The New Energy Material with Great Potential Positron

Yixiong Wang*, Jinxi Li, Wenbing Wang, Peng Chen
State Key Laboratory of Intense Pulsed Irradiation Simulation and Effect, Northwest Institute of Nuclear Technology, Xi’an 710024, China

*Corresponding author: yixiong_wangw3694@foxmail.com

Abstract. Positron has attracted much attention in particle research for it was the first antiparticle discovered. Due to its extreme instability, positron is easy to annihilate with electron and release photons or form unstable positronium. Positron releases 1000 times more energy than nuclear fission of the same mass with no radioactive substance. As a new energy source, positron has more potential than other energy sources. With the rapid development of technology, the problem of how-to storage positron is solved gradually which makes a good foundation for annihilation of positron and electron beams. In this paper, the energy released by collision between electron and positron beams is deduced by theoretical analysis, based on the latest experimental results. The positron beam is the same energy of 10 MeV as the electron beam, which is adopt. After the pulses cross each other, the energy released is closed to 15mJ with current intensity $10^{10}$e$^+$/s. The energy difference of different radius of pulses is studied. This work has great potential value in further research.

Keywords: Positron, Annihilation, New energy, Theoretical analysis.

1. Introduction
Dirac predicted positron and it was found in cloud chamber by Anderson in 1932[1], which caused extensive concern in the science field. As the first antiparticle discovered by people, positron was researched to reveal the mystery of antimatter. Positron is extremely unstable and tend to annihilate with electron or forms positronium. By analyzing the spectrum, it is possible to get hidden information about structure of material due to the characteristic γ-ray released in the annihilation. Its unique nondestructive detection and accuracy are different from the traditional detection methods, thus forming an important means in material detection, Positron Annihilation Spectroscopy. Nowadays, Positron Annihilation Spectroscopy has become an important research tool in the field of material microstructure [2]. At the same time, electron-positron plasma exists widely in the early universe, such as the solar atmosphere, the galactic center and so on. The study of electron-positron pair is beneficial to reveal the changes of the space environment and study the mysteries of the universe under laboratory conditions. When a huge star collapses, the charge separation field caused by special environment exceeds the limit of Swinger [3], which will lead to the generation of electron-positron plasmas. In the process of photons released by annihilation of positron and electron, mass is converted into energy completely and the annihilation products are not radioactive. Positron has the highest energy density by far, up to $10^{17}$J/kg [4], which will provide ideas for the development of small optical maser. What’s more, positron is expected to be...
used in interstellar travel for spaceship. The efficient acceleration of positron in the Penning Trap has made some experiments possible. Some research group obtained positron beams with energy of 10MeV, and the current intensity reached $10^{20} \text{e}^+ / s$ by using optical maser in SJTU. The annual production of positron can be obtained in milligrams under the condition of enough experimental time.

| Matter                        | Energy density J / kg |
|-------------------------------|-----------------------|
| TNT                           | $4.7 \times 10^6$     |
| Nuclear Fission (100%)         | $7.1 \times 10^{13}$  |
| Nuclear Fusion (100%)          | $7.5 \times 10^{14}$  |
| Positron                      | $1.8 \times 10^{17}$  |

2. Positron Generation

2.1. Conventional positron source

Conventional positron source is that radioactive isotope will release positrons because of the $\beta^+$ decay, such as $^{22}\text{Na}$, $^{64}\text{Cu}$ and so on. The resulting positron beam intensity is not more than $10^6 \text{e}^+ / s$ generally.

\[ ^{22}\text{Na} \rightarrow ^{22}\text{Ne} + e^+ + \gamma (1.28\text{MeV}) \]

However, the positron energy spectrum generated by $\beta^+$ decay is diverging, which is not conducive to practical operation and application. Therefore, it is necessary to use moderator to slow the positron energy to a certain energy range, which is convenient for collection.

For isotopes that could happen $\beta^+$ decay have a short half-life period, it is difficult to realize positron collection and acceleration. The half-life period of some proton-rich nuclides and positron energy are listed in table 2. With the rapid development of laser technology, people can get high charge and high energy positron beam through the interaction between laser and target, which is the advanced technology to get positron.

| Isotope  | $\beta^+$ Branching Ratio | Energy (MeV) | Half-life Period | Generating Mechanism |
|----------|---------------------------|--------------|------------------|----------------------|
| $^{22}\text{Na}$ | 0.89                      | 0.545        | 2.6y             | $^{24}\text{Mg}(d,\alpha)$ |
| $^{58}\text{Co}$ | 0.15                      | 0.474        | 71d              | $^{58}\text{Ni}(n,p)$ |
| $^{68}\text{Ge}$ | 0.86                      | 1.89         | 275d             | $^{66}\text{Zn}(\alpha,2\alpha)$ |
| $^{64}\text{Cu}$ | 0.19                      | 0.653        | 12.6h            | $^{63}\text{Cu}(n,\gamma)$ |
| $^{11}\text{C}$  | 0.99                      | 0.96         | 20.3m            | $^{11}\text{B}(p,n)$ |

2.2. Laser positron source

After a series of theoretical analysis and experimental verifications, the positron generation mechanisms from the collision between laser and target can be divided into three types: Trident process, BH process and BW process [6, 7].

