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CAGALOGLU ANATOLIAN HIGH SCHOOL

Nuclear Spallation Efficiency: Target Material Optimization

Introduction

Nuclear spallation occurs when high-energy particles interact with heavy atomic nuclei, causing the emission of various secondary particles. This method is widely used in neutron production, minimizing nuclear waste and supporting multiple applications in nuclear physics.

Our project aims to compare the neutron production efficiency of three (cylindrical shaped) materials: Tungsten, Lead and Copper; which differ in atomic number and physical and neutron-related properties. We irradiate them with 1 GeV (2 mm FWHM if possible) proton beams and analyze the total number of emitted neutrons, their angular distribution, and energies to assess their suitability for neutron production and spallation applications.

Using 15 cm for diameter and 60 cm for height — dimensions suggested as optimal in [1] to ensure complete interaction of 1 GeV protons with the target — we also proposed additional experiments with thicknesses adjusted to match proton range. This will allow us to study the impact of thickness on neutron production and compare with standard "optimal" dimensions.

Thus, our project investigates both the effect of material type and target thickness on neutron production. All proposed experiments were simulated using Geant4, and the results are included in our report.

Overview Of The Experiment

As stated in the introduction, we investigate the number, energy, and angular distribution of neutrons produced by a 1 GeV proton beam hitting cylindrical metal targets. Our experiments will involve Tungsten, Copper, and Lead, with two different thicknesses for Tungsten and Lead. While we aim to include Tungsten in our setup, its use depends on BL4S authorities due to budget limitations.

Table 1.1: The experiments we aim to conduct.

Material	**Characteristics of the Proton Beam (if possible at 2mm spatial FWHM width)**	**Dimensions of the cylinder**
Tungsten	1 GeV	diameter = 15 cm height = 60 cm
Tungsten	1 GeV	diameter = 15 cm height = 30 cm
Lead	1 GeV	diameter = 15 cm height = 60 cm
Lead	1 GeV	diameter = 15 cm height = 50 cm
Copper	1 GeV	diameter = 15 cm height = 60 cm

We selected Tungsten, Lead, and Copper due to their common use in neutron production and differing properties. Tungsten and Lead, being heavier atoms, are generally more efficient, while Copper offers high thermal conductivity and good mechanical strength. Comparing these materials helps us understand how atomic weight and different physical and neutron-related properties affect spallation. Since radioactive materials are not permitted easily at CERN, all three being non-radioactive makes them suitable for our experiment. Their relevant properties are summarized in Table 1.

Table 1.2: Physical and neutron-related properties of target materials

Element	**Heat Deposition (MeV/cm^3)**	**Neutron Yield (n/p)**	**Calc. Error (%)**	**Melting Point(°C)**	**Boiling Point (°C)**	**Density (g/cm^3)**	**Thermal Conductivity (W/m·K)**
Pb	8.74	21.5	0.59	327.46	1,749	11.35	35.00
Cu	8.08	9.74	0.65	1,084	2,562	8.96	385.0
W	9.50	24.8	0.57	3,422	5,555	19.30	173.0

In the article [1], different measurements were tested using MCNPX 2.6.0. in order to find the optimal cylindrical size that will maximize the neutron yield for some materials (including W, Pb and Cu) while balancing material efficiency. Through the simulations, 15 centimeters for diameter and 60 centimeters for height was found to be the optimal size for interactions with a 1 GeV proton beam with 2 mm spatial FWHM distribution.

The 60 cm thickness ensures sufficient proton interaction depth to maximize neutron production, while the 15 cm diameter balances neutron leakage and material usage. Smaller diameters reduce neutron leakage, while larger diameters increase self-absorption and thicker targets might produce more neutrons, but there's a point where increasing size doesn't help due to neutron absorption or other losses. The chosen dimensions strike a balance between these effects.

Depending on this article, we will also use the given 15 cm x 60 cm dimensions for three of our experiments.

However, from a different perspective, to maximize neutron production, the target length should be close to the proton range, so that the protons are fully stopped inside the material and can interact with as many nuclei as possible.

Therefore, based on the findings of SRIM simulations from [1], NIST's PSTAR program, and [2]; we've also decided to conduct experiments using our chosen materials' proton ranges to compare them with the found optimal sizes at [1]. We selected lengths of 30 cm for tungsten and 50 cm for lead, which align closely with their proton ranges. Since copper's proton range is near 60 cm, no alternate size was tested. To isolate the effect of length, the target diameter was fixed at 15 cm.

