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Existing Source for Muon-Catalyzed Nuclear Fusion Can Give Megawatt Thermal Fusion Generator

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ABSTRACT — *Fusion power generators employing muon-catalyzed nuclear fusion can be developed using a new type of laser-driven muon generator. Results using this generator have been published, and those data are now used to derive the possible fusion power using this generator. Muon-catalyzed fusion has been studied for 60 years, and the results found in such studies are used here to determine the possible power output. Since the muon source gives complex mixtures of mesons and leptons, which have very different interactions with the measuring equipment, the number of negative muons formed is not easily found exactly, but reasonable values based on numerous published experiments with different methods are used to predict the energy output. With deuterium-tritium as fuel, a fusion power generator employing the novel muon generator could give more than 1 MW thermal power. The thermal power using pure deuterium as fuel may be up to 220 kW initially: It will increase with time up to over 1 MW due to the production of tritium in one reaction branch. The power required for running a modern laser and the muon generator is estimated to be of the order of 100 W, thus giving a total energy gain of more than 10 000. The harmful radiation from such fusion power generators is mainly in the form of neutrons from the fusion reactions. Thus, thick radiation shields are necessary as for almost all other fusion concepts. This means that medium-scale thermal fusion power generators of the muon-catalyzed fusion type may become available within a relatively short time.*

Keywords — *Muon-catalyzed fusion, nuclear fusion, ultra-dense hydrogen.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

Several published studies from our group prove the formation of mesons and muons with up to 100 MeV u^{-1} energy by laser-initiated processes in ultra-dense deuterium D(0) and ultra-dense protium p(0) (Refs. 1 through 6). Ejection of such particles proves that highly energetic nuclear processes take place. Ultra-dense deuterium D(0) is a spin-based material which exists in several different spin levels as shown by time-of-flight (TOF) experiments.[7] The most commonly observed level with spin quantum number s = 2 has a measured D-D distance of 2.3 pm in good agreement with theory.[7] Rotational spectroscopy of D(0) gives precise D-D distances for spin quantum numbers s = 2, 3, and 4 (Refs. 8 and 9). Due to the extreme density of ultra-dense deuterium D(0), it is expected to be an excellent fuel for nuclear fusion by inertial confinement fusion.[10–12] The density is so high that only an exciting laser pulse is required and no further compression is needed to reach nuclear reaction conditions. Gamma radiation[13] and lepton pair production[14] are observed from these nuclear processes, as well as ^4He and ^3He ejection.[15] The total energy in the ejected particles

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is so large that the nuclear reaction process is above break-even.[16] The nuclear processes taking place are both laser-induced nucleon + nucleon annihilation–like processes[2–6] and ordinary D + D fusion partly of the muon-catalyzed type. That ordinary D + D fusion takes place is shown by neutron detection[17] and by TOF mass spectrometry studies.[15]

One important aspect of our studies with laser induction in H(0) is that high-energy, unstable particles are observed to be ejected by relatively weak laser pulses.[3–6] A few types of methods have been used previously to form particles with energy in the mega-electron-volt range from hydrogen by fusion or other nuclear processes, normally requiring much higher laser energy intensities than used here. The high-energy particles studied previously are normally stable particles like protons and neutrons, not unstable mesons and leptons as reported from our laboratory. Such stable particles are only ejected by energetic means, by intense laser pulses,[18–20] or by application of a high voltage to the system. The most common type of method is certainly plasma methods like the one used under the name inertial electrostatic confinement. Such devices have also been developed for nuclear fusion.[21,22] The first and most well-known example of this type of device is the fusor.[23] Similar devices are used for generation of neutrons for isotope production.

The main problems solved in the present contribution are the reaction processes involved in the muon-catalyzed fusion and the energy output from them. Such a comprehensive treatment has not existed earlier, and it is also motivated by our recent results with neutron emission[17] from the patented[24] muon generator indicating muon-catalyzed fusion. The patent[24] describes the muon generator which is intended for a muon-catalyzed fusion energy reactor.