Trident process means high-energy electrons obtained by laser acceleration interact with the nucleus to produce positrons.

\[ e^- + Z \rightarrow Z^+ + e^- + e^- \]

$Z$ is the atomic number. The nucleus of high $Z$ can provide a strong nuclear inner field and high-energy electrons generate electron-positron pairs by interacting with the nuclear inner field, such as Au, Pb and so on.
BH process refers to the interaction between the high-energy electrons and the nucleus achieved by photons. Electrons interact with the nucleus to get photons by bremsstrahlung radiation and photons interact with the nucleus again to get electron-positron pairs.

\[ e^- + Z \rightarrow Z + e^- + \gamma \]

\[ \gamma + Z \rightarrow Z + e^+ e^- \]

BW process is the interaction between the photons from electron radiation and laser photons to produce electron-positron pairs. The BW process is a multi-photon process and the higher energy electron-positron pairs generated are likely to continue to annihilate to get high-energy photons, resulting in an avalanche effect, which requires a higher laser energy. Compared with the Trident process and BH process, the BW process is dominant under the condition of higher laser power. At present, scientists make efforts to increase the positron yield and optimize the positron beam quality in the laboratory.

3. Positron Generation Experiment
Theoretical work related to positron generation has been ongoing. Due to the limitations of experimental equipment, scientists optimize the experimental scheme in an attempt to obtain large charge, high energy positron beam. The exploration of collimating positron beam has great significance for material detection, medical diagnosis.

The earliest positron experiment is that Anderson bombarded solid targets with \( \gamma \) rays, which was a successful observation of positrons in experiment for the first time. With the rapid development of laser technology, collimating and high energy electron beam can be got by laser wake fields. This has the very big effect on positron yield and the positron beam quality. Compared to other ways that get positrons, it is easier to operate in experiment. As shown in figure 1, it is experimental schematic diagram. High energy electron beam is obtained by interaction between laser and gas target, reaching 250 MeV. Positrons produced by interaction between high-energy electron beam and solid target (Wu) are pinched by collimator to decrease the divergence angle. It requires additional magnetic field to separate the electrons and positrons and they get to IP board and signal about positrons is detected. Through the analysis of signal on the IP board and data processing, we can get information about positron spectroscopy and positron yield. If the condition of experimental is well prepared, it is possible to do multiple experiments to collect enough positrons.

![Figure 1. Experimental schematic diagram](image)

Many significant experiments have been carried out in the laboratory. Wu Yuchi [8, 9] carried out relevant experiments on the device XGIII. The spatial-temporal profile of incident laser is \( a = a_0 \exp(-\tau^2 / \tau^2) \exp(-\tau^2 / \sigma^2) \), where \( a_0 = 3.3 - 5.4 \), \( \tau = 0.4 \text{ ps} \) is the full width at half maximum (FWHM), and spot radius \( \sigma \) is 24\( \mu \text{m} \). The oblique incidence angle is 15°. The Ta target thickness is fixed as 1mm with radius from 0.5mm to 5mm. In the experiment, positrons have been observed successfully. In figure 2, there are two curves including background signal and positron signal. It is obvious that the
peak energy of positron is about 5MeV. What’s more, particle distribution of the positron beam is concentrated from figure 2(a).

![Figure 2](image)

**Figure 2.** Positron signal in IP board(a) and Energy spectrum including background (b)[10]

According to FLUKA (Monte Carlo simulation program), it is found that the positron yield of multilayer target is significantly higher than that of single-layer target with the same electron beam. This experiment has been carried out on the 200TW optical maser at Shanghai Jiao Tong University. The electron beam energy is about 250MeV. The thickness of Wu target is 5mm. The experimental results are in good agreement with the simulation results. The energy of positron beam concentrates on 10MeV when a single-layer target is used. In the experiment, it is found that higher energy of electron beam does not significantly increase the energy of positron beam. Most of the generation of positrons is from interaction between nuclei and electrons. The process has a certain range of energy.

