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Compact Accelerator Based Neutron Sources (CANS)

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REACTIONS OF NEUTRON PRODUCTION

- Fission of Heavy and Light Nuclei by Neutrons

$$U^{235} + n \rightarrow A + B + 2.52n + 195\ \text{MeV} \qquad \nu = 2.34 + 0.15E\ (U^{235})\ \ E > 1\ MeV$$

$$U^{238} + n \rightarrow A + B + 4.515n + 200\ \text{MeV} \qquad \nu = 2.3 + 0.16E\ (U^{238})\ \ E > 1\ MeV$$

ν - the number of neutrons ν produced in one reaction

$$Li^{7} + n \rightarrow T + He^{4} + n - 2.47\ \text{MeV}$$

This reaction takes place at neutron energies exceeding 4 MeV and performs tritium reproduction without neutron losses.

- Fusion of Light Nuclei in Solid, Gaseous, and Plasma Targets

$$D + T \rightarrow He^{4}(3.5\ \text{MeV}) + n(14.17\ \text{MeV}) \qquad S = 1.1 \times 10^{-24}\ n_D n_T T^2\ \text{m}^{-3}\text{s}^{-1}$$

$n_D = n_T = 10^{20}\ m^{-3}$ and $T = 10\ keV$ from 1 m^{-3} $Y_n \sim 10^{18} n/s$

Introduction

REACTIONS OF NEUTRON PRODUCTION

- Fusion of Light Nuclei in Solid, Gaseous, and Plasma Targets

D + D → ^{3}He (0.82 MeV)+ n (2.45 MeV) (Branching ratio = 50%)

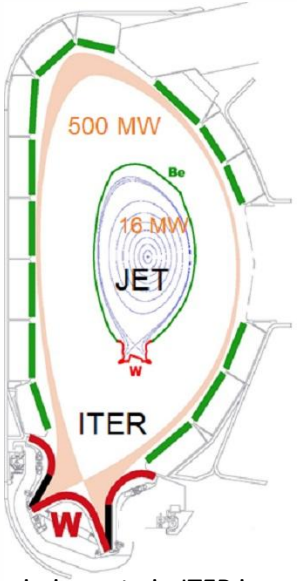
D + D → ^{3}H (1.01 MeV) + p (3.02 MeV) (Branching ratio = 50%)

D + T → ^{4}He (3.56 MeV)+ n (14.03 MeV)

T + T → ^{4}He + n + n (11.3 MeV)

T+ ^{3}He → p + α + n + (12. 1 MeV) (Branching ratio = 55%)

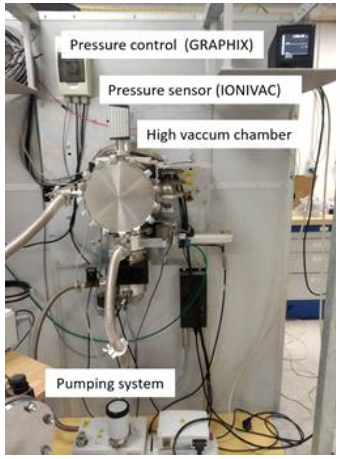
T + ^{3}He → p + α + n + (12. 0 MeV) (Branching ratio = 4%)



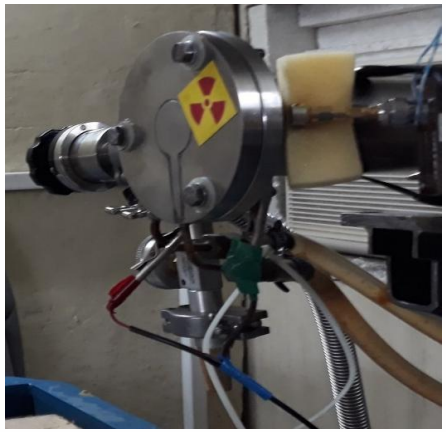
The neutron emission rate in ITER is expected **from 10^{14} n/s** during DD plasma to **10^{21} n/s** with DT plasma.



