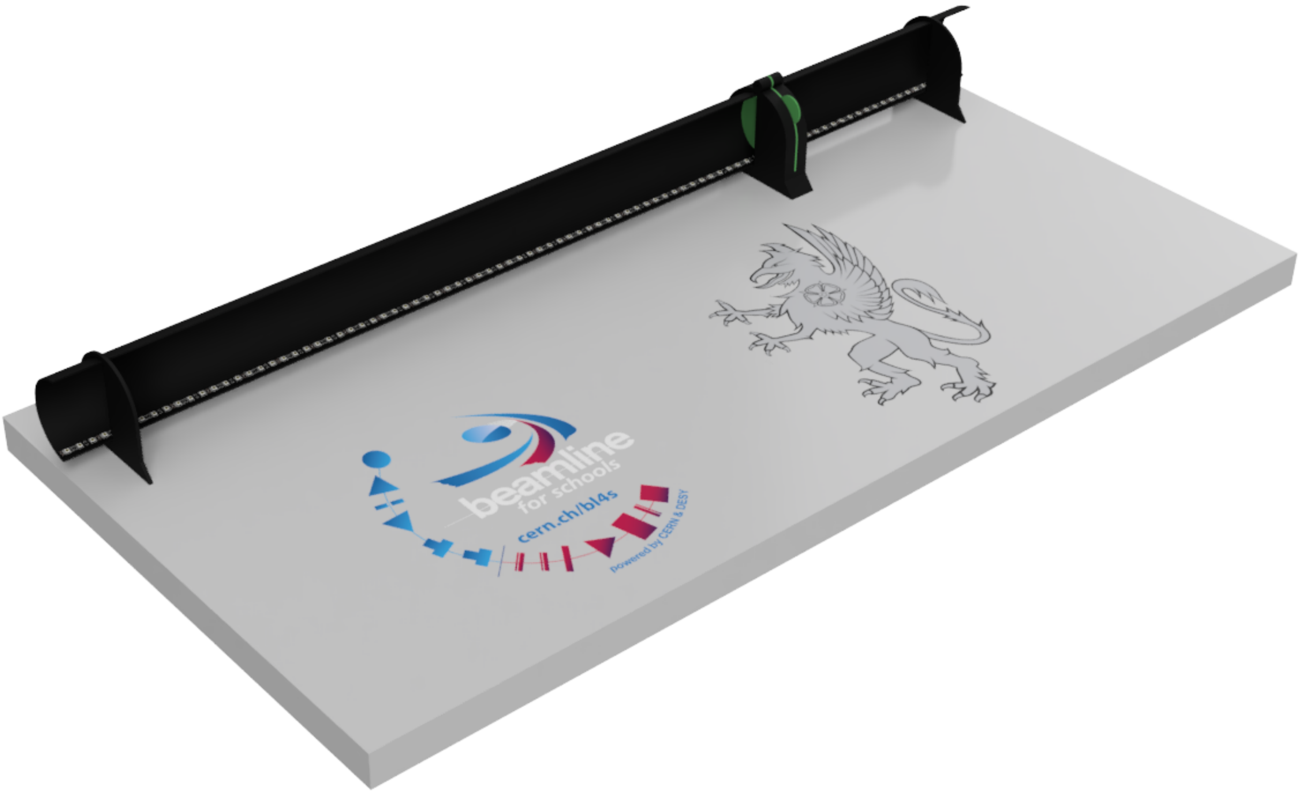
Moderately Good - Examining the qualities of a new Moderating Material



Abingdon School -
James Gibson, Euan Baldwin, Ashwin Tennant, Jasper Trilk, Benjamin Broadbent, Scott Yap, Freddie Nicholson

Proposal

A chromium-nickel-tungsten alloy is to be tested for its qualities as a moderator with high energy positrons, these being the positron work function and the efficiency of moderation.

Why do we want to come to DESY, and what will we take away?

We, a team of A level students from the UK, are seriously interested in physics. Together, we have had the opportunity to visit some of the most incredible science experiments of the 21st Century, including CERN, the Diamond Light Source and the Swiss Plasma Center. Seeing all this physics in action has inspired us to want to do an experiment of our own, and the chance to do this experiment at the DESY II Synchrotron was too exciting to miss. By coming to DESY, we also wish to establish a legacy at our school for increased scientific interest, and we hope that future years may also want to participate in this fantastic experience.

The Experiment

Introduction to moderation

Positrons beams are useful in many areas of science and medicine and can be produced in several ways. Positrons emitted from a decay source are fast and have a broad distribution of energies. Positron moderators are often needed to create a beam of uniform velocity and low energy, equal to the materials positron work function, which is useful in several applications, such as analysing materials by positron refraction or reflection. This is an area of current research, and progress in the field is being made regularly.

