REVIEW OF LOW-ENERGY POSITRON BEAM FACILITIES

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Abstract

Positrons are produced by processes such as positive beta decay from radioactive isotopes, in nuclear reactor cores from both in-situ radioisotope radiation and pair production, and by accelerator driven beams hitting a converter target. The purpose of this paper is to review some of the prominent existing low-energy e^+ facilities.

INTRODUCTION

For decades, positron based physics and its applications have attracted researchers with very different backgrounds from nuclear physics to space science. In addition to their usage for years in high-energy physics, e^+ beams have been used in low-energy physics such as the study of solid surfaces, defect profiling, exotic element research with Positronium, and in medical physics. In this paper, we briefly evaluate some of the existing low-energy e^+ source facilities with regarding to production methods, beam characteristics, and transport. The review is divided into three categories, isotope-based, reactor-based, and accelerator-based e^+ facilities. However the emphasis and details are given on reactor-based and accelerator-based facilities.

ISOTOPE SOURCES

There are numerous small laboratories around the world using e^+ for solid state and atomic physics research, where they usually operate by using small radioactive sources such as ^{22}Na and ^{64}Cu.

The most common isotope used for e^+ physics is ^{22}Na due to its low cost, availability, high yield, and lifetime. The half-life of ^{22}Na is 2.6 years, which is much longer than that of most other e^+ isotope emitters. Another advantage of ^{22}Na is its high Branching Ratio (BR) of 90.4%, whereas the BR of ^{64}Cu is only 17.4%. In the β_+ decay process, in which a proton is converted to a neutron in the nuclei, a positron, a neutrino, and a nuclear photon are released. The release of the γ (1.274 MeV) simultaneously with the e^+ allows lifetime measurements in Positron Annihilation Lifetime Spectroscopy (PALS). The energy spectrum of the beta particles emitted from ^{22}Na is very wide up to 600 keV. We review here two facilities that use ^{22}Na as their e^+ source.

Radioisotope Based e^+ Source at UCSD (US)

At the University of California, San Diego (UCSD), e^+ source is a 50 mCi ^{22}Na sealed source, which is about 3 mm in diameter. The efficiency is about 30% with e^+ flux $\sim 5\times10^8$ e^+/s in the forward $2\,\pi$ radians. With a solid neon moderator $\sim$ 6 - 9 x 10^6 slow e^+ per second in a 100 gauss field with a beam diameter of 1.0 - 1.2 cm are obtained. Energy spread of the slow e^+ is $\sim$ 1.9 eV (FWHM).

The UCSD group has developed a multi-staged buffer gas trap method in order to accumulate large numbers of e^+ allowing them to reach high instantaneous currents [1]. With recent improvements, in a Penning-Malmberg trap 10^{15} e^+ can be stored [2]. This allows them to use high-intensity bursts of e^+ in atomic physics experiments.

Radioisotope Based e^+ Source at UCR (US)

At the University of California, Riverside, a e^+ source from a 25 mCi ^{22}Na has been used, where the e^+ are moderated with a solid neon moderator to generate a slow e^+ beam. Moderators are usually grown at a temperature of 7 K with ultra-pure 99.999% neon in 7 minutes. Beam intensities obtained after moderation are greater than 6×10^6 slow e^+/s. The UCR group also uses a trapping device to create intense pulses of low energy e^+; where 6x10^7 e^+ are compressed to a width of 1 ns. This translates to an average e^+ current of 10 mA during the pulse [3].

REACTOR CORE BASED SOURCES

There are only a few nuclear reactor-based e^+ sources, which create e^+ by pair production from γ both through neutron activation and directly from the core. The slow e^+ intensity of the source depends on the power of the core, converter material, and moderator geometry.

Reactor Core Based e^+ Source at PULSTAR (US)

PULSTAR is a 1-MW reactor source located at North Carolina State University. Main user interests are in neutron diffraction, ultra-cold neutron studies, and intense e^+ beams. Positrons are created from a converter-moderator assembly surrounded by a cadmium blocks located adjacent to the 1 MW PULSTAR core [4]. At the source, e^+ are created both by the γ rays emitted from the core and also with neutron capture in the cadmium, where γ are released as a result of this interaction.. The Cd reaction is as in the following, where a total of 9 MeV γ is released as a result [5]:

$$^{113}Cd + n \;\rightarrow\; ^{114}Cd + \gamma(9\ MeV) \qquad (1)$$

The tungsten target is as close as 30 cm to the core. The PULSTAR reactor beam currently uses two tungsten arrays as e^+ converters and moderators. Each array is 22 cm in diameter and 2.5 cm in length. An array is comprised of interlocking tungsten strips with each 250 μm thick. The moderator is integrated to this assembly. After calibration with a Na-24 source, it is estimated that 5×10^8 slow e+/s

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are created, which is in agreement with their simulation results [6].