II. ULTRA-DENSE HYDROGEN H(0)

Ultra-dense hydrogen H(0) is a quantum material at room temperature. It is described in several publications, with detailed studies of the structure of ultra-dense deuterium D(0) (Refs. 7 and 25) and also of its protium analog p(0) (Ref. 26). It is spin-based Rydberg matter[7] with orbital angular momentum $l = 0$ for the electrons. Due to the measured very short p-p and D-D distances of 2.3 pm (Refs. 25 and 27) and below, the density of H(0) is very high, in fact higher than the density of any hydrogen fuel useful for fusion believed possible by any compression method. Thus, it should be possible to initiate nuclear fusion by relatively weak laser pulses in the H(0) material. It is likely that the main process initiated by the laser pulse is a transition from level $s = 2$ with H-H distance of 2.3 pm, to level $s = 1$ with distance close to 0.56 pm (Ref. 7) from where fusion or other nuclear reactions are spontaneous. This distance is close to that found for muon-catalyzed fusion, giving fusion within 1 ns (Refs. 28 and 29). Since it appears that this transition to level $s = 1$ can also take place spontaneously, a spontaneous nuclear process exists similar to those named low-energy nuclear reaction.[30,31] Spontaneous ejection of mega-electron-volt particles has indeed been observed.[32] Particle energies up to 50 MeV u^{-1} have been reported in laser-induced experiments.[1,2] Recently even faster particles with relativistic energies have been observed.[6]

The mechanism of formation of ultra-dense matter starts with the formation of higher normal Rydberg matter levels in hydrogen (l = 1 to 3) (Ref. 25), which are formed spontaneously at the catalyst surface used. This implies that H(0) is formed from ordinary Rydberg matter levels $l = 1$ to 3 falling down to the lower-energy ultra-dense states.[10] The spin-circling electronic charges provide the necessary shielding of the nuclei which keeps the material strongly bound, similar to ordinary Rydberg matter but with much larger binding energies in the kilo-electron-volt range. The nuclear processes taking place in H(0) spontaneously and under laser impact are still not completely known. However, several different steps have been studied separately. The total process giving the negative muons required for muon-catalyzed fusion starts with the ultra-dense hydrogen particles $H_N(0)$, and is proposed to be

$$H_N(0)\ (s=1) \rightarrow (p^+e^-)(p^+e^-) \rightarrow K^{\pm} + K^0_L + K^0_S + \pi^{\pm} \rightarrow \text{decay} \rightarrow \mu^-\ ,$$

where (p^+e-) is a closely bonded quasi-neutron.[33] The mesons formed are all types of observable kaons and pions,[34,35] and it is likely that three kaons are formed from each $H_2(0)$ particle since this conserves the number of quarks as $(p^+e-)(p^+e-) \rightarrow 3$ K. The number of quarks may be unchanged in such a meson formation step, but a further pion pair may be created by which process the number of quarks is not conserved. The process shown is highly exoergic and gives 390 MeV to the three mesons ejected from each pair of protons, and 111 MeV in total if a further pion pair is created. This should be compared to ordinary D + D fusion, which has an output per pair of deuterons of only 14 MeV.

The present description is concerned with the production of negative muons and the use of them as catalytic agents in muon-catalyzed fusion. This process has been known since the 1950s (Refs. 36 and 37) and has been studied in detail by several groups, notably in the United States, in the Soviet Union, and in Switzerland and Austria. Recently, a patent has been granted for our muon generator as the central device in a muon-catalyzed fusion reactor.[24] The fusion function of this reactor has been verified by neutron detection.[17]

III. PROCESSES IN MUON-CATALYZED FUSION IN D_2

Muon-catalyzed fusion is often stated to be possible due to the similarity of the negative muon $\mu-$ to a heavy electron. Due to the large mass of the muon, the distances in the hydrogen muonic atom Hμ and molecular muonic ion $(HH\mu)^+$ (with the negative muon as the only bonding negative charge) should be a factor of approximately 200 smaller than with an electron (105.7 MeV/0.511 MeV = 207). Thus, instead of the interatomic distance of 106 pm in normal H_2^+, the distance in $(HH\mu)^+$ is expected to be 0.51 pm. This distance is close to that observed for $s = 1$ in the experiments in ultra-dense hydrogen H(0) at 0.56 pm according to theory.[7] This means that the nuclei can tunnel rapidly (order of 1 ns) to fuse. The rate-limiting step in the fusion process is normally considered to be the rate of formation of the muonic ion $(HH\mu)^+$. The plus sign indicates the charge of the compound ion, with two hydrogen nuclear positive charges and one negative muon.