Table 1.3: Proton ranges of target materials according to different sources.

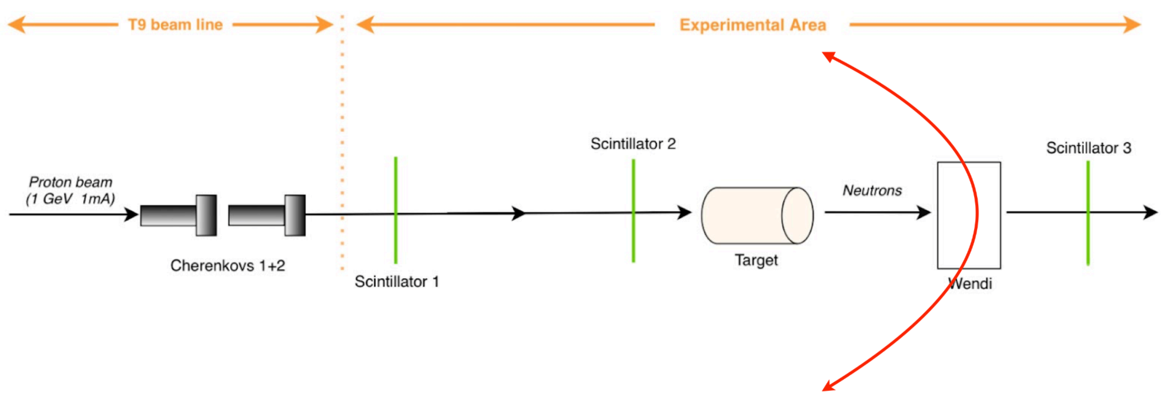
	according to SRIM (from [1])	according to [2]	according to NIST's PSTAR program
Tungsten (W)	30.705	26.35	31.27
Lead (Pb)	53.741	45.85	54.77
Copper (Cu)	53.204	50.64	53.09

It is also worth mentioning why 1 GeV, positive proton beam was selected for our experiment. We chose a 1 GeV positive proton beam because it is commonly used in spallation research, including the study we referenced for optimal dimensions. This facilitates direct comparison with existing data and ensures our experiment aligns with current scientific standards.

Secondly; as proton energy increases, the neutron yield also increases as well, but so does the proton range in matter. This allows us to create targets that are thick enough to make use of most of the beam's energy, while still keeping the target size and material cost practical.

Finally, it gives us the opportunity to tag protons using the time-of-flight (ToF) method, otherwise we would need to rely on Cherenkovs which we are not sure if they go high enough pressures.

Experimental Setup



In this experimental setup, we aim to fill one Cherenkov detector to high enough pressures for tagging e^+,μ^+, π^+ and other Cherenkov detector to e^+,μ^+, π^+ and K^+. This would allow us to conclude the remaining particles are protons. If Cherenkovs cannot get high enough pressure values, by measuring the time it takes for protons to travel from Scintillator 1 to Scintillator 2 (given they have around 8m distance between them) using time-to-digital converters (TDC), we aim to tag protons in our analysis for filtering of the data.

When the proton beam reaches the target, the interaction between the protons and the target material induces spallation reactions, resulting in the emission of secondary neutrons. The generated integrated neutron flux rate is monitored using a WENDI detector. We tried to access the simulation codes for WENDI by reaching out to the relevant authorities via email, but unfortunately we didn't get a response. We aim to move WENDI along the red arrow to cover $\pm 90°$ with respect to the direction of the beam with a small radius to have high solid angle coverage. We plan to divide the day into five time zones, during which WENDI will be placed at five different positions spending the most time at the center since we have the most neutron production around there.

We have included the final scintillator in order to count how the particle number changed after interacting with the target and WENDI, and for capturing all the information available at the experimental zone.

