# Muon-catalyzed fusion and annihilation energy generation will supersede non-sustainable T+D nuclear fusion

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## Abstract

Background: Large-scale fusion reactors using hydrogen isotopes as fuel are still under development at several places in the world. These types of fusion reactors use tritium as fuel for the T +D reaction. However, tritium is not a sustainable fuel, since it may require fission reactors for its production, and since it is a dangerous material due to its radioactivity with main risks of release to the environment during tritium production, transport and refuelling operations. Thus, widespread use of fusion relying on tritium fuel should be avoided. At least two better methods for producing the nuclear energy needed in the world using deuterium or ordinary hydrogen as fuel indeed already exist, and more need to be developed. It should be noted that the first experiments with sustained laser-driven fusion above break-even using deuterium as fuel were published already in 2015. Similar results for T+D fusion do not exist yet, which gives no confidence in this approach.

Results: The well-known muon-induced fusion (conventionally called muon-catalyzed fusion) can use deuterium as fuel. With the recent development of a high intensity ($10^{13}$ muons per laser shot) muon source (patented), this method is technically and economically feasible today. Due to the low energy cost of producing muons at < 1 MeV with this new source, the length of the so-called catalytic chain is not important. This circumvents the 60 year-old enigma with the alpha sticking process. The recently developed annihilation energy generation uses ordinary hydrogen in the form of ultradense hydrogen H(0) as fuel.

Conclusions: muon-induced fusion is able to directly replace most combustion-based power stations in the world, giving sustainable and environmentally harmless power (primarily heat), in this way eliminating most $CO_2$ emissions of human energy generation origin. Annihilation-based power generation has the potential to replace almost all other uses of fossil fuels within a few decades, also in mobile applications, including spaceflight where it is the only method able to give relativistic rocket propulsion (Acta Astronautica 2020).

Keywords: ultra-dense hydrogen; nuclear fusion; annihilation; mesons: muon-catalyzed fusion;

## 1. Introduction

The experimental and fundamental physics of the quantum material ultra-dense hydrogen H(0) was described in a recent review in Physica Scripta) [1]. With measured interatomic distances of 2.3 ± 0.1 pm in the most commonly observed spin level $s = 2$ (at low pressure and temperature in the laboratory [1,2]), this is the densest form of matter that exists on Earth and probably also in the Universe (at spin level $s = 1$ it has the same density as white dwarf stars). This ultra-dense material has been extensively studied using laser-induced processes like Coulomb explosions (CE), coupled to time-of-flight (TOF) and time-of-flight mass spectrometry (TOF-MS) analysis [2] of its molecular fragments, but also using rotational emission spectroscopy [1,3,4] and nuclear processes. Rotational spectroscopy gives a precision of the interatomic distances in the femtometer range. The CE experiments observe molecular fragments with up to 2.5 keV $u^{-1}$ energy without nuclear processes [5].

Particles with kinetic energy in the MeV range are easily released by nuclear processes in H(0) using < 0.4 J laser pulses [1,6,7]. Clear signs of D+D fusion like $^4$He and $^3$He ions have been observed [8]. Heat generation above break-even from nuclear fusion processes was also reported for D+D fusion in $D_2$ at [9] in 2015 for the first time ever. The MeV particle (meson) signal from laser-induction is so large $10^{13}$ per laser shot [10] that it can be measured by a fast oscilloscope (with no pre-amplifiers) directly connected to a metal collector, thus giving undistorted ns-range timing intensity distributions. The decaying signals after the laser pulse agree accurately with kaon (charged and neutral) and charged pion lifetimes [1,10-13]. The muon lifetimes have also been confirmed accurately [14]. These fast particles can be observed at distances up to 2 m in a vacuum giving good time resolution [6,7,15,16]. The particle velocities measured by direct timing and by decay dilation correspond to –up to 500 MeV $u^{-1}$ [10,11,17], and are thus relativistic. By using two [9] and three [15] collectors in line, it is confirmed that the fast particles have mass. Magnetic deflection studies confirm that the mass of the charged particles is less than 1 u, thus mesons and muons, and that many of the initially formed particles are neutral [18] thus neutral kaons. Measurements with current coils show that many of the relativistic particles are charged and [12,16,17]. The generation of muons from the meson decay is confirmed by accurate measurement of the decay-time for the muons [14] and also by detecting neutrons from muon-induced fusion and muon capture [19].