There are three different possible $HH\mu^+$ ions giving nuclear reactions of interest in the case of initial pure deuterium as fuel, namely $dt\mu^+$ (deuterium-tritium), $dd\mu^+$ (pure deuterium), and $pd\mu^+$ (protium-deuterium), since both tritium and protium are produced in the nuclear reactions. (The case with $tt\mu^+$ will also be possible after enough T has accumulated, but it is not included here.) All these three ions react differently. The most energetic reaction is

$$dt\mu^+ \rightarrow {}^4He^{2+} + n + \mu^- \qquad 17.6\ \text{MeV}\ , \qquad (1)$$

which gives a high-energy neutron (at approximately 14 MeV kinetic energy). Reaction (1) releases the muon which may form $dt\mu^+$ repeatedly before the muon decays, giving a catalytic process which may have more than 100 steps.[28] Only a small fraction, around 0.5% of the process, gives the μ effective sticking process[28]:

$$dt\mu^+ \rightarrow {}^4He\mu^+ + n \qquad 17.6\ \text{MeV}\ . \qquad (1a)$$

This reaction prevents further catalytic steps for the muon, which decays within its normal free lifetime of 2.2 µs. The total experimental fusion rate is found to be approximately $200 \times 10^6\ s^{-1}$ (Refs. 28 and 29).

The $dd\mu^+$ (pure deuterium) ion behaves differently. There exist four different channels for this reaction[38]:

$$dd\mu^+ \rightarrow {}^3He^{2+} + n + \mu^- \qquad 3.3\ \text{MeV} \qquad (2)$$

$$dd\mu^+ \rightarrow {}^3He\mu^+ + n \qquad 3.3\ \text{MeV}\ , \qquad (2a)$$

$$dd\mu^+ \rightarrow T^+ + p^+ + \mu^- \qquad 4.0\ \text{MeV}\ , \qquad (3)$$

and

$$dd\mu^+ \rightarrow T\mu + p^+ \qquad 4.0\ \text{MeV}\ . \qquad (3a)$$

The ^{3}He-muon sticking reaction (2a) has a large probability close to 0.13 of the total flux in these reactions,[38] which means that only a small number of catalytic cycles ≈7 steps is possible for this reaction. The T + muon sticking probability is probably small. The branching between reactions (2) and (3) are close to unity or slightly larger, thus with reaction (2) more likely than reaction (3) (branching ratio 1.0 to 1.4) (Ref. 38). The total experimental fusion rate is found to be approximately $400 \times 10^6\ s^{-1}$ (Refs. 28 and 38).

The $pd\mu^+$ (protium-deuterium) ion gives simple reactions[39]:

$$pd\mu^+ \rightarrow {}^3He^{2+} + \mu^- \qquad 5.5\ \text{MeV} \qquad (4)$$

and

$$pd\mu^+ \rightarrow {}^3He\mu^+ + \gamma \qquad 5.5\ \text{MeV}\ , \qquad (4a)$$

with gamma radiation emission in reaction (4a). The total experimental fusion rate is quite low, of the order of $0.5 \times 10^6\ s^{-1}$ (Refs. 39 and 40). The muon sticking probability in reaction (4a) as $^3He\mu^+$ should be similar to that in reaction (2a), giving a few catalytic cycles only.

IV. MUON FLUX

The muon-catalyzed fusion processes require a muon generator able to provide a large intensity of negative muons. Both laser-induced and spontaneous processes in ultra-dense hydrogen H(0) generate muons as a result of the initial formation of kaons and pions. Both positive and negative particles are formed. Recently, a patent describing an efficient muon generator was granted.[24] Here, the muon flux from experiments with meson and muon generation will be evaluated. Two main, somewhat different types of generating devices have been used, both

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with and without laser induction. Below, the number of particles per second (charges per second) are given for several different constructions. Of course, not all these particles detected are muons since both kaons and pions are observed initially.[3,4] However, all mesons observed (charged and neutral) decay to 1 to 3 muons after a time less than 100 ns. Short-lived neutral kaons K_S^0 give only gamma photons in the end with 31% probability, but they are not directly observed due to their short decay times. (For the remaining 69% each short-lived neutral kaon K_S^0 gives two muons in the end, one positive and one negative). Thus, the total number of particles detected is assumed to be close to the number of muons formed.