Predictions based on Geant4

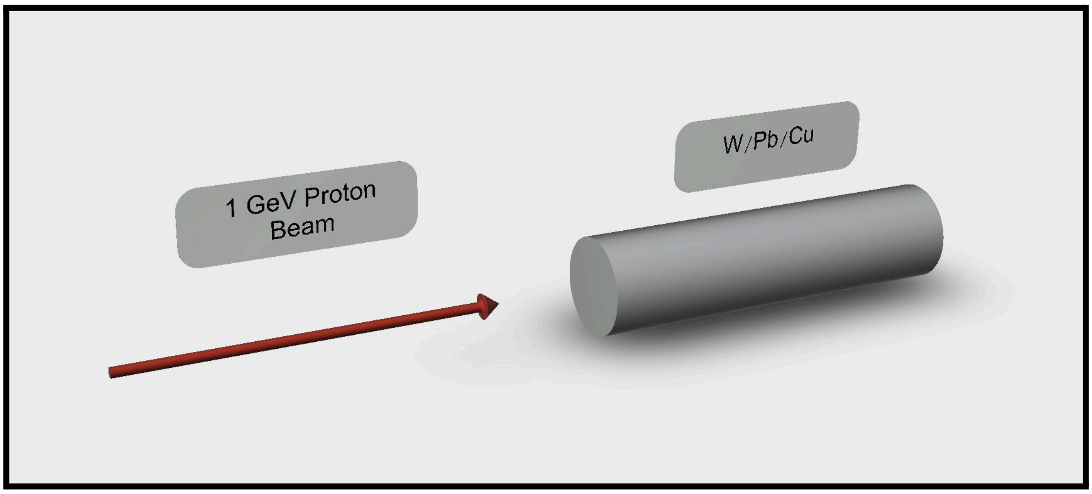
Using Geant4, we simulated a 1 GeV proton beam consisting of 1000 protons interacting with cylindrical targets of Tungsten, Lead and Copper. Our code can be found at [3]. The data we obtained through Geant4 is categorized into two parts: the number of neutrons at each angle and the number of neutrons at each energy level. The energy distribution shows us that the generated neutrons can be detected by WENDI.

In two different experimental setups, the target materials are divided into **G4_W**, **G4_Pb and G4_Cu**. In order to compare different geometric dimensions, we performed five distinct experiments. Due to computation limits, we have restricted our studies to a little bit of low statistics, but we are aware the yields we've obtained are restricted by poisson error. We aim to make detailed simulations with high statistics before conducting the experiments.. The results, corresponding graphs and detailed simulation are presented below:

Table 2.1: Total Number of Neutrons Generated in Different Experiments, based on Geant4 Simulations using 1 GeV proton beam of 1000 protons.

Material	**Dimensions (cm^2)**	**Total Number of Neutrons Generated**
Tungsten	15x60	8673
Tungsten	15x30	6723
Lead	15x60	9457
Lead	15x50	9578
Copper	15x60	3815

Figure 1.1: Detailed Simulation Photo (Both Earth scale and atomic scale):



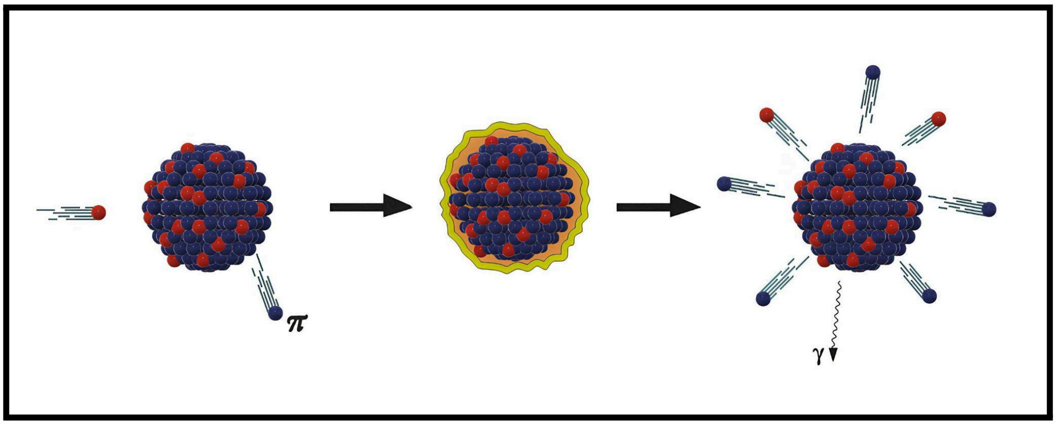


Figure 2.1: A histogram showing the number of neutrons at each energy level resulting from all the experiments.