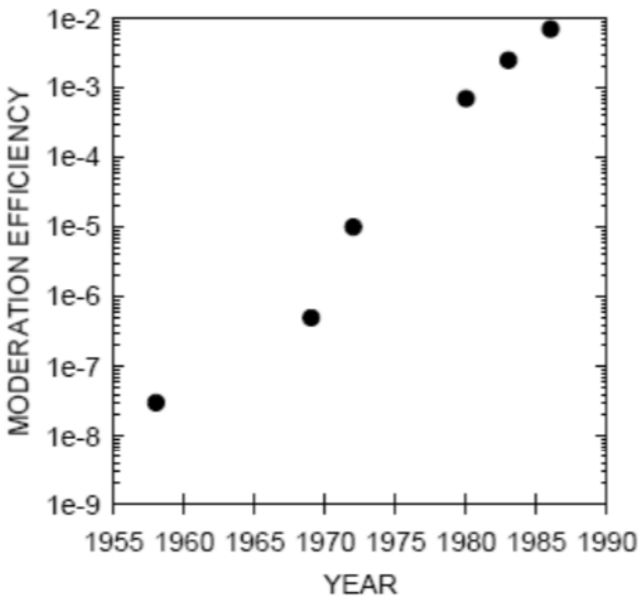


Figure 1 Growth in measured positron efficiencies since 1958 (Hugenschmidt, 2016)

Theoretical Background

Moderation is achieved by a positron being absorbed into a material and losing its energy through Bremsstrahlung radiation when in the higher energy range and ionisation and excitation of electrons at lower energies. This results in the positrons being thermalised, which means they have reached equilibrium with the metal surrounding them. Then the positron can diffuse to the surface, where it is ejected perpendicular to the foil's surface.

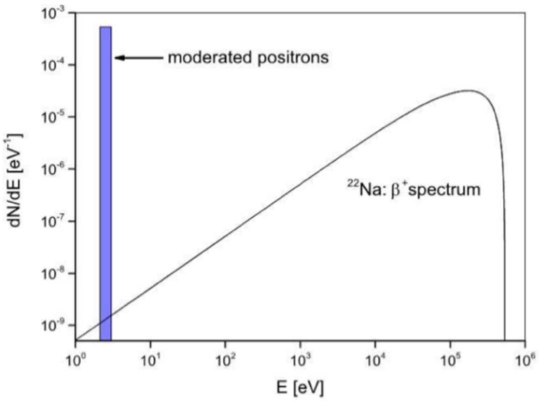


Figure 2 The intensity of positrons at different velocities from a Na-22 source after moderation

The work function is the sum of two terms: the chemical potential, and the surface dipole potential (Tong, 1971).

$$\Phi^p = \Delta\phi^p - \mu^p$$

As the positron has the opposite charge as the electron, the surface dipole (ϕ) has the reverse effect on positrons as it does on electrons. Therefore, it tends to decrease the positron work function. If ϕ is large enough to overcome the chemical potential, the work function can be negative. This is a mathematical manifestation of the fact the positron ground state lies higher in energy than the vacuum level. Thus, positrons may be spontaneously reemitted from the metal.

Efficiency

Low efficiency is caused by the fact that things other than absorption and remission can happen when the positron strikes the target, for a Tungsten target $\epsilon_m \sim 10^{-4}$. The moderation process is rapid and takes only around 10^{-12}s for the positron to be slowed to thermal energies. This leaves very little time for the positron to interact with electrons and annihilate. However, once thermalised, the positron is likely to annihilate with an electron before reaching the metal's surface.

If they reach the surface before annihilating, there are still different possible outcomes. These include desorption as a positronium atom or direct re-emission of a moderated positron beam.

Another potential outcome is that some positrons may pass through without being thermalised, further decreasing the moderator's efficiency. This means that the foil thickness must be optimised to achieve the highest efficiency.

Deciding on an alloy

Metals that can moderate positrons can do so because they have a negative positron work function. This work function's value has been calculated for most pure elements, but no data exists for alloys, which is what we aim to find. Using the list of metals (Au, Al, Cr, Cu, Ni, Pt, Ta and W) with a negative positron work function, the alloys of these were then researched to see which of them were suitable to be made into foils. Certain alloys weren't possible, and some of the alloys didn't have appropriate physical properties (e.g., malleability) to be made into targets. Research led to an alloy of three metals on this list: a chromium-nickel-tungsten alloy in the ratio of 75:20:5.

$$\Phi^p \simeq \Delta\varphi^e - \mu_c^p + O\left(\frac{N_p}{N}\right)$$

$N_p = Number\ of\ positrons$
$N = Number\ of\ electrons$
$\Delta\varphi^e = The\ electrostatic\ potential\ across\ the\ metal\ surface\ due\ to\ the\ double\ layer\ taken\ from\ the\ electron\ work - function\ calculation$
$\mu_c^p = The\ correlation\ contribution\ to\ the\ positron\ chemical\ potential\ at\ the\ mean\ electrostatic\ potential$

Method

Due to the moderating process's low efficiency, high-intensity positrons of 2 GeV will be used, allowing for the best moderation data to be obtained. The Cr-Ni-W moderator can be obtained as a thin foil and then layered to reach the optimum thickness for moderation. If more precise thickness control is needed, the foil can be placed at an angle to the incident beam.