Ion source at IGN14 (IFJ PAN, Kraków)



PF24 at IFJ PAN, Kraków



T/Ti target at IGN14 (IFJ PAN, Kraków)

REACTIONS OF NEUTRON PRODUCTION

- Muon Catalysis

  Muons are produced via the decay of $\pi^- \rightarrow \mu^- + \tilde{\nu}_e$.

  π^- mesons are produced due to the bombardment of a low-Z target by a beam of charged particles (e.g., protons) with energies of a few GeV.

  In the presence of muons in a DT mixture with a density equal to that of a liquid or a gas at room temperature and a pressure of 1000 atm, an electron in a tritium or deuterium atom is replaced with a muon over a time of 10^{-8} s.

  Over a time of $5 \cdot 10^{-9}$s, DTμe meso-molecules are produced. Then, over 10^{-12} s, the D and T nuclei enter into the fusion reaction.

About 150 of DT reactions per muon were detected experimentally and the possibility of increasing this number to more than 300 was discussed.

REACTIONS OF NEUTRON PRODUCTION

- Spallation of Nuclei

In a spallation reaction occurring within a target containing nuclei of heavy elements (such as Hg, W, U, and Ta), a single 1 GeV proton produces, ***on average, between 20 neutrons (for Hg and Pb) and 50 neutrons (for U).*** During this process, approximately 30 MeV of energy is released within the volume of the target for every "useful" neutron produced.

The spectrum of generated neutrons is very broad, extending up to 1 GeV, with the average energy of neutrons resulting from the evaporation process being approximately 2 MeV. The shape of the high-energy "tail" of this distribution depends strongly on the detection angle relative to the direction of the incident proton beam.

REACTIONS OF NEUTRON PRODUCTION

- Reactions Involving Light Nuclei *(Be, Li, and H)*

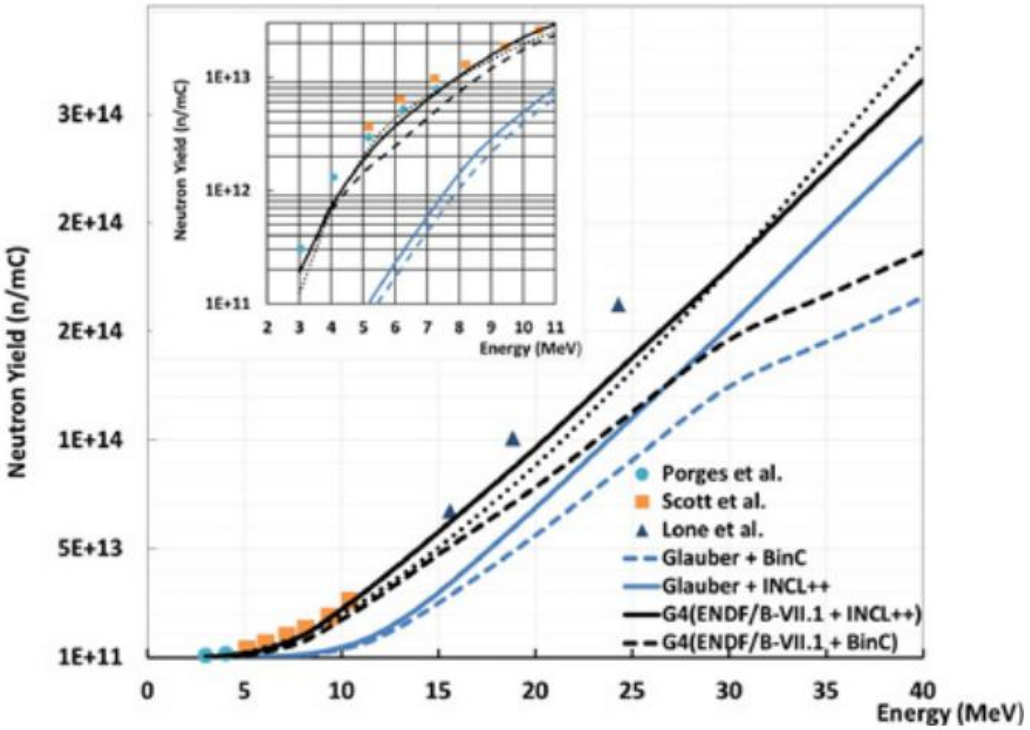
$$Li^7 + D \rightarrow Be^7 + 2n - 3.87\ MeV$$
$$Li^7 + D \rightarrow Be^8 + n + 15.03\ MeV$$
$$Li^6 + D \rightarrow Be^7 + n + 3.38\ MeV$$
$$Li^7 + p \rightarrow Be^7 + n - 1.65\ MeV$$
$$Be^9 + p \rightarrow Be^9 + n - 1.85\ MeV$$
$$Be^{10} + D \rightarrow Be^{10} + n + 4.36\ MeV$$
$$H^3 + p \rightarrow H^3 + n - 0.76\ MeV$$