IV.A. Laser-Induced Signal

The simplest construction uses a separate source for the H(0) generation and a laser target surface supporting the H(0). This surface is usually metallic, typically of stainless steel, Pt, or Ta. In one apparatus using this construction, the three directions characterizing the experiment, thus the laser impact direction, the surface normal of the target, and the direction of observation of the particle flux, are all different. This means in this case that the main direction of the observed particle flux is close to 60 deg from the surface normal, thus unlikely to give any enhanced flux (for example due to an angular distribution peaked at the surface normal) in this almost arbitrary direction. The direct current measurements[1,2] at 10^{-5} mbar pressure give large signal currents. In one of them[1] the total number (over the full 4π sphere) of particles released was calculated to be 1×10^{13} particles per laser shot, thus 1×10^{14} s^{-1} at the laser repetition rate of 10 Hz. These values assume that the efficiency of the current measurement (thus particle conversion to charge at the collector) is unity. The secondary coefficient of charge ejection due to particle impact may be both smaller and larger than unity, depending on particle type and kinetic energy. One complexity is certainly that the particles reaching the foil collectors and measured as a current there are normally pions or muons, not the initially ejected kaons. For the kaons, it is assumed that the charged kaons produced by laser induction from H(0) give a secondary coefficient of charge ejection of the order of 10, while the neutral kaons give a smaller secondary coefficient of charge ejection of the order of unity. The signal intensity in Ref. 2 is similar to or larger than that in Ref. 1. Further studies with the same setup give similar results.[6] This indicates that the variation with energy and signal-generating particle type is anyway relatively small. See also further discussion in Section IV.C.

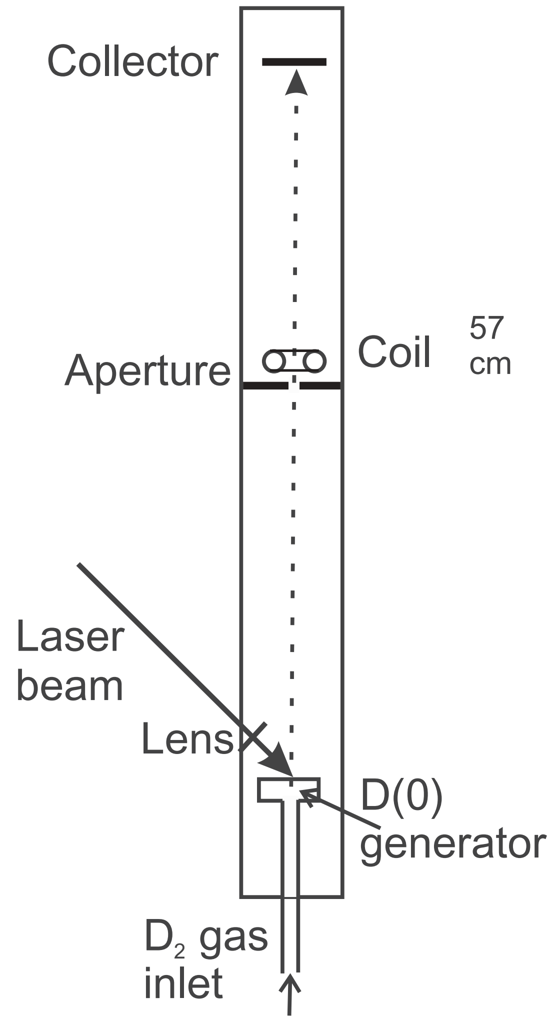

Fig. 1. Typical setup for total particle emission measurements using the novel muon generator.

In another setup, improved versions of the muon generator have been studied, both with separate and integrated formation of H(0). In this setup, shown in Fig. 1, the signal detection is in the direction of the normal of the laser target and the laser-induced TOF particle current to a collector is measured[3,4] at relatively high pressure, below 1 mbar. The signal measured in these experiments is caused by mega-electron-volt particles passing through or stopping in metal foil collectors with thicknesses from 20 μm to 1.5 mm. One example of the signals obtained is given in Fig. 2. The total number of particles emitted is in the range 1×10^{14} to 7×10^{14} per laser shot, thus 1×10^{15} to 7×10^{15} per second at a laser pulse rate of 10 Hz assuming a secondary coefficient of charge ejection of unity. This