## 2. Nuclear energy

Many of the nuclear processes observed in H(0) to give meson ejection take place in small clusters $H_3(0)$ and $H_4(0)$ [12,20]. The muons formed from the decay of the kaons and pions have kinetic energies >100 MeV $u^{-1}$ [15,16,18]. The processes observed are not primarily D+D fusion processes, even if such fusion processes also exist in this system [8]. Instead, two baryons form three light meson pairs (kaons and pions) [21-24]. Such a process is energetically possible and gives a large excess kinetic energy to the particles formed. The kinetic energies of the kaons and pions have been measured from their relativistically dilated decay-times [11]. The masses of the particles formed and their kinetic energies agree within a few MeV with baryon + anti-baryon annihilation (see the Appendix).

For the future of energy generation, fission processes using U or Th are believed to soon be phased out, not only due to considerable risks for accidents with their operation (for example, the Three-Mile Island, Chernobyl and Fukushima reactor accidents) but also due to the problems with large volumes of radioactive waste products and the costs and risks associated with the storage of radioactive waste for many thousand years. On the other hand, fusion processes based on T+D fusion reactions in the form of magnetic confinement (like the ITER research facility and other tokamaks) have attracted large interest and large government funding around the world. The possibility of technological and commercial success with this large-scale advanced technology can still not be estimated reliably after 60 years of development. Also laser-induced ICF (inertial confinement fusion) setups like the world´s largest laser (the National Ignition Facility (NIF) at Lawrence Livermore, California, USA) has required large investments and support, so far without much success [25,26]. (However, the NIF facility may anyway have been built mainly for weapons research.)  Besides all the technical and scientific problems surrounding these two main trends in developing fusion power, there are more basic problems related to their fuel which make these large-scale fusion methods non-sustainable. Both methods are intended to use T+D fusion, since this is the only hydrogen fusion reaction that can work under the conditions attainable in such reactors (it has the lowest ignition temperature). For example D+D fusion cannot be used.

However, the fuel T does not exist in nature, and it may need to be produced in fission (uranium) reactors and be transported to the fusion reactor sites, or produced in separate facilities on-site [27,28]. This indicates that fusion methods using DT fuel are not more sustainable than fission. Large-scale breeding of tritium from Li (breeding blankets) in Tokamaks is not proved yet [27] and is probably not operational for a long time. Besides this, laser based ICF has no such option. Breeding from D by muon-induced fusion is much simpler (see further below) and is now possible due to the availability and low cost of muons from the new patented muon source [29].

The other problem with tritium is that it is radioactive and accidents with leakage to the atmosphere are likely to take place. In fact, the large-scale use of tritium is questionable since tritium is a radioactive gas which is difficult to detect. It should be observed that tritium emits beta radiation (electrons) with quite low energy, at a maximum of 18.6 keV. This means that it cannot be detected by standard radiation instruments like Geiger counters (GM tubes), due to the windows necessary in such devices. Thus, it is not easy to detect a leakage of tritium to air from any type of device. Leakage of tritium to the atmosphere will give enhanced radioactivity in breathing air, finally in the form of water which is easily absorbed in lungs and which gives radioactive damage and risk for cancer [30]. (As given in various safety data sheats SDS: GHS Signal Word: Danger. Exposure Routes: ingestion, inhalation, puncture, wound, skin contamination absorption).. Ordinary undamaged skin is stated to not be penetrated by the beta radiation from tritium [31]. No such obstacles exist in the lungs, so the tissue in lungs will be damaged by this beta radiation.

With stringent and costly measures at the fusion reactor sites, the tritium release to the environment may become quite well controlled, but with a large number of fusion reactors (for example comparable to the number of fission reactors today) the tritium leakage to the environment will be substantial. Even in existing fission reactors, tritium emission to the atmosphere takes place which is a serious problem [30]. It is also clear that the largest risks of tritium emission in DT fusion energy production are during transport, maintenance, and repair as in all handling of dangerous chemicals and especially during fuel filling and refilling. A gas handling system of this size can never be perfect. This is one obvious reason why we still do not have a large hydrogen-based energy sector.  The problems with tritium are of course much more severe than with ordinary hydrogen.