When the energies of incident particles lie in the range 25–40 MeV, the efficiencies of these reactions can be fairly high.

A specific feature of these reactions, which proceed at energies below the threshold energy for spallation reactions, is that neutrons are mainly emitted along the beam injection line. It means, that this allows one to implement testing zones with directed and slowly varying neutron flux density.

In the d-Be reaction, the proportion of high-energy neutrons (in the MeV range) is lower than in the d-Li reaction and tritium is produced in an amount corresponding to roughly half the number of neutrons generated.

Neutron Yield

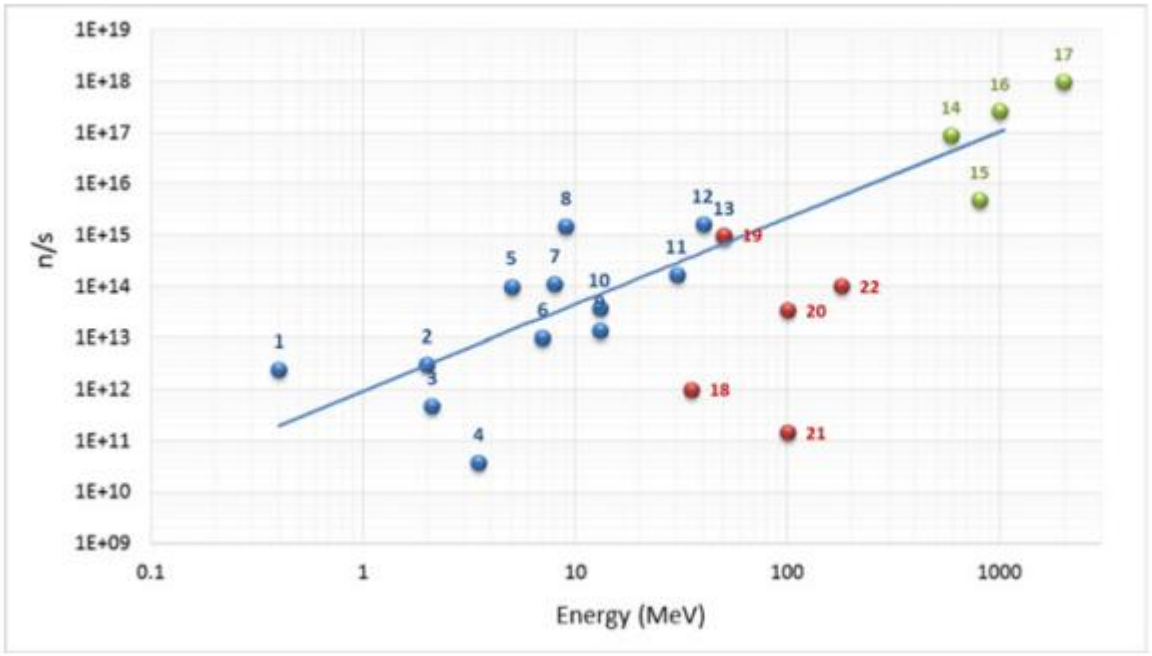


Neutron yields calculated (lines) for different options in Geant4 and compared with existing experimental data (symbols) as a function of the incident proton energy on thick ^{9}Be target.

