Detection of spontaneous neutral kaons K0L and K0s from ultra-dense hydrogen H(0)

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Abstract

We here report muon and gamma photon signatures from decay of neutral kaons K0L and K0s to complement the published results of kaon generation from laser-induced baryon annihilation in H(0) (Holmlid and Olafsson, High Energy Density Physics 2021, and Holmlid, International Journal of Hydrogen Energy 2021). One well-known complication in the kaon detection is the oscillation process between the neutral kaons K0L and K0s caused by interaction with matter. Particle energy measurements with plastic scintillators identify one process which generates two muons simultaneously from one mode of decay of

. Particle energy measurements with Al converters (without scintillator) in the separated, enclosed charged particle detector identify further modes of decay of K0L and K0s, all producing a few simultaneous high-energy gamma photon peaks in the approximate energy range 20 - 100 MeV. Neutral kaons are observed only when ultradense hydrogen H(0) is deposited in the meson generator. The results presented are mainly from spontaneous reactions in H(0). The experimental setup uses an enclosed PMT with Al foil converter and a multichannel analyzer (MCA) for pulse energy analysis. Using this method the radiation damage from neutral kaons can be investigated. Due to the low cross section of the neutral kaons in interaction with matter there exists no other method to identify them with certainty outside large physics laboratories.

1. Introduction

Meson formation from laser interaction with the novel nuclear fuel ultra-dense hydrogen H(0) has been reported from several experimental studies, with examples in [1–4]. The reason for the meson formation in these experiments is laser-induced baryon annihilation [5, 6]. Similar processes are also observed without laser induction, thus spontaneously [7]. The physics of mesons has been studied for a long time [8–11]. Ultra-dense hydrogen H(0) is a spin-based dense form of Rydberg matter [12, 13] and a quantum material. In a review in 2019 [13], the 50 published studies of H(0) during the period 2009–2019 were summarized. In a recent review, the molecular processes involved in the production of H(0) have been described in detail [14]. The baryon annihilation energetics for the meson formation was recently proven accurately [5, 6]. The velocity of the ejected mesons is often relativistic at energies of 70–100 MeV [3, 6]. The muons formed by meson decay have kinetic energies in the range 100–500 MeV [8–11]. These muons have been identified, after thermalization, from their decay time of 2.20 µs [15]. Negative muons are also identified by their neutron production from muon-catalyzed nuclear fusion [15, 16]. Charged pions π±, charged kaons K± and neutral long-lived kaons K0 ± are all identified by their characteristic decay times after laser induction [5]. Similar nuclear reactions can also be identified in H(0) as spontaneous processes without laser induction. In such spontaneous annihilation experiments, energy spectra measured with scintillators and converters were used successfully to identify muons µ± [7, 17]. Similar methods are used here to identify spontaneously emitted neutral kaons. The detector will always observe a mixture of long-lived neutral kaonsK0L and short-lived neutral kaons K0S due to the oscillation [8, 9]
between these two states. This oscillation will always exist, and cannot be removed by experimental design. The detection of the short-lived kaon $K_S^0$ confirms and complements the previously found $K_L^0$. It complements also the previous observations of the charged kaons $K^\pm$ [18] from baryon annihilation in $H(0)$ [1, 2, 3, 5, 6, 13]. The experiments show that all four types of kaons are formed from the nuclear reactions in $H(0)$. There is no evidence for other mesons than kaons and pions formed in the baryon annihilation. The detailed nuclear processes behind the baryon-annihilation meson-formation behaviour [19] are described in recent publications [5, 6] and they are also summarized in Section 2 below.

This study provides an identification of short-lived neutral kaons $K_S^0$. This complements the earlier decay-time observations of long-lived neutral kaons $K_L^0$ and of charged kaons $K^\pm$.

Evidence for $K_L^0$ comes from the gamma photon peak at the highest energy corresponding to six gamma photons, and for $K_S^0$ from the gamma peak corresponding to four gamma photons and from two simultaneously detected muons.

The organization of this paper is as follows. After the sections on theory and experimental details, Section 4 contains results from both main measurement methods used. Gamma photon peak detection with anAl converter and muon detection constitute the two main measurement methods in this paper. A brief general discussion is included in Section 5. The previously measured decay time constants which are important background information are collected in an Appendix, to help in the review and classification of previously published results [5, 6].

2. Theoretical Background

Ultra-dense hydrogen $H(0)$ is a quantum material which is superfluid and superconductive at room temperature. It is is spin-based Rydberg matter [12, 13, 20] with angular momentum $l = 0$ for the electrons and a spin quantum number $s$ with observed values 1, 2, 3 and 4. Only a few properties of special interest for the present study will be summarized here.