Reactor Core Based e^+ Source at NEPOMUC (Germany)

The in-pile e^+ source **NE**utron induced **PO**sitron source **MU**ni**C**h (NEPOMUC) [7] is a 20 MW reactor-based facility. Positrons are generated by pair production of high energy γ rays from neutron capture in cadmium: ^{113}Cd (n,γ)^{114}Cd. Inside the Cd cap, a structure of Pt and a stack of W foils are placed for converting the γ rays into e^+-e^- pairs. Pt is used as converting material due to is higher e^+-e^- cross-section than W.

Inside the Cd cap, the mean γ-flux with energy greater than 1.022 MeV is expected to be 4.1x10^{13} γ/cm^2/s. About 15% of the γ-radiation of 6.2x10^{12} γ/cm^2/s originates from the core and d(n,γ)t reaction in the surrounding heavy water. The e^+-e^- conversion and moderation of fast e^+ is illustrated in Fig. 1.

The maximum of the energy spectrum of the e^+ produced is about 800 keV. The tungsten foils also act as a moderator assembly. The e^+ are accelerated by electric lenses and guided by magnetic fields. The beam diameter is less than 18 mm (FWHM) in a magnetic guiding field of 6 mT [7]. The measured yield is close to 10^9 moderated e^+/s with an energy of 1 keV [8].

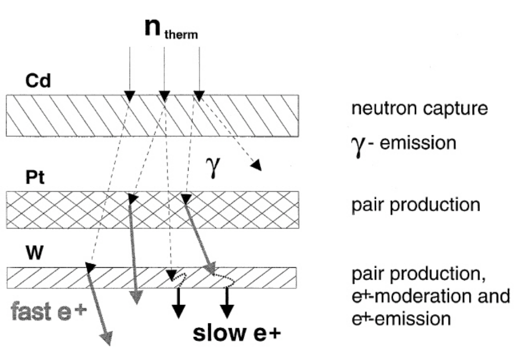

Figure 1: Mechanism of e^+ creation at NEPOMUC [9].

Reactor Core Based e^+ Source at POSH (Netherlands)

The intense slow e^+ beam (POSH) at the Delft Research Reactor (Delft, Netherlands) is a 2 MW reactor based e^+ facility [10]. Fast e^+ are produced by pair production from gamma radiation close to the reactor cores. Following their creation, these fast e^+ are immediately sent onto a tungsten moderator. Successful results have been obtained with the construction of a stable high intensity reactor-based source close to 10^8 slow e^+/s [11].

ACCELERATOR-BASED SOURCES

Accelerator-based positron sources can produce the highest e^+ intensity as well as a variable time structure when compared to isotope-based and reactor-based sources. Due to the complexity and cost, there are only a few accelerator-based facilities for low-energy e^+ production. Positrons are created inside a converter target via γ conversion into e^+-e^- pairs. Electron beam from a linac is the typical driving beam to produce bremsstrahlung γ. There are also other methods e^+ production involving accelerators, such as using a Van der Graaf generator to accelerate p or d up to 4 MeV [12]. Accelerated d beam hits a graphite target creating a e^+ emitter via ^{12}C (d,n)^{13}N reaction. An important issue with accelerator-based sources is dealing with the dissipated power in the converter.

Accelerator Beam Driven e^+ Source at EPOS (Germany)

ELBE Positron Source (EPOS), is mono-energetic e^+ beam (0.2 - 40 keV) built for materials research [13]. Positrons are created via pair production at a W target using the 40 MeV e^- beam of the ELBE Super-Conducting (SC) e^- linac.

The primary e^- beam parameters at ELBE are, bunch structure 77 ns repetition time (or 13 MHz) of 5 ps bunches and beam energy 40 MeV with 1 mA current [14]. Owing to the SC linac technology, the time structure of the e^- bunches can be as short as 2 ps with a 26 MHz repetition rate and can be operated in CW mode.

The e^- beam has a diameter of 5 mm when entering the converter area. The beam passes next to a stainless steel window (0.3 mm), then 0.1 mm of water, followed by a stack of 50 tungsten foils, in which each has a thickness of 100 μm. The tungsten foils are separated by 100 μm slits, through which the cooling water runs. The simulated fast e^+ integrated yield per second is $\sim 5 \times 10^{13}$. The moderator, which is made of W, is positioned close to the converter. The projected slow e^+ intensity after moderation is about $5{\times}10^8 - 10^9$ e^+/s. The converter target is a directly water cooled tungsten target, which the calculated power deposition from the incoming e^- beam is about 14 kW. The e^- beam dump is water-cooled Al.