Experimental uncertainties are not indicated but should be of the order of 10–20%.

[Alain Letourneau et al., EPJ Web of Conferences 146, 03018 (2017) , DOI: 10.1051/epjconf/201714603018]

Compact neutron source in the world

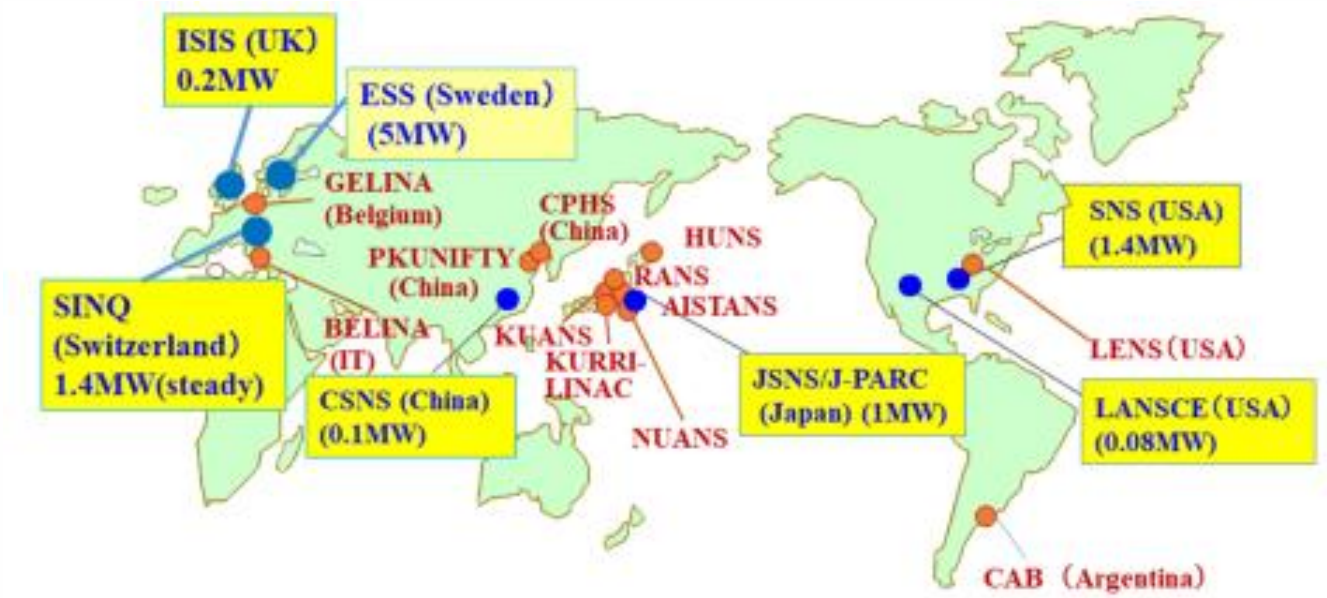


1 HINEG2	14 PSI (SINQ)
2 PKUNIFTY	15 ISIS TS2
3 Franz	16 SNS
4 KUANS	17 ESS
5 Legnaro	
6 RANS	18 HUNS
7 iBNCT	19 Ariel
8 IFMIF-Lipac	20 Gelina
9 LENS	21 Pohang
10 CPHS	22 Orela
11 Kurri	
12 SARAF 2	
13 ESS Bilbao	

Existing and projected neutron sources classified as a ***function of their neutron brightness***, incident beam energy, and technology: protons or deuterons on lithium or beryllium targets (from 1 to 13); protons on heavy metal targets (from 14 to 17) and electrons on heavy metal (from 18 to 22)

[Alain Letourneau et al., EPJ Web of Conferences 146, 03018 (2017) , DOI: 10.1051/epjconf/201714603018]