Another problem is of course the risk of explosive processes in the fusion reactor. Plasma based methods have such risks, since the fusion process is thermonuclear and may support itself in an ignited mode. Of course, by using picomol quantities of the fuel, the risks are smaller but the usefulness for large-scale energy generation also disappears. Other methods of fusion which do not use plasmas (like muon-induced fusion) cannot give any explosive processes and are intrinsically much safer. Explosions in plasma based fusion devices can be dangerous and devastating. Future experience from accidents will of course give a better background.

Thus, it is argued here that a sustainable nuclear fusion process must use deuterium or protium as hydrogen fuels, or possibly other more complex processes for example based on boron [32]. Suitable sustainable hydrogen nuclear reaction methods do exist. We will describe and discuss two of them below under the headings 2a. muon-induced fusion and 2b. annihilation. Much more research on new nuclear energy production is needed since it seems that DT fusion gives more problems than society and environment can accept.

One central aspect which is of great interest is the efficiency of the nuclear process in the fuel, which may be characterized by the fraction of the two fuel nuclei masses which is converted to energy. Such data are given in Table 1. While D+T fusion has an efficiency of only 0.3%, annihilation has a measured efficiency of approximately 46%, thus more than 100 times higher [33]. This means that no refueling during the lifetime of the device will be necessary for many applications. From Table 1, it is seen that D+D fusion by muon induced (catalyzed) fusion should be the primary choice of a sustainable fusion process at present . This is probably the first and also only generation of fusion reactors which needs to exist, since the next generation of nuclear power generation after that is likely to be annihilation power using ordinary hydrogen in the form of H(0) as fuel, or some other new nuclear process.

## 2a. Muon-induced fusion

The central reactions in muon-induced fusion D+D in $D_2$ gas with energy out given for each step are [10,34]

| | | |
|---|---|---|
| $Dde^+ + \mu^- \rightarrow dd\mu^+ + e^-$ | | (1) |
| $dd\mu^+ \rightarrow {}^3He^{2+} + n + \mu^-$ | 3.3 MeV | (2) |
| $dd\mu^+ \rightarrow {}^3He\mu^+ + n$ | 3.3 MeV | (2a) |
| $dd\mu^+ \rightarrow T^+ + p^+ + \mu^-$ | 4.0 MeV | (3) |
| $dd\mu^+ \rightarrow T\mu + p^+$ | 4.0 MeV | (3a) |

A similar reaction scheme also exists for T+D muon induced (catalyzed) fusion [10]. Reaction (1) is the step where a muon replaces an electron in the $D_2^+$ ion inside a $D_2$ molecule. This gives a shorter d-d bond distance in approximate proportion to the ratio of the masses of the muon and the electron, thus 105.7 MeV/0.511 MeV = 207 times shorter distance . Thus, instead of the interatomic distance of 106 pm in normal (electron bound) $D_2^+$, the d-d distance in $(dd\mu)^+$ is expected to be 0.51 pm. In reactions (2) and (3), the muons are released after the DD fusion which means that the muons can take part in several such reactions as Eq. (1) before they decay with lifetime 2.20 μs. This feature is the reason for the name muon-catalyzed fusion with the muon as the non-consumed catalyst. The number of such catalytic steps intiated by one muon has been an important point for research and discussion since the first observations of muon-induced fusion in 1957 [35]. However, with the recent development of intense muon generators giving cheap muons [29] this point is no longer of great concern, since the process is both technically and economically feasible with a small number of catalytic steps. The muon-induced and muon-catalyzed fusion processes have been studied by large groups since 1957 with impressive results [34,36,37]. Reactors of this type were recently analyzed carefully in a Ph.D thesis in London 2018 [38] by R.S. Kelly. The energetics of the nuclear reactions using the existing patented muon generator have been analyzed [10]. The function of the muon generator was proved further by the observation of neutrons from fusion in $D_2$ gas [19].

Since the energy cost of producing muons by accelerators has been very large, of the order of GeV, the old problem since the 1950's has been how many fusion reactions each muon can induce (or so-called catalyze) before decaying within its decay life-time of 2.20 μs. This problem is enhanced by the reaction (2a) above, where the muon sticks to the He nucleus and the (so-called catalytic) chain is broken. In reality, this sticking process is so efficient that a chain length of 180-200 steps is the maximum expected and reported [34,38]. However, with the new muon generator, of the order of $10^{13}$ muons are formed for each laser pulse of 0.4 J. This means an energy cost of $0.4/1.6\times10^{-19}$ eV per pulse or 0.25 MeV per muon, a decrease by a factor of more than $10^3$ from accelerator technology. This means that the muons are not expensive to use or lose. The processes used for their production are the same as for annihilation described below: kaon and pion formation from baryon annihilation giving muons by meson decay. The patent description [29] is complete and can be repeated easily by anyone knowledgeable in the fields of vacuum and chemical catalysis. A complete description of the science and technology behind the production of ultradense hydrogen [1] will soon be published [39]. The importance of carbon surfaces for the formation of Rydberg species at surfaces was known long before 1998, when the key reference [40] was published. Another useful review is found in [41].