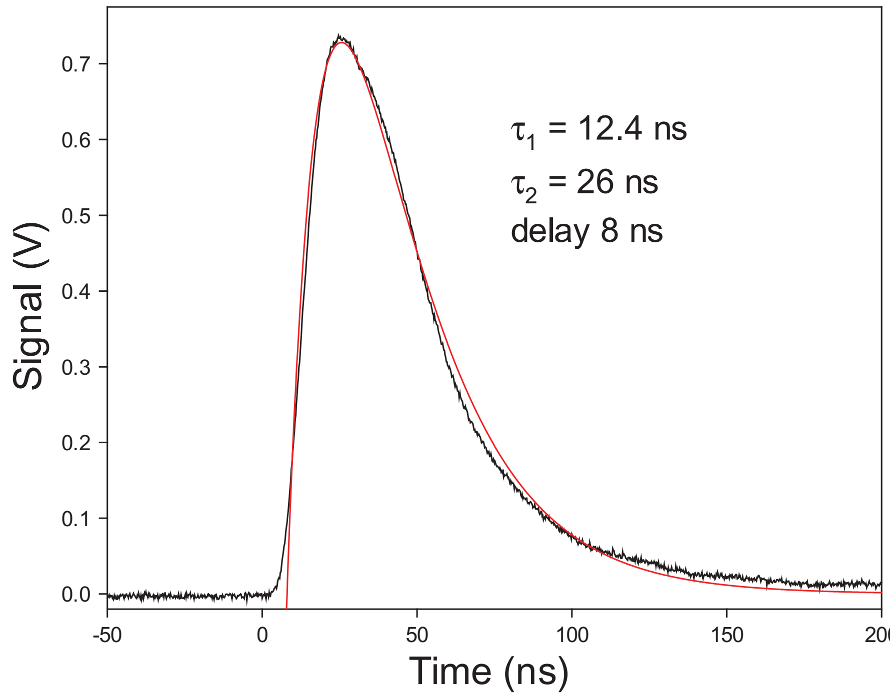

Fig. 2. Decay of charged pions with lifetime 26 ns observed with H_2 pressure of 0.4 mbar, at collector with negative bias (see Fig. 1). Calculated curve is in red. The rise time τ_1 is due to decay of charged kaons with lifetime 12.4 ns to the observed charged pions. The peak current is 14 mA. The delay is relative to the trigger from the laser pulse.

is calculated further assuming that the ejected flux density is independent of the direction, which may give too high values of the total flux. However, the relatively constant value found in many experiments with different angular acceptance and angular direction in the flux measurements indicates that any peaking effect of the ejected flux is rather small.

IV.B. Coil Measurements

By using a wire coil wound on a ferrite core as current transformer, the current of charged particles through the coil can be determined as shown in Fig. 1. The wire is wound around a ferrite toroid core, with around 20 turns of wire on a toroid of a few-centimeters diameter. The pulse of charges from the laser-induced nuclear processes on a target is observed as an induced current in the coil. The voltage out from the coil depends on the rate of change of the current. By using a fast oscilloscope, the true rise time of the signal, which must be comparable to the laser pulse rise time, can be found. Direct comparisons of the coil signal with the signal to a collector behind it have been made, which gives a calibration of 30 to 50 mV mA^{-1} assuming one elementary charge per detected particle. This is a standard method of measuring the pulse current, for example, in electron accelerators with the particles moving at relativistic velocities giving similar calibrations.[41,42] Photons or other neutral particles like neutral pions and neutral kaons cannot induce any current in the coil. An experiment of this type with a simple planar laser target in a pressure of 10^{-5} mbar is shown in Fig. 3. The signals at both a coil and a collector are shown with the same decay times. This decay time of 12 ns is characteristic for charged kaons $K^{\pm}$. The longer decay time of 26 ns also observed is typical for charged pions. The total signal (over the full 4π sphere) of particles (charges) can be calculated to be close to 10^{13} per laser shot or 10^{14} s^{-1}, similar to the collector results. This is not unexpected since the internal calibration assumes one observed charge per particle at the collector. It is concluded that this signal is due to charged particles, primarily charged pions and muons formed by charged kaons decaying relatively close to the laser target.

Experiments have also been performed with a coil current transformer using a more advanced muon generator in gas pressures up to 1 mbar. The distance from the generator to the coil was 0.5 m, and the defining aperture had a diameter of 10 mm. The total particle signal in a very sharp first peak observed by the coil was 3×10^{13} per laser pulse or 3×10^{14} s^{-1}. This peak is probably due to decay of short-lived neutral kaons K_S^0 (paper to be published). The simultaneous collector current with negative bias recalculated to the whole sphere

