A composite target for two-stage emission of neutron

I First stage

The process of **spallation** is the impact of a projectile on a target with production of fragments (spall). In nuclear physics, the hit by a high-energy particle on a heavy nucleus produces numerous nucleons. A particle accelerator may be used to produce **a beam of protons of high-energy** (around 1 GeV). If this beam is shot onto **a target of heavy metal**, then, the nuclei are excited and 20 to 30 neutrons are emitted per nucleus (and several protons). The process doesn't produce a chain reaction. Example of spallation reaction :

$$p + {}^{181}_{73}Ta \rightarrow kn + k'p + {}^{a}_{b}X \tag{1}$$

$$(20 \leqslant k \leqslant 30\ ;\ a < 181\ ;\ b < 73\ ;\ k' = 182 - k - a = 74 - b) \tag{2}$$

As can be seen, in addition to neutrons, **a number of low energy protons are also emitted**.

II Second stage

When **low-energy protons** ($\approx$ 1 MeV) hit **a target of light atoms** (Li, Be, Al...), neutrons are emitted. Examples :

$$p + {}^{7}_{3}\mathrm{Li} \rightarrow {}^{7}_{4}\mathrm{Be} + n \tag{3}$$

$$p + {}^{9}_{4}\mathrm{Be} \rightarrow {}^{9}_{5}\mathrm{Be} + n \tag{4}$$

The idea we want to test is explained by the figure below : a high-energy beam of protons is projected onto a heavy metal target. The spallation produces neutrons (“*primary neutrons*”) and protons of lower energy. The impact of these protons on a target of light atoms (Li, Be or Al) could produce what we call *“secondary neutrons”*.

Our goal is therefore to create a cascade of neutrons : in a first stage, a high-energy beam of protons strikes a heavy metal target (W) and generates primary protons and neutrons ; in a second stage, the primary protons (of lower energy) strike a second target of light elements (Al) and produce secondary neutrons.

A) Target of heavy metal (without light metal element) :

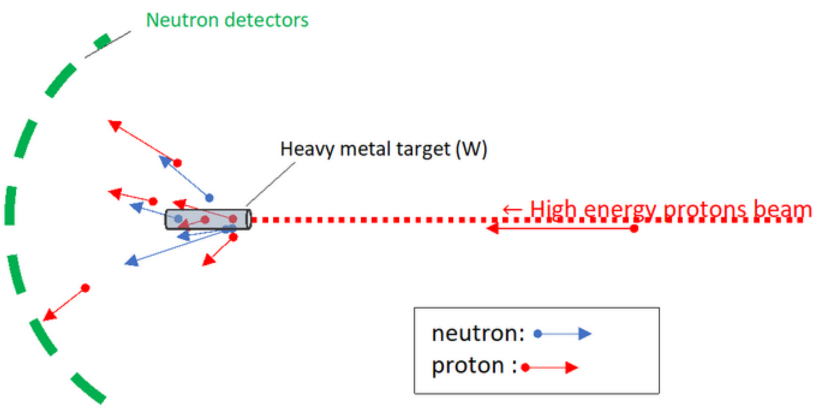

FIGURE 1 – Detection of primary neutrons (without light metal target).

B) Target with the light metal element :

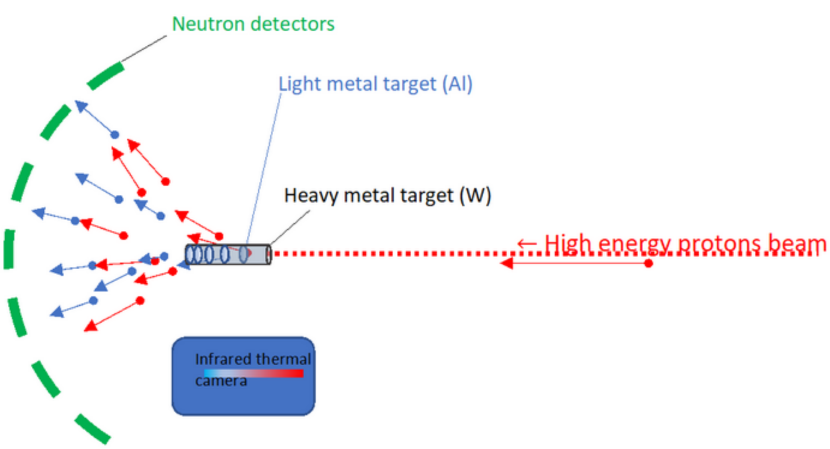

FIGURE 2 – Detection of neutrons (with light metal target)

An excess of neutrons is expected when layer of light elements is positioned within the heavy metal target. The objective is to assess the **neutron production amplification factor** obtained by this sequence (heavy metal target + light element target).