The most important aspect of muon-induced fusion is that it can use deuterium as fuel. As seen in reaction (3) this fusion process gives tritium as one product. Tritium can then fuse with deuterium by the muon-induced process, giving a more energetic reaction step [10]. This means that the composition of the fuel in the reactor and thus also the energy output changes with time, giving increased energy output when the fuel becomes richer in tritium [10,38]. This increase in tritium may take years of running the muon-induced reactor. This tritium does not need to be handled openly, and the risk of leakage to the atmosphere is small. It is envisaged for the first commercial muon-induces reactors that the central reactor gas container is exchanged when the high-pressure vessel needs service (inspection, testing) so that the gas in the reactor is exchanged to lower tritium content after a period of several years. In this way, an environmentally safer way of production of tritium also exists, cutting the ties from fission to fusion reactors and thus making fission reactors obsolete even if large-scale fusion has finally been developed and fills a demand for large-scale electricity generation.

In the same way, it is also possible to produce deuterium from protium in a muon-induced fusion reactor. However, this reaction is probably too slow to to be useful (giving too low power) [10,36,37]. Anyway, ordinary hydrogen is possible to use as a fuel in the annihilation energy generation process described below.

## 2b. Annihilation

The most important property of a nuclear process for energy generation is of course that it is possible to reach break-even, thus that more energy can be generated by the process than what is required to start and maintain it. The first such report on break-even in fusion was published in 2015 [9] in a system using ultra-dense deuterium D(0) as fuel. (The so called scientific break-even in NIF [25] is a special definition of break-even which is of limited practical interest). The nuclear process taking place in D(0) in Ref. [9] was mixed as can be concluded now after 5 further years of research, with contributions from both muon-induced fusion and annihilation energy generation. At the time of the experiment, the annihilation process and the muon generation had not yet been identified, so the process was thought to be laser-induced ICF using the D +D reaction which was until then considered to be impossible.

The annihilation process generates fast mesons, especially charged and neutral kaons at typical energies of 100 MeV or 200 MeV $u^{-1}$ [11,13,17]. From this high kinetic energy, it is estimated that 600 – 1200 MeV kinetic energy is generated per pair of nucleons, thus 30-60% of the nucleon pair mass is converted to useful kinetic energy. The mass of the kaons is also transferred to lighter particles and to kinetic energy by the kaon and subsequent pion decays, but this energy is partly lost to neutrinos and gammas. For one typical decay pattern which was analyzed in detail, 46% of the mass of the initially reacting nucleon pair is converted to useful energy with the main loss to neutrinos [11]. (See further in the Appendix). A conservative estimate is used in Table 1 as 10-50% to thermal or kinetic (mechanical) energy. Since the technology for transfer to mechanical energy is not yet fully developed, this value is just an estimate. The first description of a rocket drive for relativistic interstellar travel was recently published [13], using the momentum of the kaons generated by the annihilation process for the rocket drive. This constitutes a first step in the development of entirely new technology to utilize the annihilation energy process.

As an example of the general results on mesons, a simple meson-decay signal from laser-induced annihilation in D(0) is shown in Fig. 1. The results agree with the decay of stationary charged pions [21-24]. This means that there is no time dilation for these pions and their observed lifetime agrees with standard values [24], in this case within 0.4%. In this experiment, a pair of magnets was used to deflect and separate the particles with different charge, and the difference between the two deflected fluxes was measured including their sign. In this way, the signal due to neutral kaons was suppressed. The lightest and slowest mesons thus the charged pions should be the easiest magnetically separated particles, as observed. The good agreement with the accepted decay time for pions $\pi^{\pm}$ proves that high energies and large particle masses exist in the laser-induced annihilation process. Results on charged and neutral kaons are also found in other references [10,12,15,16,18]. See further in the Appendix.