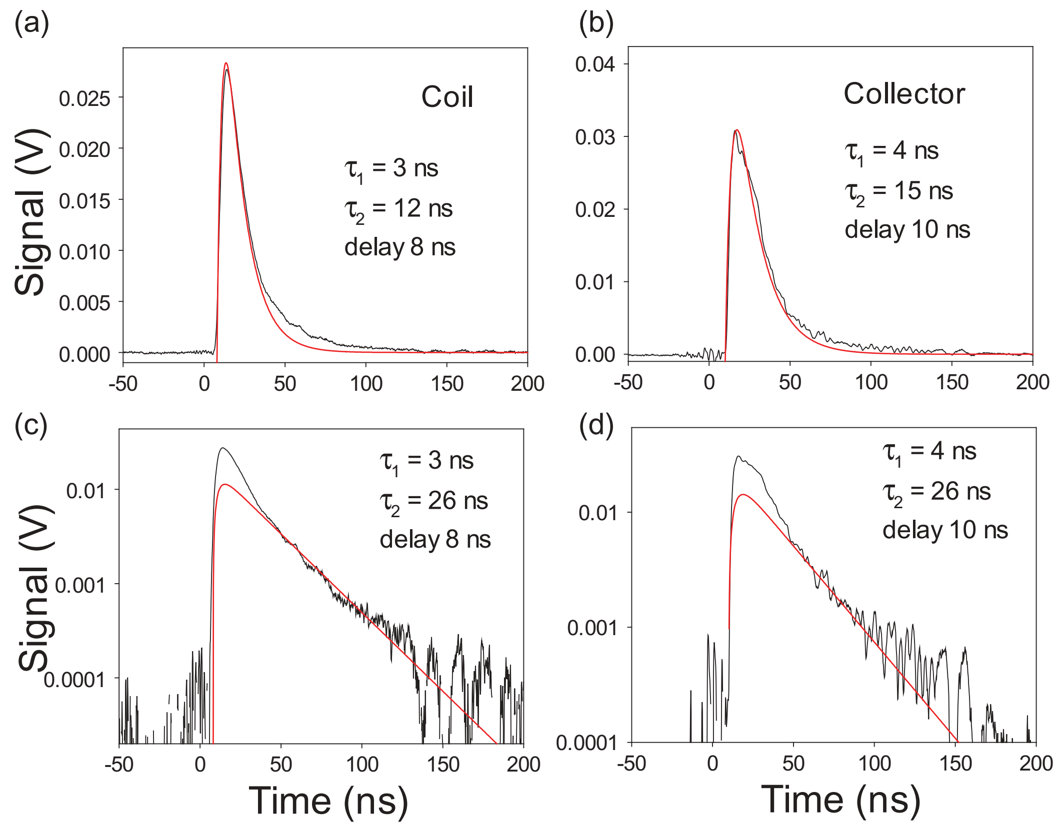

Fig. 3. (a) and (b) Decay of charged kaons and pions with lifetimes 12.4 and 26 ns observed at coil and collector at zero bias with D_2 gas at 10^{-5} mbar (another setup than in Fig. 1). (c) and (d) The same data with logarithmic vertical scale. Calculated curves are in red. The formation time constant τ_1 is due to the laser pulse width. The delays are relative to the trigger from the laser pulse.

was larger, corresponding to a particle rate up to 2×10^{14} per laser pulse or 2×10^{15} s^{-1}. These results indicate that a large part of the collector signal is due to neutral particles like neutral kaons which decay to muons in less than 100 ns.

The charge sign of the particles can be found by separate calibration of the coil using a pulsed current in a wire through the coil. In the low-pressure experiments described above the signal was due to positive kaons. At higher pressures using the muon generator described here, the mesons and other particles observed are mainly negative, thus giving negative muons. Also neutral long-lived kaons K_L^0 which have a decay lifetime of 52 ns and in the end give both positive and negative muons are observed at the collector using the decay time for particle identification. In such cases, the observed signal is quite complex.

IV.C. Scintillator-PMT Particle Counting

In experiments with a converter or scintillator and photomultiplier (PMT) detector,[32,33,43] the number of particle counts can be recorded directly. Such experiments have been done both separated from the vacuum chamber containing the H(0) generator and attached to the vacuum chamber through a thin metallic window or similar. Measurements done have been both laser induced and spontaneous. Under conditions where the apparent signal gain due to lepton pair production is relatively small, the total number of particles detected in the multi-channel analysis (MCA) experiments is 5×10^4 in maximum 200 channels, thus 10^7 particles during a 500-s measurement period. This means 2×10^4 particles per second or up to total 1×10^9 s^{-1} into 4π using a normal detector distance in the experiments of 1 m. This value is much smaller than the one found with particle current detection in vacuum described above, which indicates that saturation processes influence the pulse counting results. Certainly, several effects which give a saturated pulse counting signal are known to exist. With the shaping time of 500 ns used in the main amplifier[32] the total signal count cannot be more than approximately 10^5 s^{-1} for 10% overlap, corresponding to 2.5×10^9 s^{-1} over the whole sphere. Thus, the measured values are expected to be limited by the pulse overlap. This effect is not easily separated from other saturation processes.

In many high-intensity experiments not included here, even the overlap of the pulses directly from the PMT detector is large which means that the particle signal is too large to be measurable by MCA pulse counting. It is thus clear that the particle signal often is much larger than observed in the MCA spectral results.