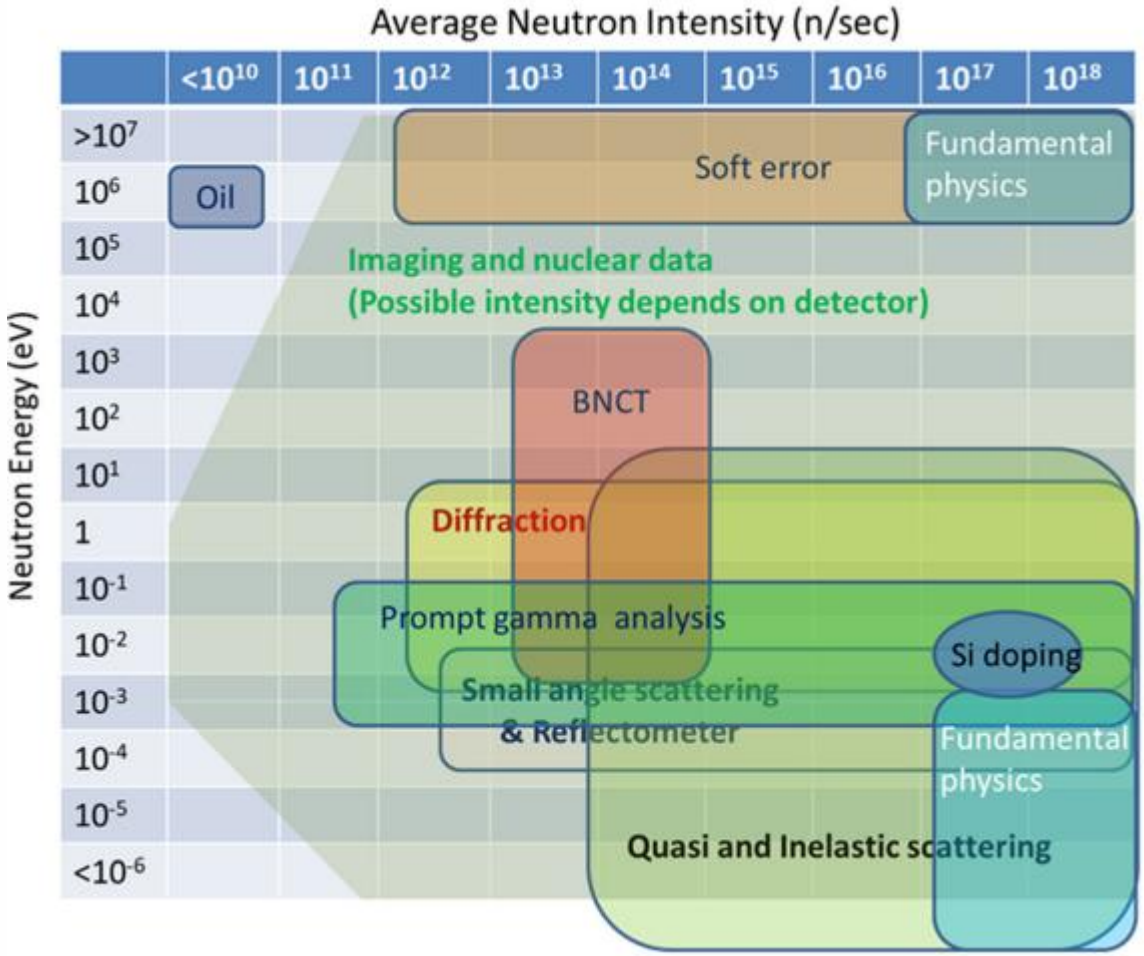
Accelerator-driven neutron sources



Kiyanagi AAPPS Bulletin (2021) 31:22
https://doi.org/10.1007/s43673-021-00022-3

The spallation neutron sources are indicated by a yellow background color

Applications



Kiyanagi AAPPS Bulletin (2021) 31:22
https://doi.org/10.1007/s43673-021-00022-3

Applications

Experimental Neutronics and Device Development

Optimization of CANS systems:

- Achieved through the engineering of the target–moderator assembly and the design of the neutron system;
- The moderator and reflector assembly functions as an optical system for beam extraction; it includes neutron-beam-focusing devices that leverage the optical and magnetic properties of neutrons.