## Appendix: mesons formed and their kinetic energies

The experimental results on meson identification and decay from Ref. [11] are displayed in Table 2.

The annihilation energy conservation for proton + antiproton annihilation becomes, with kinetic energy in parantheses from Table 2:

$$
\begin{aligned}
&p + \overline{p} \rightarrow 2\mathrm{K}^{\pm}(96\mathrm{MeV}) + 2\pi^{\pm}(69\mathrm{MeV}) + 2\pi^{\pm}(0\mathrm{MeV}) \\
&2 \times 938 - 2 \times (494 + 96) - 2 \times (140 + 69) - 2 \times (140) = \\
&1876 - 1878 = -2\mathrm{MeV}
\end{aligned}
$$

The charged kaon pair may be replaced with a neutral kaon pair, either long-lived or short-lived pairs since the neutral kaons are their own antiparticles. The experimental error limits from the particle kinetic energies given in Table 2 will give an error larger than the difference – 2 MeV indicated. The agreement in the energy matching is accurate within a few MeV or 0.2%, showing that annihilation is the process giving the mesons (of course, no other real alternative exists even without this energy matching since numerous mesons are formed).

## Ethical Approval and Consent to participate

Not applicable.

## Consent for publication

Not applicable.

## Availability of supporting data

All data are available or cited in the paper.

## Competing interests

The author is co-owner of a company that works with development of muon catalyzed fusion, but there are no competing interests since the sustainability problems of different fusion fuels are regonized.

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## Authors' contributions

LH has contributed alone to all aspects of the paper.

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Table 1. Characteristics of different hydrogen-based nuclear reactions for energy production. Est. means estimated. ….. means that the fuel composition changes over time in a closed reactor.

| Fuel reaction | Method | Reactor type | Power Range (thermal or electricity as indicated) | efficiency (%) | Sustained over-break-even operation demonstrated | Commerci start |
|---|---|---|---|---|---|---|
| T + D | Plasma | Magnetic or inertial confinement | $GW_{el}$? | 18/4500 = 0.3% | ----- | Much later than 2030? |
| T + D | Muon induced fusion | Tube reactor | $MW_{th}$ | 18/4500 = 0.3% | ----- | 2022 |
| D+D…..T+D | Muon induced fusion | Tube or planar reactor | 15 $kW_{th}$…$MW_{th}$ | 4/3600 = 0.1%..... | partial power 2015 | 2022 |
| D+D | Annihilation | Planar reactor | 200$kW_{th}$-MW | 10-50% estimated | partial power 2015 | 2025 est. |
| D+D | Plasma | Magnetic or inertial confinement | - | 4/3600 = 0.1… % | ------ | Never? |
| p+D… D+D | Muon induced fusion | Tube reactor | <<20 $kW_{th}$? | 5.5/2700 = 0.2% | | Never? |
| p+p | Annihilation | Planar reactor | 200$kW_{th}$-MW | 10-50% est. | | 2025 est. |
| p+p, D+D | Annihilation | mechanical | $kW_{el}$-$MW_{el}$ | 10-50% est. | | 2030 est. |

Table 2. Summary of previous results on meson decay time constants. The error limits are standard errors from converged non-linear least squares fits with two parameters (SigmaPlot 14). (adjusted) means manual adjustment of the rate constants for the best visual fit as in Ref. [1,13].

| Observed decay-time (ns) | Particle | Particle decay-time (ns) [24] | Dilation factor | Velocity/*c* | Kinetic energy (MeV) | Fig. and a few Refs. |
|---|---|---|---|---|---|---|
| 13 (adjusted) | $K^{\pm}$ | 12.38 | 1.05 | 0.305 | 29.4 | Ref. 12, 13 |
| 14.81 ± 0.05 | $K^{\pm}$ | 12.38 | 1.196 | 0.549 | 95.7 ±2.0 | Ref. 11 |
| 26 (adjusted) | $\pi^{\pm}$ | 26.033 | 1.0 | low | low | Ref. 1, 10, 12 |
| 25.92 ±0.04 | $\pi^{\pm}$ | 26.033 | 1.0 | low | low | Fig. 1 |
| 39 (adjusted) | $\pi^{\pm}$ | 26.033 | 1.5 | 0.745 | 68.9 | Ref. 42 |
| 40.43±0.10 | $\pi^{\pm}$ | 26.033 | 1.555 | 0.766 | 76.7 ±0.5 | Ref. 11 |
| 52 (adjusted) | $K_L^0$ | 51.16 | 1.016 | 0.18 | 16 | Ref. 1, 13 |
| 61.3 ±0.07 | $K_L^0$ | 51.16 | 1.198 | 0.551 | 97.4 ±0.7 | Ref. 11 |