The pulse counting signal observed is not strongly dependent on the source-detector distance, which may indicate scattering of neutral particles in the surrounding laboratory so that a quite constant radiation field exists. The pulse overlap was thus not easily decreased by increasing the source-detector distance. Since the PMT particle counting experiments require that the initially ejected particles have penetrated through many millimeters of steel and often also have moved a long distance in air, it is unlikely that muons formed by charged mesons are observed in these experiments. It is instead likely that the signal observed in these PMT experiments is mainly due to muons formed by decay of long-lived neutral kaons which pass much more easily through materials and are scattered around in the laboratory.

IV.D. Radiation Damage on Biological Systems from the Muon Source

From the collected evidence discussed above and in previous studies, we argue that the particles emitted into the laboratory environment by the muon source are not mainly charged kaons which would give dangerous, maybe even lethal radiation levels to the personnel in the laboratory. The radiation in our laboratory has been checked by hand-held G-M counters (mainly Mirion RDS-80) close to the muon source, and no dangerous radiation levels have been observed. Of course, the G-M device response is limited to one count per laser shot so the real intensity may be higher. The sensitivity of this type of device is otherwise high enough to easily observe random radioactive decay in antireflective coatings on optical parts like lenses and windows. Instead of charged kaons, mainly neutral kaons seem to pass out into the laboratory, and the interaction of such particles with matter is believed to give considerably lower radiation levels, maybe mainly due to their longer decay times which allow them to move further before decay, thus depositing much of their energy in the building walls and in the laboratory equipment. They will also have a smaller direct Coulomb interaction with atoms in materials. Further, more energy is given off by gamma radiation from neutral kaon and pion decay, also distributing the radiation energy over a larger volume of materials. Certainly, more radiation research is required to give secure conclusions on this point.

Another important factor is that the muon-matter and kaon-matter interactions are not well known. We have observed and studied a dominating pair-production interaction mechanism which is not yet understood completely (paper submitted) and which is not included in the radiation generating mechanisms normally considered for muons, pions, and kaons. First experimental results are published in Refs. 32, 33, and 43.

V. FUSION POWER PREDICTIONS

It is now possible to use the energy output from the various fusion reactions in Sec. III with the particle formation numbers given in Sec. IV to predict the power of various muon-catalyzed fusion reactors. The number of particles given in Sec. IV depends on the not very well known secondary charge emission coefficient for particle impact on the foil collectors used. We will assume that the total number of particles formed gives negative muons which lead to muon-catalyzed fusion in hydrogen gas at a pressure of several tens of bars.[38] This may be a factor of 2 too optimistic, since equal numbers of positive and negative muons are likely to be formed in many processes. It will further be assumed that all negative muons react in the gas, thus that no muons can pass through or out from the reactor. This may in reality not be the case, depending on the physical size and shape of the reactor. The reaction probability will vary directly with the gas pressure in the real reactor.

In the case of pure D_2 gas, the reactions (2) and (2a) give an energy per each reaction step of the average of 3.3 MeV and a number of steps of approximately 7, using a sticking probability of 0.13 (Ref. 38). Reactions (3) and (3a) give 4.0 MeV and probably a short chain, here assumed to only be one step as in reaction (3a). The branching is here assumed to be close to 50% in the two channels (2) and (3). The initial kinetic energy of the muons is not known, even if some of the precursor mesons have an energy of 200 MeV u^{-1}. This energy, which in reality is comparable to the energy released by the nuclear fusion, is not included at this step but estimated further below. Thus, we calculate the total fusion power with $N = 7 \times 10^{15}$ muons s^{-1} for the existing muon generator:

$$E_{fus} = N \times (3.3\ \text{MeV} \times 0.5 \times 7 + 4.0\ \text{MeV} \times 0.5) = 15.2\ \text{kW} . \tag{5}$$

This means approximately 3×10^{16} D + D reactions per second, or 3×10^{16} D_2 molecules consumed per second. This corresponds in turn to 50 nmol of D_2 gas, or 0.2 μg D_2 consumed per second. Thus, 1.6 mol D_2 is consumed per year, producing 130 MW·h.