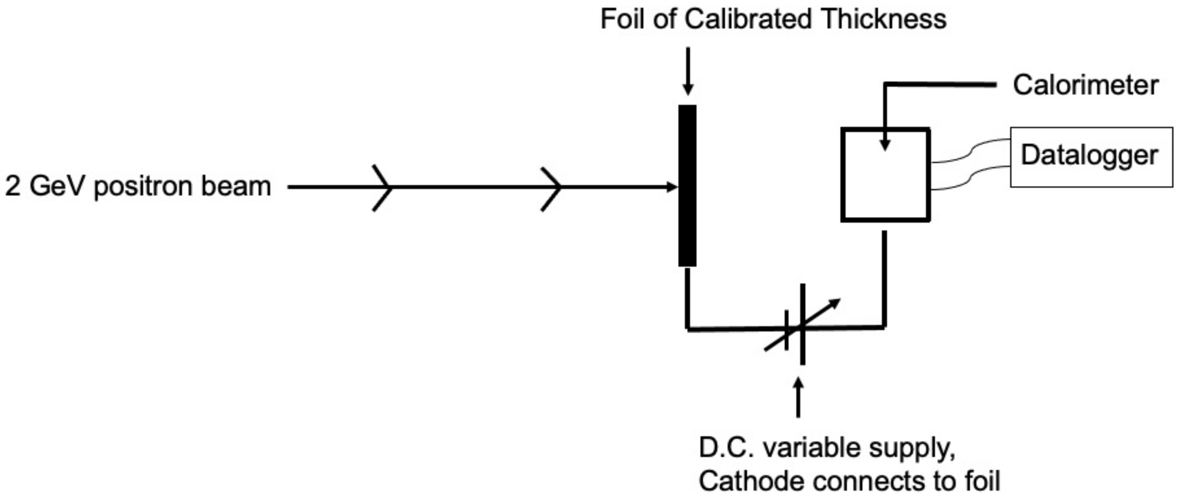


Figure 3 Proposed set-up of the experiment

A calorimeter will detect the positrons being emitted from the back of the foil. However, the calorimeter's energy resolution limits the calorimeter's ability to distinguish between moderated positrons and low energy unmoderated positrons. This is because the energy released by the positron annihilation is significantly greater than the kinetic energy of a moderated positron, providing too much background noise for effective calorimetry.

Calculating the positrons' kinetic energy (and hence the alloy's positron work function) and the moderator's efficiency will be done by establishing a potential difference between the moderator and the detector. When the potential difference is raised such that the positron's kinetic energy is not sufficient to overcome the repulsion of the detector, there will be a fall in the number of positrons detected. This stopping potential is equal to the positron work function.

$$\boldsymbol{\beta_k^+ = -eV}$$

$\beta_k^+ = The\ kinetic\ energy\ of\ the\ positron$
$e = The\ charge\ on\ an\ electron$
$V = Potential\ difference$

The number of positrons blocked by the potential difference will be equal to the number of moderated positrons. By dividing the number of positrons from the beam by the number moderated, the efficiency is found.

$$\epsilon_m = \frac{N_{mp}}{N_{\beta^+}}$$

$\epsilon_m = The\ efficiency\ of\ the\ moderator$
$N_{mp} = Number\ of\ moderated\ positrons$
$N_{\beta^+} = Number\ of\ incident\ positrons$

Bibliography

Amarendra, G., 2021. *Positronannihilation.net.* [Online]
Available at: http://www.positronannihilation.net/index.htm
[Accessed 11 February 2021].

Gidley, D. W., 2021. *Nanopos - Positron physics.* [Online]
Available at: http://positrons.physics.lsa.umich.edu/home.html
[Accessed 18 March 2021].

Hugenschmidt, C., 2016. Positrons in surface physics. *Surface Science Reports,* 71(4), pp. 547-594.

Mills, A. & Wilson, R. A., 1982. Transmission of 1 - 6-keV positrons through thin metal films. *Physical Review A,* Volume 26, pp. 490-500.

Taqqu, D., 1990. High efficiency positron moderation. *Helvetica Physica Acta,* 63(4), pp. 442-447.

Tong, B. Y., 1971. Negative Work Function of Thermal Positrons in Metals. *American Physical Society,* 5(4), pp. 1436-1439.

Williams, A. I. et al., 2015. Moderation and diffusion of positrons in tungsten meshes and foils. *Journal of Applied Physics,* 118(10).