Experimental Neutronics and Device Development

Materials Characterization

At CANS (Compact Accelerator-based Neutron Source) facilities, research programs utilizing neutron scattering methods for material characterization have been established.

These programs complement the activities conducted at large-scale research facilities by encompassing education, user training, "proof-of-principle" experiments, and research projects for which lower neutron flux levels do not pose a limitation.

In general, CANS facilities primarily host research based on elastic scattering—namely, small-angle scattering, reflectometry, and total scattering measurements.

Experimental Neutronics and Device Development

Interrogation

When used as a research probe, the neutron offers several significant advantages, including:

- the capability for remote detection,
- a non-destructive measurement process,
- high sensitivity to chemical density (enabling, among other things, the creation of three-dimensional volumetric models and the identification of elements and materials),
- rapid data acquisition,
- visualization.

Applications

Experimental Neutronics and Device Development

Systems called (n, γ) devices.

A suite of techniques based on the “neutron-in, gamma-out” reactions, including prompt-gamma neutron activation (PGAA) analysis and delayed (after irradiation) neutron activation analysis, has been established.

The field of applications includes art and archaeology, mineralogy and geology, environmental protection, industrial product inspection, landmine detection, explosives, nuclear substances and contraband, well logging, medical therapy, basic research, and education.

Applications

Experimental Neutronics and Device Development

Irradiation Effects of Electronics

Semiconductor devices—such as large-scale integration (LSI) circuits, including memory chips—are subject to random phenomena known as bit errors.

A "soft error" is a temporary bit error occurring within a semiconductor. Such errors are triggered by single-event upsets (SEUs), which are caused by the presence of unexpected charged particles.

These particles can be generated as secondary ionizing particles resulting from nuclear reactions, primarily occurring between a silicon nucleus and a neutron.

Neutron Capture Therapy (talk of Prof. Olko)
Isotope Production (talk of Prof. Mietelski)

Experimental Neutronics and Device Development

Nuclear Data

Nuclear data are measured properties and numerical quantities that describe nuclear reactions. For example, information about various cross sections, decay half-lives, gamma-ray emission characteristics, spin states, and Q-values belongs to nuclear data.

Because we are not yet able to calculate and predict nuclear phenomena precisely, for example, from first-principles formalism, our understanding of nuclear matter and interactions is rooted in the establishment of nuclear data. Such data, organized and managed by the international nuclear science community, encompass an enormous energy range from 10^{-5} to 10^{9} eV for hundreds of nuclides and thousands of radioisotopes.