Detectors dedicated to neutron detection could be used to measure this amplification factor.

III The heavy metal target

The properties of a high power target for spallation source are :

— High Atomic number
— High density
— High melting point
— High heat capacity
— High thermal conductivity

Tungsten, W					
Atomic number	Standard atomic weight (u)	Density ($g.cm^{-3}$)	Melting point (°C)	Heat capacity ($J.kg^{-1}.K^{-1}$)	Thermal conductivity ($W{\cdot}m^{-1}{\cdot}K^{-1}$)
74	183,4±0,01	19,254	3422	132	174

FIGURE 3 – Some properties of tungsten metal

Tungsten meets the first three requirements, but performs poorly when it comes to thermal properties.

The PSTAR program (NIST) calculates the stopping power for protons in various materials

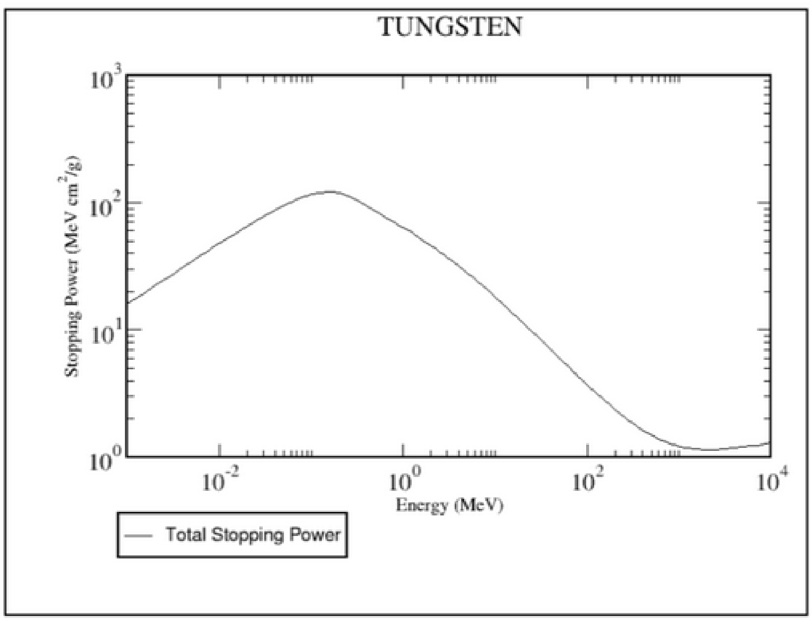

FIGURE 4 – The total stopping power for a tungsten target. https://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html

This application allows us to design the heavy metal target.

For example, for a tungsten target, an incident proton of 500 MeV will completely lose its kinetic energy after about 12 cm, as this simulation shows :

x (cm)	KE (MeV)
0	500
1	4,71E+02
2	4,41E+02
3	4,10E+02
4	3,76E+02
5	3,40E+02
6	3,02E+02
7	2,62E+02
8	2,20E+02
9	1,74E+02
10	1,25E+02
11	7,06E+01
12	9,26E+00
(13)	-6,21E+01

FIGURE 5 – Simulation of the kinetic energy of a 500 MeV proton travelling in a tungsten target

The calculation with the CSDA range gives the same value :

$$Range\,(cm) = \frac{Range\left(\frac{g}{cm^2}\right)}{\rho\left(\frac{g}{cm^3}\right)} = \frac{221\frac{g}{cm^2}}{19.254\frac{g}{cm^3}} \approx 11.49\,cm \tag{5}$$

We want to explore the 500 MeV-1 GeV range, which is compatible with targets no longer than 31 cm. We would also like to evaluate the beam broadening in the target.

IV The light metal target

Aluminium's advantageous thermal properties (better heat capacity and thermal conductivity) could compensate for tungsten's shortcomings in this respect.

Aluminium, Al					
Atomic number	Standard atomic weight (u)	Density ($g.cm^{-3}$)	Melting point (°C)	Heat capacity ($J.kg^{-1}.K^{-1}$)	Thermal conductivity ($W{\cdot}m^{-1}{\cdot}K^{-1}$)
13	26,982±0,001	2,7	660,3	897	237

FIGURE 6 – Some properties of aluminium metal

The proton beam will have to be adjusted so that the temperature does not approach the melting temperature of the aluminium because most of the energy in the beam is deposited in the target in the form of heat. An infrared thermal camera will be used to measure the surface temperature of the target.