During the operation of a reactor with D_2 gas, the reactions (2), (2a), and (3a) convert the deuterons to T and ^{3}He. This means that also reactions (1) and (1a) start to operate. Also p is produced, but reactions (4) and (4a) are not included in this calculation since these reactions are slow. The fusion power after 50% conversion to T can now be calculated approximately as

$$E_{\text{fus}} = N \times (14\ \text{MeV} \times 0.5 \times 200 + 3.3\ \text{MeV} \times 0.25 \times 7 + 4.0\ \text{MeV} \times 0.25) = 1.58\ \text{MJ s}^{-1} = 1.58\ \text{MW} . \quad (6)$$

The estimated time for such a degree of conversion is of the order of years, depending on how much gas is used in the reactor. Without tritium extraction, the power of the reactor may thus increase from 12.9 kW to 1.6 MW in a period of a few years. The consumption of D_2 decreases correspondingly. Alternatively, the reactor may be employed as a tritium-producing equipment, with gas separation and regeneration.

The total power added from the decay of the initial mesons formed by the laser-induced nuclear processes[3,4] is estimated to be at least

$$E_{\text{mesons}} = N \times 200\ \text{MeV} = 110\ \text{kJ s}^{-1} = 220\ \text{kW} , \quad (7)$$

which is considerably larger than the fusion energy using pure D_2 as fuel. Thus, an optimal reactor design may give a starting power of the order of 220 kW with pure D_2 fuel, increasing to at least 1.7 MW after a few years of operation.

VI. DISCUSSION

The muon generator developed,[24] which is evaluated here, is just a second-generation muon-fusion device (with first-generation devices being described in the literature[2,13,14]). It is highly likely that devices that generate even larger amounts of negative muons can be developed in the near future. It should be observed that the energy output from such a generator is much larger than the possible fusion energy output using deuterium as fuel. Thus, any such a device is a first step toward useful fusion power, and it may alternatively be considered as a device for tritium production.

The power required for running our old flash lamp–pumped Nd:YAG laser at 1- to 5-W laser power is of the order of a few hundred watts. It is believed that a modern diode-pumped optimized laser will use less than 100 W. The muon generator requires some slight heating of a few watts. The total power for running the fusion generator is thus of the order of 100 W. Pumping of gases for cooling and energy output is also necessary. This gives a total energy gain of 10 000 at 1-MW output. The harmful radiation from such fusion power generators is mainly in the form of neutrons from the fusion reactions and from the possible leakage of tritium to the atmosphere, but also some types of kaons and pions are ionizing particles and decay to ionizing particles. Thus, thick radiation shields and tight enclosures are necessary as for all other fusion concepts. This means anyway that small- to medium-scale thermal fusion power generators of the muon-catalyzed fusion type may be available within a relatively short time.

It is expected that neutrons will be ejected from a nuclear fusion process. Relatively small but significant fluxes of neutrons have been detected in our experiments using laser-induced nuclear fusion in D(0) (Ref. 17). There seems to be several reasons for the low neutron ejection rate. The most important factor is the large density of D(0), which makes it difficult even for neutrons to leave the material without numerous collisions with the deuterons.[11,44] Mean free paths as short as 150 nm even for 14-MeV neutrons can be calculated in D(0) (Ref. 44). It is however possible to observe ejected ^{4}He and ^{3}He after collisions with D clusters by TOF (Ref. 15). The D(0) is superfluid and forms a layer on the target. Thus, it will transport energy rapidly to its surface from where particles are ejected in the form of a sheath.[1,2] This allows the observation of $D_N(0)$ cluster fragments and their products.

One aspect of this development is that the power generated is calculated as total thus thermal power. Due to the relatively low energy density of the catalyzed processes in the hydrogen gas, it seems less likely that a high-temperature version of this process, useful for electricity production, can be developed rapidly. Thus, the devices described are mainly useful for thermal energy production. However, this is a type of energy which is in demand in many parts of the world, certainly in this form which is very useful and environmentally friendly due to very low fuel cost and fuel consumption without any green-house gas emissions. Thus, this may become a significant step in the development of clean and sustainable energy sources throughout the world (see patent in Ref. 24), replacing the present fossil-fueled boilers delivering hot water for residential heating.

VII. CONCLUSIONS

The existing muon generator can be used for thermal energy generation by using the well-studied processes of muon-catalyzed fusion. This generator produces enough muons to give more than 1 MW thermal energy, either directly from tritium-deuterium gas or from pure deuterium gas after running the process for a time of the order of 1 year, when the amount of tritium produced in the reactor has increased strongly. This total energy output is based on numerous experiments which measure the number of muons formed; however, the uncertainty in this number is relatively large due to the complex mixture of mesons and leptons formed by the present generator. Anyway, relatively safe and cheap fusion reactors of 1-MW size may be produced: They may be running in a relatively short time based on the patent in Ref. 24.

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