![Figure 3](image)

**Figure 3.** Positron energy spectrum in experiment

4. **Positron annihilation energy derivation**

Antiparticles tend to combine with surrounding matter and instantly release energy. In the process, it satisfies the conservation of energy. If the electron energy exceeds its rest energy 0.511MeV, it will be in an extreme relativistic state. The creation and annihilation of electron-positron pairs will be important
for some physical process. The cross section of the interaction when the electron and positron annihilate into two photons. [11]

\[
\sigma = \frac{Z \pi r_0^2}{\gamma + 1} \left[ \frac{\gamma^2 + 4 \gamma + 1}{\gamma^2 - 1} \ln(\gamma + \sqrt{\gamma^2 - 1}) - \frac{\gamma + 3}{\sqrt{\gamma^2 - 1}} \right]
\]  

(1)

\(r_0 = 2.8179 \times 10^{-13}\ cm\) is the electron classical radius. \(Z\) is the nuclear charge of the atom. \(\gamma\) is the Lorentz factor for the positron. Based on the latest results of the experiment and simulation, it is easy to get \(\gamma = 19\), \(\sigma = 5.52 \times 10^{-26} Z cm^2\) when \(Z=1\). Reaction cross section definition is

\[
\sigma = \frac{\Delta n}{N h S}
\]

(2)

\(\Delta n\) is the number of reactions per second. Because the thickness of the target \(h\) is very small. \(N h S\) is the number of nuclei. \(I\) is the intensity of incident particle. It is obvious to get \(\Delta n = 9.1 \times 10^9 / s\) when \(I = 10^{20} e^+ / s\). According to the particle energy of the reaction, the output energy per second can be up to 15mJ. Considering the high energy of \(\gamma\) ray produced by the annihilation of electron-positron pairs, it will produce electron-positron again, which will result in increase of energy. In the simulation, the transverse radius of the positron beam is 140 \(\mu m\). Based on the formula above, we get

\[
E_{\text{eff}} = \Delta n \cdot E
\]

(3)

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure.png}
\caption{The number of particles in annihilation with different radius of pulse}
\end{figure}

According to the picture above, numerical value of annihilation section is negative at lower energy, which is a violation of the empirical formula. This is because the electron and positron annihilate when the energy is greater than 0.511 MeV. There is no annihilation process at low energy actually. The reaction will reach saturation for higher energy because of constant cross section coefficient.

According to formula 3, the energy released after annihilation of electron and positron beams can be obtained as shown in figure 5. In particular, the transverse size of the beam affects the probability of particle annihilation. Smaller radius is more conducive to annihilation, which releases more energy.
Figure 5. Energy released by annihilation with different radius of pulse

5. Conclusion
Positron that has the highest energy density is the best potential energy material undoubtedly. With the development of various miniaturized power devices, the choice of energy material becomes more stringent especially the high-level requirements of spacecraft. Research on positron storage and energy transformation is advancing rapidly. In this paper, according to the latest experimental results, the positron annihilation theory is deduced, and the positron energy transformation is quantitatively analyzed. The energy is up to 15mJ with intensity of $10^9 e^+ / s$ and pulse radius of 140μm. The potential value of positrons will be revealed more with researches going on.

References
[1] Dirac P A M. Quantum Mechanics of Many-Electron Systems [J]. Proceedings of the Royal Society of London. 1929, 123 (792): 714 – 733.
[2] Coleman C F. Positron annihilation-a potential new ndt technique Part 2. Applications [J]. Ndt International. 1977, 10 (5): 235 – 240.
[3] Berezhiani V I, Shatashvili N L. Self-guiding of electromagnetic beams in degenerate relativistic electron-positron plasma [J]. Physics of Plasmas. 2016, 23 (10): 3809.
[4] Wang Shaojie. Research progress of positron Energy Conversion [C]. Annual Academic Conference. 2004.
[5] Han Rongdian, Zhou Xianyi. Application and development of slow positron beam technology [J]. Progress in Physics. 1999, 19 (3): 305 – 330.
[6] Gahn C, Tsakiris G D, Pretzler G, et al. Generation of MeV electrons and positrons with femtosecond pulses from a table-top laser system [J]. Physics of Plasmas. 2002, 9 (3): 987 – 999.
[7] Ridgers C P, Brady C S, Duclous R, et al. Dense electron-positron plasmas and bursts of gamma-rays from laser-generated quantum electrodynamic plasmasa) [J]. Physics of Plasmas. 2013, 20 (5): B667 – 229.
[8] Yuchi Wu, Dan Han, Tiankui Zhang, et al. Optimization of positrons generation based on laser wakefield electron acceleration. Phys. Rev. Accel. Beams 2016, 19: 081303.
[9] Yuchi Wu, Kegong Dong, Yonghong Yan, et al. Pair production by high intensity picosecond laser interacting with thick solid target at XingGuangIII. High Energy Density Physics 2017, 23: 115 - 118.
[10] Heitler W. The Atomic Nucleus. New York: McGraw-Hill, 1955
[11] Nakamura T, Hayakawa T. Quasi-monoenergetic positron beam generation from ultra-intense laser-matter interactions [J]. PhysicsofPlasmas.2016, 23 (10): 267.