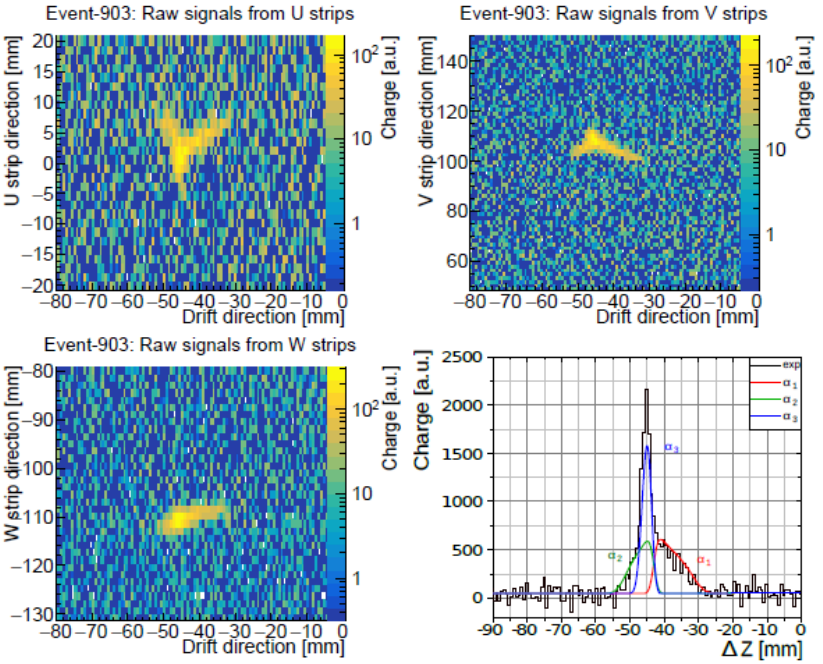
Applications

Experimental Nuclear Astrophysics

- One of the most important open questions in nuclear astrophysics concerns the creation of carbon and oxygen in the stars.
- The basic observable to resolve the reaction rates is the cross section, which has to be determined at the relevant energies (at the Gamow peak) and is also required as input information for star evolution models
- One way to determine the reaction cross section is to study its inverse reaction by using an active target together with photon and neutron beams.

$$
\begin{aligned}
n + {}^{12}C &\rightarrow n' + {}^{12}C^* \\
&\rightarrow \alpha_1 + {}^{8}Be^*_{(GS\ or\ 3\,MeV)} \\
&\rightarrow \alpha_2 + \alpha_3 \\
n + {}^{12}C &\rightarrow \alpha_1 + {}^{9}Be^* \\
&\rightarrow n' + {}^{8}Be^*_{(GS\ or\ 3\,MeV)} \\
&\rightarrow \alpha_2 + \alpha_3 \\
n + {}^{12}C &\rightarrow \alpha_1 + {}^{9}Be^* \\
&\rightarrow \alpha_2 + {}^{5}He^* \\
&\rightarrow n' + \alpha_3
\end{aligned}
$$

Reaction	Q-value [MeV]	Threshold [MeV]
$^{12}C(n, \alpha)^{9}Be$	−5.701	6.180
$^{12}C(n, n'+3\alpha)$	−7.275	7.886
$^{12}C(n, p)^{12}B$	−12.59	13.64
$^{13}C(n, \alpha)^{10}Be$	−3.835	4.133
$^{13}C(n, n'+\alpha)^{9}Be$	−10.65	11.47
$^{13}C(n, 2\alpha)^{5}He$	−11.25	12.12



Event reconstruction example for a 12C(n, n')12C∗
The 2D plots show the raw data (U-, V -, W-strip position versus time bin) re-scaled to mm.
The bottom right plot shows the charge distribution along the track(s) and the charge profile(s) fit.

Perspectives

- In the field of fundamental materials research, the development of a number of CANS (Accelerator-Based Compact Neutron Source) systems is anticipated—systems optimized for source brightness, beam throughput, and a diverse range of experimental stations.
- From a practical perspective, as neutron production techniques and instrumentation for CANS evolve, the use of epithermal and fast neutrons will become increasingly widespread across technologies related to energy, materials diagnostics, security, biomedicine, and the preservation of cultural heritage.
- One particularly interesting area of research involves the study of microscopic magnetism in engineering materials, biological systems, and complex structures containing hydrogen; this field leverages properties unique to neutrons—namely, their ability to engage in magnetic interactions and their sensitivity to the presence of hydrogen atoms.
- Moreover, it appears that the use of polarized neutrons, combined with techniques for polarizing the nuclear spins of hydrogen, will open up a new horizon for neutron applications.

References

1. Kiyanagi AAPPS Bulletin (2021) 31:22 https://doi.org/10.1007/s43673-021-00022-3
2. Alain Letourneau et al., EPJ Web of Conferences **146**, 03018 (2017) , DOI: 10.1051/epjconf/201714603018
3. B. V. Kuteev, et al., Plasma Physics Reports, 2010, Vol. 36, No. 4, pp. 281–317.
4. I.S. Anderson, et al., Physics Reports, http://dx.doi.org/10.1016/j.physrep.2016.07.007

Thank you for the attention