Accelerator Beam Driven e^+ Source at AIST (Japan)

Advanced Industrial Science and Technology (AIST) is an e^- accelerator-based slow e^+ facility, which is located in Tsukuba, Japan. The e^+ beam is mainly used for material science experiments to evaluate atomic scale defects in various materials. These types of laboratories usually obtain e^+ beams on the order of mm in transverse size, but AIST by using brightness enhancement method.

The e^+ are created by pair production by bremsstrahlung γ, in which an e^- beam with an energy of 70 MeV (1 μs pulse with 3 μA average current - 100 Hz) from a

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linac hits a Ta converter target. The average deposited power in the convertor is about 200 W. After fast e^+ (keV-MeV range) are produced, they are immediately moderated through tungsten films (25 μm) and are re-emitted as slow e^+ into the vacuum. The converter and moderator target mechanism is illustrated in Fig. 2. These slow e^+ are transported from the e^+ source to the experimental room by a magnetic transport system which is about 20 m long in order to reduce the background radiation. The magnetic field strength is about 7 mT in this transport system. The slow e^+ beam energy is about 10 eV and the diameter of the beam at this location is more than 10 mm. The measured beam intensity is about 2-3$\times 10^7$ e^+/s.

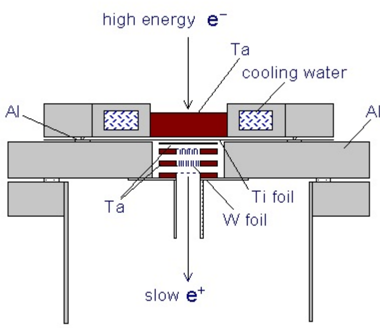

Figure 2: AIST slow e^+ creation target system is illustrated, where the pair creation of e^+ and moderation occurs consecutively [15].

Brightness enhancement method is used to reduce the beam spot size substantially at the expense of losing beam intensity. The beam is extracted from the magnetic field before it reaches the experimental room. The extracted beam is focused by a lens on a re-moderator to enhance its brightness. The re-moderator is a 200 nm thick single-crystal W. After re-moderation, the spot size at the sample is measured $\sim$ 30-100 μm [16]. The efficiency of the transmission in re-moderator is about 5%, which reduces the intensity to $\sim 10^6$ e^+/s [17].

SUMMARY AND CONCLUSION

We have reviewed some of the existing low-energy isotope based, reactor-based, and accelerator beam based e^+ facilities. The essential parts of e^+ production, capture and transport systems are briefly discussed. It is worth noting that, due to the complexity of the measurement process, none of the facilities has directly measured the fast e^+ (MeV range) coming out of the converter. The simulations are taken as a basis for designing the beamline. The slow e^+ efficiency after moderation is measured as it is much easier to measure.

To date, the highest intensities of slow e^+ are reported in two reactor-based e^+ sources close to 10^9 slow e^+/s as provided in NEPOMUC and PULSTAR sources. Linac-based facility, EPOS, is also projected to reach 10^9 slow e^+/s when fully operational. With a Na-22 isotope source, estimating $\sim$ \$800/mCi [18] , it would cost about \$8M to reach these intensities. Only intense bursts of slow e^+ can be produced with trap-based beams.

The primary characteristics of the reactor-based and accelerator-based sources are that the W (or other metal) moderator is integrated to the converter assembly or in the close proximity of it. The advantage is that it is possible to interact with a much larger portion of the emitted e^+ from the converter, but the low moderation efficiency ($\sim 5\times10^{-4} - 10^{-3}$) offsets this advantage. Delicate high-efficiency cryogenic Rare-Gas Moderators (RGM) cannot be located close to the converter because of the high-radiation emitted from the converter and surroundings. If large numbers of e^+ can be transported from the high-radiation area, then RGM with efficiencies as high as $\sim 10^{-2}$ can be used. With a super-conducting CW linac, it is possible to produce CW e^+ with intensities on the order of 10^{10} slow e^+/s. There are few operational CW linacs with SC technology, such as Free Electron Laser (FEL) at Jefferson Lab. With modest modification, FEL can be a home for a high-intensity slow e^+ facility [19]. High-intensity e^+ beams will open new research opportunities that are not possible with currently available intensities [20, 21].

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