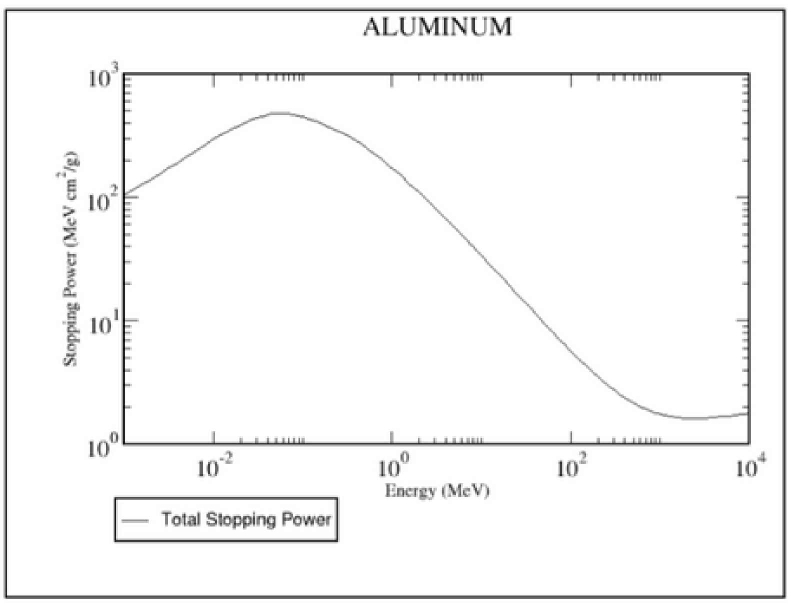

FIGURE 7 – Stopping power for an aluminium target

For a proton with an energy of 20 MeV, the penetration power in an aluminium target is around 2 mm.

V Assembly of the components

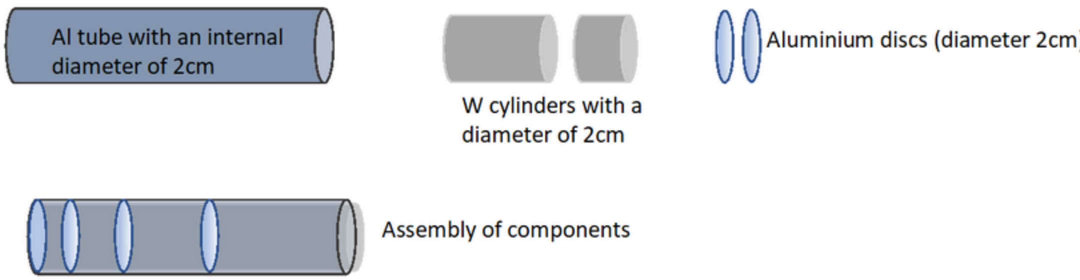

Figure 8 – Assembly of the components of the target

Aluminium will encourage the production of neutrons by exploiting slow protons, while allowing better conduction of heat to the outside of the target.

VI Supplies and materials

All these supplies are easy to obtain and not too expensive.

Figure 9 – Aluminium tube, solid round bar in pure tungsten and aluminium discs

VII Why is it useful to produce neutrons ?

Long-lived radioactive waste has a radioactive half-life greater than 30 years. In the fission products of nuclear power plants, they represent about 6% of the waste. They are particularly troublesome because they take a long time to disappear. Among these radioisotopes, technetium-99 is very abundant and has a half-life of 211,000 years. However, it can be eliminated by neutron capture.

Neutron capture is a nuclear reaction in which neutrons collide with atomic nuclei and fuse to form heavier nuclei. Neutrons have no electrical charge and can therefore easily make their way into nuclei. The aim is to obtain a reduction in the radioactive decay period of fission products by **transmutation**.

The capture of a neutron by technetium-99 is described by the following reaction :

$$^{99}_{43}Tc +^{1}_{0} n \rightarrow^{100}_{43} Tc + \gamma \tag{6}$$

The half-life of technetium-100 is only 16 seconds!

But there is another opportunity, a very promising one : **MYRRHA** (Multi-purpose hYbrid Research Reactor for High-tech Applications) is a project of a nuclear reactor coupled with a proton accelerator. It can work in a **sub-critical configuration**. The project is managed by the Belgian Centre for Nuclear Research (SCK CEN). The idea is to arrange the fuel so it is always below criticality. Without external neutron input, the power of the reactor would decrease rapidly. In order to produce power, some other source of neutrons has to be provided. It is the proton accelerator which is responsible for carrying out this production of neutrons.

VIII Conclusion

Our goal is therefore to design a composite, two-layer target, the first of which is a heavy metal and the second a light one. It will be necessary to optimize the nature, shape and dimensions of these two layers so as to emit a maximum of neutrons. This optimization will have to take into account the broadening of the beam in the target.

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X References

— National Institute of Standards and Technology (NIST). (2021). PSTAR : Stopping Power for Protons. Retrieved February 2025, from `https://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html`