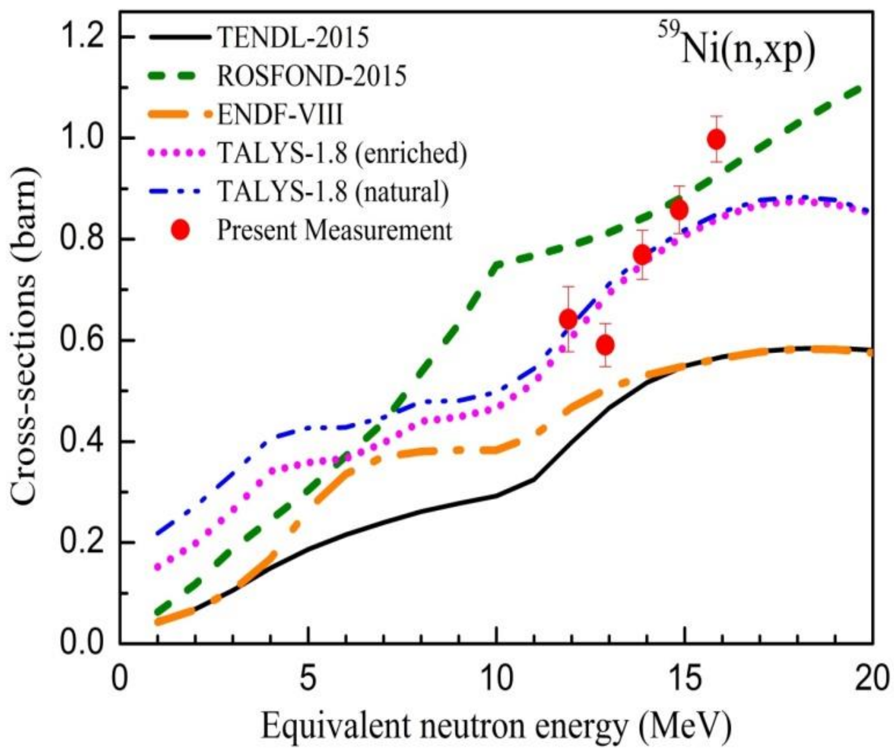


Fig. Comparison of the ^{60}Ni(n,xp) experiemental data available in EXFOR with the values obtained from JENDL-4.0 library (Reference surrogate reaction used in surrogate ratio method).

Hence, the ratio of the proton evaporation cross section of compound nuclei ^{60}Ni* to that of ^{61}Ni* can be obtained by employing following expression:

$$\frac{\sigma^{^{59}\mathrm{Ni}(n,xp)(E^*)}}{\sigma^{^{60}\mathrm{Ni}(n,xp)(E^*)}} = \frac{\sigma^{\mathrm{CN}}_{n+^{59}\mathrm{Ni}}(E^*)\,\Gamma_p^{^{60}\mathrm{Ni}}(E^*)}{\sigma^{\mathrm{CN}}_{n+^{60}\mathrm{Ni}}(E^*)\,\Gamma_p^{^{61}\mathrm{Ni}}(E^*)}. \qquad (2)$$



Physical Review C 99, 014611 (2019).

Fig. The ^{59}Ni(n,xp) cross-section as a function of equivalent neutron energy along with the ones from nuclear data libraries and TALYS-1.8 nuclear model calculations for the cases of enriched and natural targets.

Summary & Conclusions

- We have mainly focussed on the study of nuclear data for various radionuclides (A~50-60) relevant for fusion nuclear technology.

- **First time ^{59}Ni(n,xp) reaction cross-section** have been measured in the energy range 11.9-15.8 MeV by surrogate ratio method. ^{59}Ni(n,xp) reaction experimental study (outgoing proton energy spectra) and nuclear model calculations with TALYS-1.8 code indicate that the reactions is predominantly goes through compound nuclear process (Maxwellian distribution).

- In ^{59}Ni(n,xp) reaction the protons of energy 3-5 MeV are emitted with maximum probability

- The present measurement of ^{59}Ni(n,xp) cross-section is in good agreement with our TALYS-1.8 calculations.

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

- The cross section and activation study have been done using TALYS-1.8, EASY and ACTYS for various nuclides of fusion reactor.