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## Figure captions

Fig. 1. Time variation of meson signal from an annihilation experiment. D(0) on laser target, 50 mbar $D_2$ gas in 2 m long tubular vertical chamber. The decay time is obtained by a converged non-linear least sqares 2-parameter fit in the program SigmaPlot 14 using 560 measured points for the fit. The time constant value found agrees within 0.4% with the accepted decay time for a stationary charged pion, at 26.033 ns [22].

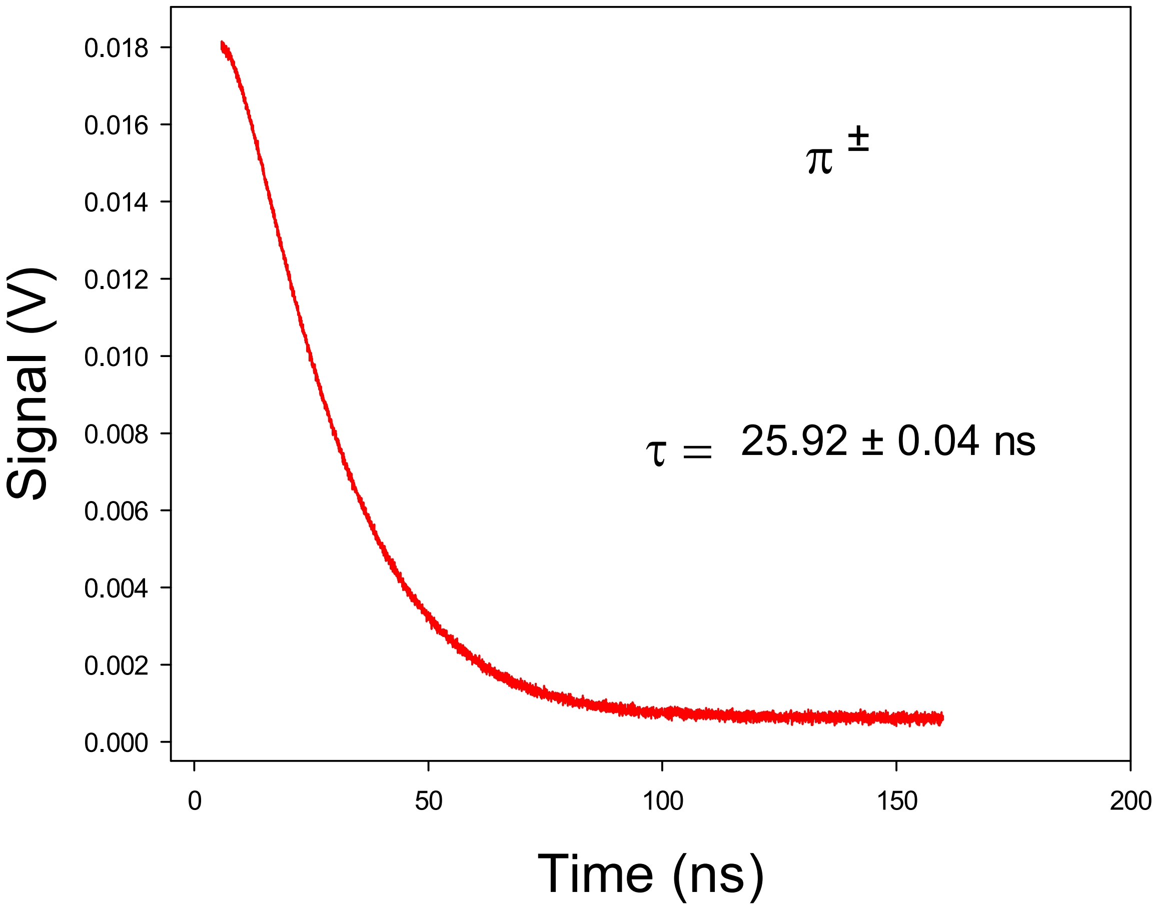
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Signal (V)
0
50
100
150
200
Time (ns)
π ±
τ = 25.92 ± 0.04 ns

Fig.1