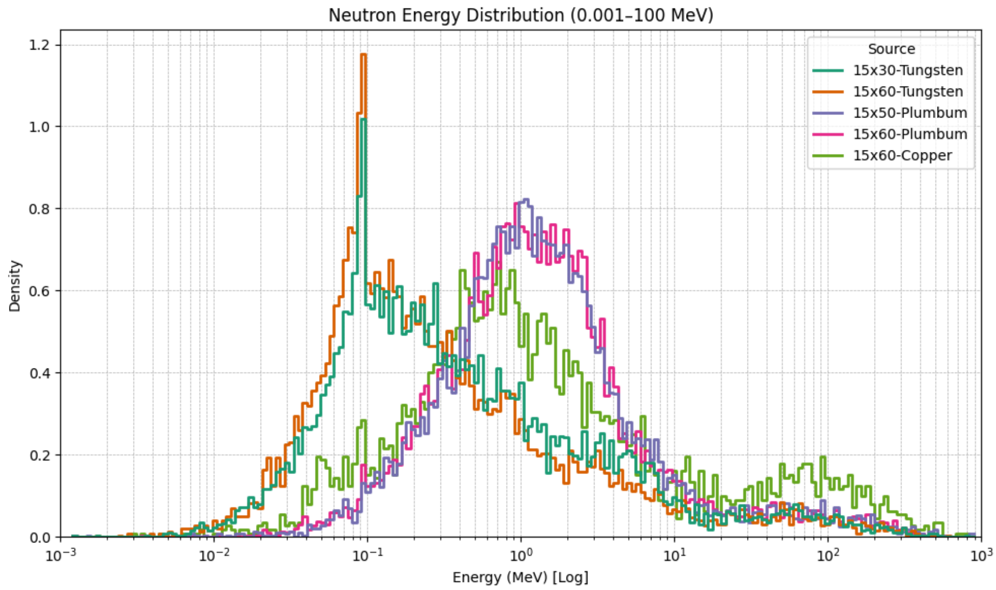


Figure 2.2: A graph showing the number of neutrons emitted at each angle for 15x60 cm^2 tungsten. (Total Neutrons: 8673)

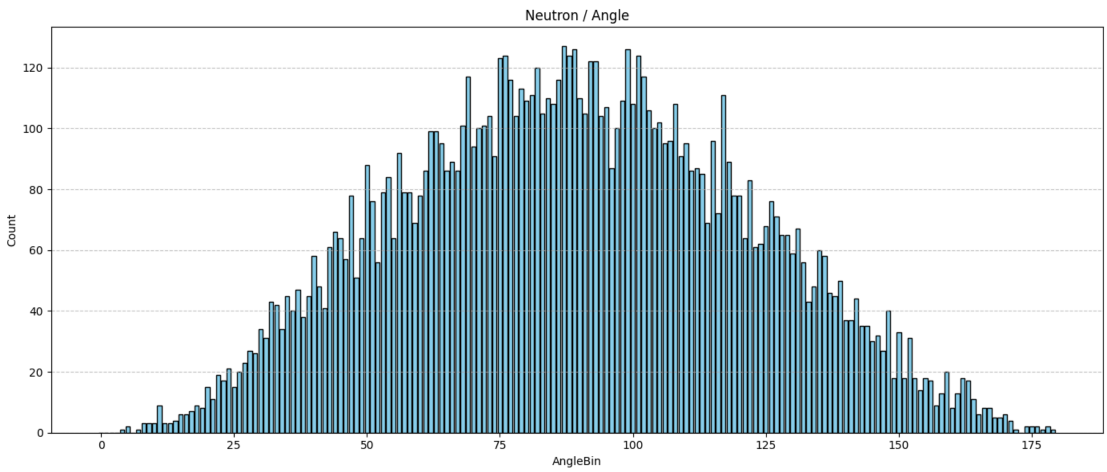


Figure 2.3: A graph showing the number of neutrons emitted at each angle for 15x 30 cm^2 tungsten.(Total Neutrons: 6723)