References

- A.J. KONING et al. , " TALYS User Manual : A Nuclear Reaction Program , User Manual",NRG-1755 ZG Petten, The Netherlands (2011).
- B. PANDEY et al., "Estimate of (n,p) cross-section for Radionuclides ^{55}Fe Using EMPIRE and TALYS " , Nuclear Science and Engineering 179, 313 (2015) .
- 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).
- J.ESCHER et al., "Compound-Nuclear Reaction Cross-Sections from Surrogate Measurements," Rev. Mod. Phys.," 84, 353 (2012) .
- R.A.FORREST, "Data Requirements for Neutron Activation Part I : Cross- Sections," Fusion Eng. Des.,81,2143(2006).
- M.R. Gilbert, S.L. Dudarev, S. Zheng, L.W. Packer, and J.-Ch. Sublet"Transmutation, gas production, and helium embrittlement in material under neutron Irradiation", CCFE-PR(12)02.
- R. Rayaprolu, S. Moller, Ch. Linsmeier et al., "Simulation of neutron irradiation damage in tungsten using higher energy protons", Nuclear Materials and Energy 9 (2016) 29-35.
- Wallner, A.; Buczak, K.; Lederer, C.;Vonach, H.; Faestermann, T.; Korschinek, G.; Poutivtsev, M.; Rugel, G.; Klix, A.; Seidel, K. ; Plompen, A.(2011)., "Production of Long-lived Radionuclides 10Be, 14C, 53Mn, 55Fe, 59Ni and 202g Pb in a Fusion Environment." *J. Kor. Phys. Soc*, *59*, p.1378.

- M.R. Gilbert, J. Marian, J.-Ch. Sublet, " Energy Spectra of Primary Knock-on Atoms Under Neutron Irradiation", Journal of Nuclear Materials, 467, 121-134 (2015).

- Mohamed Abdou, Neil B.Morley, SergeySmolentsev, AliceYing, Siegfried Malang, ArthurRowcliffe, MikeUlrickson"Blanket/first wall challenges and required R&D on the pathway to DEMO" Fusion Engineering and Design, 100, 2015, 2-4.

- Steve Fetter, E.T. Cheng and F.M. Mann, "Long-term radioactivity in fusion reactors", Fusion Engineering and Design 6 (1988) 123-130.

- L.R. Greenwood, "A new calculation of thermal neutron damage and helium production in nickel", Journal of Nuclear Materials 115 (1983) 137-142.

- Bo-Young Lee, Joo-Hee oh and Seung-Kook Ko, "Journal of the Korean Physical Society", Vol. 63, No. 1, July 2013, pp. 36~40.

- Sai Chaitanya Tadepalli , Priti Kanth et al., "Development and validation of ACTYS, an activation analysis code", Annals of Nuclear Energy 107 (2017) 71–81.

- S.J.Zinkle, G.S.Was, "Materials challenges in nuclear energy", Acta Materialia Volume 61, Issue 3, February 2013, Pages 735-758.

- Gary S. Was, "Fundamentals of radiation materials science: metals and alloys". Springer, 2016.

Acknowledgement

- **I am very thankful to**

Dr. H. M. Agrawal (My Guide) ,G.B. Pant University of Agriculture & Technology, Pantnagar.

Dr. Bhawna Pandey (My Sister), G.B. Pant University of Agriculture & Technology, Pantnagar.

Dr. B.K. Nayak, Dr. S.V. Suryanarayana, BARC, Dr. S. Santra, Dr. Asim, BARC, Mumbai.

Dr. C.V.S Rao, Dr. P.V. Subhash, Dr. S. Vala, IPR, Gandhinagar, Gujarat.

Dr. R.C. Srivastava, Dr. G.C. Joshi, Dr. Manoj Kumar , Dr. Gagan Dxit and other faculty members for their constant guidance, support and valuable suggestions in doing this work .

- **I am very thankful to the different institutes members, where I worked for long time –**

Bhabha Atomic Research Centre (BARC), Mumbai.
Tata Institute of Fundamental Research (TIFR), Mumbai.
Institute for Plasma Research (IPR), Ganhinagar, Gujarat.

- **BRNS (Board of Research in Nuclear Science), Department of Atomic Energy (DAE) for their funding in pursuing research work.**


Thank you