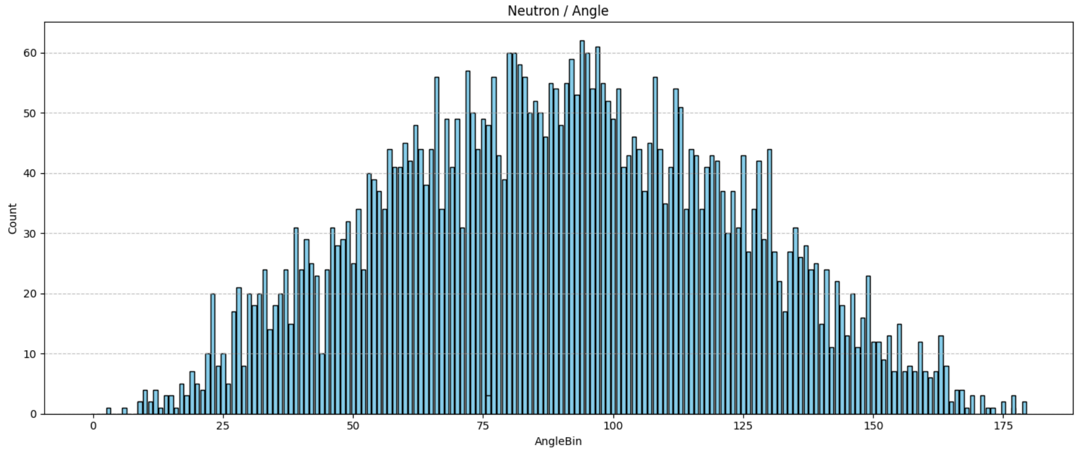


Figure 2.4: A graph showing the number of neutrons emitted at each angle for 15 x 60 cm^2 lead. (Total Neutrons: 9457)

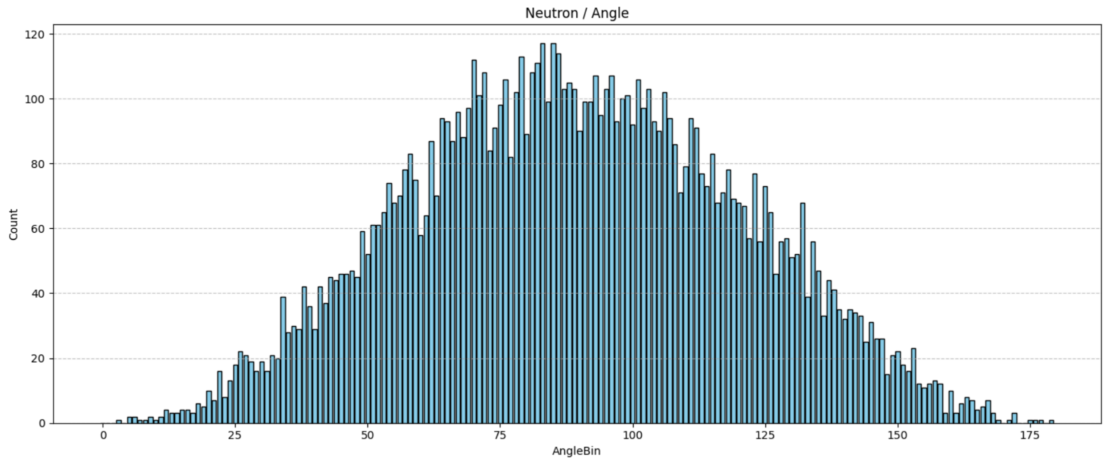


Figure 2.5: A graph showing the number of neutrons emitted at each angle for 15 x 50 cm^2 lead. (Total Neutrons: 9578)

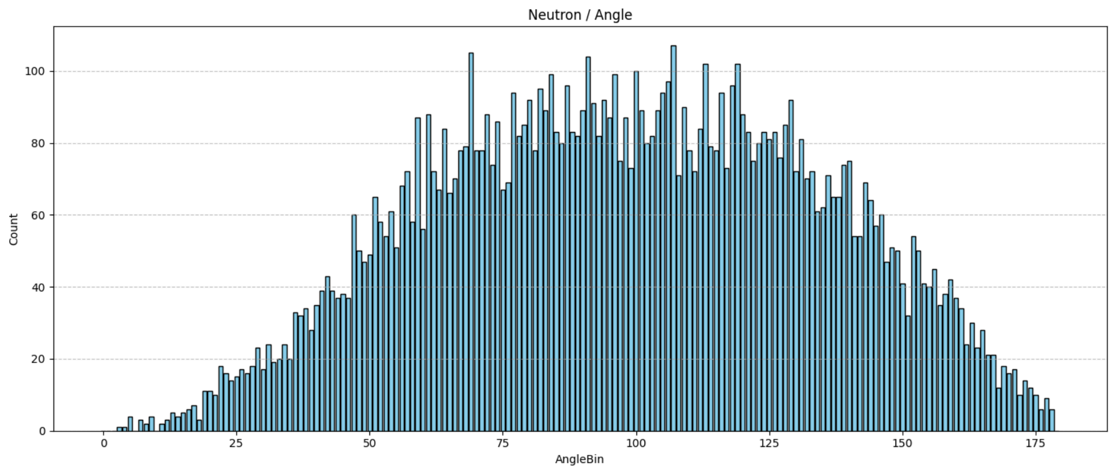
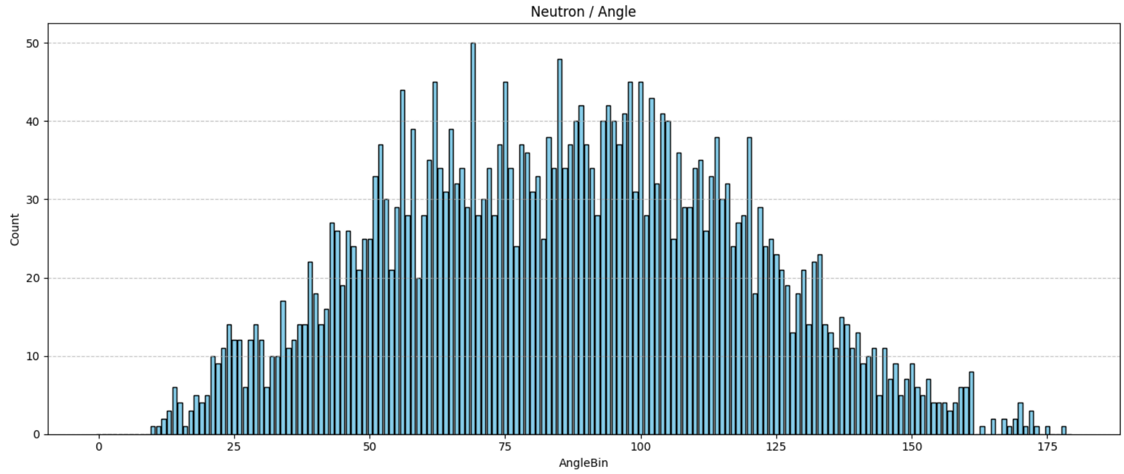


Figure 2.6: A graph showing the number of neutrons emitted at each angle for 15x60 cm^2 Copper. (Total Neutrons: 3815)



Schedule

day 1	installation
day 2	calibration of the detectors
day 3	calibration of the detectors
day 4	tungsten measurements at 1 GeV at 15 cm x 60 cm
day 5	tungsten measurements at 1 GeV at 15 cm x 60 cm
day 6	tungsten measurements at 1 GeV at 15 cm x 30 cm & analysis of the data
day 7	tungsten measurements at 1 GeV at 15 cm x 30 cm
day 8	lead measurements at 1 GeV at 15 cm x 60 cm & analysis of the data
day 9	lead measurements at 1 GeV at 15 cm x 60 cm & analysis of the data
day 10	lead measurements at 1 GeV at 15 cm x 50 cm & analysis of the data
day 11	lead measurements at 1 GeV at 15 cm x 50 cm & analysis of the data
day 12	copper measurements at 1 GeV at 15 cm x 60 cm & analysis of the data
day 13	copper measurements at 1 GeV at 15 cm x 60 cm & analysis of the data
day 14	comparison of all results among different materials and different thickness & deinstallation of the area

Why we want to go

As Cağaloğlu Anatolian High School Physics Club students, we are eager to deepen our understanding of particle physics through real experimental work. While we always work towards solid theoretical background, we believe that direct experience at CERN would offer invaluable and unique growth beyond the classroom.

The BL4S competition represents a rare chance for us to carry out a real particle physics experiment under the guidance of experienced researchers at CERN. In our project, we aim to explore how neutron production is influenced by the type of material they strike and its thickness. These insights could contribute to areas such as radiation shielding and neutron source design. We aim to find the most efficient way to neutralize radioactive waste using nuclear spallation, a method that has been gaining attention in recent times. Given that the need for energy grows every year and energy production inevitably comes with various costs, we aim to find methods that are least harmful to our green-blue planet one day. Winning this competition would make us closer to our target.

Outreach

To promote science, we launched an educational website about exoplanets and shared it with primary school children across Turkey. The site features 3D models and detailed information on nearly 20 exoplanets, along with simulations of hypothetical surfaces of 2 exoplanets. An interactive section lets users create their own constellations based on the night sky as seen from Proxima Centauri b. This feature sparked children's imagination, allowing them to explore what it might be like to stand on an exoplanet and name constellations in an alien sky.

You can access the photos of the activity from the link below:
OUTREACH BL4S PHYSICAL 2025

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References

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