Due to the measured very short H-H (most common) distance of 2.3 pm [13, 21] in the state $s = 2$, the density of $H(0)$ is very high, in fact higher than the density of hydrogen fuel for fusion believed possible by any compression method [22, 23]. Thus, it is possible to initiate nuclear processes by relatively weak laser pulses in the $H(0)$ material [24–28]. It is concluded that the main process initiated by the laser pulse is a transition from spin level $s = 2$ in $H(0)$ with H-H distance of 2.3 pm, to level $s = 1$ with H-H distance of 0.56 pm [12, 29] from where nuclear reactions are fast and spontaneous. In the well-studied muon-induced or muon-catalyzed fusion process, the D-D distance is of similar size, and the rate of fusion at this short distance is close to $10^9$ s$^{-1}$ [30]. Since the transition to level $s = 1$ also can take place spontaneously at a low rate, a spontaneous nuclear process exists. This process is further described in Refs. [2, 4].
The interaction of neutral kaons with matter is complex. This is first of all due to the oscillations between the two observable states $K_L^0$ (long-lived kaon, decay time 52 ns) and $K_S^0$ (short-lived kaon, decay time of the order of $10^{-10}$ s) [10, 11]. These states are linear combinations of the two basic neutral kaons $K^0$ and $\bar{K}^0$. The observable neutral kaons $K_L^0$ and $K_S^0$ are their own antiparticles. The oscillation starts the so-called regeneration process [6, 7] which means that the long-lived state $K_L^0$ (which is the one that can fly some distance in the present experiments due to its relatively long lifetime of 52 ns) is partially transferred to the short-lived state $K_S^0$ [8, 9]. When the long-lived kaons reach any metal parts at the encapsulated detector, they may rapidly transfer to short-lived neutral kaons $K_S^0$. At a kaon velocity of 0.5 c (see the Appendix), this short-lived kaon $K_S^0$ decays after 1.5 cm travel distance into pion pairs, in 31% of the cases into two neutral pions $\pi^0$ which each rapidly decays to two gamma quanta with different energies. With 69% probability, a pair of charged pions $\pi^- + \pi^+$ is formed instead, which then decay to muons and neutrinos [8, 11]. The long-lived kaon $K_L^0$ decays with 21% probability to three neutral pions which also each decays to pairs of gamma photons. Several other decay possibilities exist for $K_L^0$ [8–11]. The long-lived neutral kaons were clearly observed in this system previously by the decay time constant in Refs. [1, 2, 4, 13, 15] and in the Appendix. Thus the best possibility to identify the short-lived neutral kaons is by observing the high-energy gamma photon peaks which can only be formed after kaon decay to neutral pions $\pi^0$. When a gamma photon peak at intermediate energy corresponding to four gamma photons can be observed as shown in Section 4, the detection of short-lived neutral kaons $K_S^0$ is confirmed.

Some of the kaons $K_L^0$ have relatively low kinetic energy from their pair production process, determined to be < 50 MeV from experiments [1, 2, 4, 15]. However, the most important kaon formation process, i.e. from nucleon annihilation, adds a kinetic energy close to 100 MeV to the kaons. This is clearly observed for the long-lived neutral kaons and for the charged kaons, as explained in the Appendix. More details are published in Ref. [5].

The analysis based on the results in the Appendix and in Ref. [5] can be adapted to the situation of most interest here: the creation of neutral kaons from annihilation of neutrons + anti-neutrons [6]. The annihilation processes are described in Ref. [6]:

$$n + \bar{n} \rightarrow 2K^0(96\text{MeV}) + 2\pi^\pm(69\text{MeV}) + 2\pi^\pm(0\text{MeV})$$

$$2 \times 939.6 - 2 \times (497.7 + 96) - 2 \times (139.6 + 69) - 2 \times (139.6) = 1879.2 - 1883.8 = -4.6\text{MeV}$$

where the kinetic energies of the created particles in parantheses are calculated from their dilated decays [5] and the energetics is correctly accounted for at the few MeV level, with a precision within 0.2%. If instead of charged pions, neutral pions are formed directly in the annihilation reaction the energetics is
\[ n + \bar{n} \rightarrow 2K^0(96\text{MeV}) + 2\pi^{\pm}(69\text{MeV}) + 2\pi^0(0\text{MeV}) \]
\[ 2 \times 939.6 - 2 \times (497.7 + 96) - 2 \times (139.6 + 69) - 2 \times (135.0) = \]
\[ 1879.2 - 1874.6 = 4.6\text{MeV} \]

which has a similar precision. When neutral pions are formed at the meson generator (by decay of $K_S^0$ created in the annihilation), the gamma photons produced by their decay will have just a small probability to reach the PMT detector. This is due to the relatively large distance between the meson generator and the detector. Thus, the signal contribution from such directly formed $K_S^0$ is small.

Due to the large kaon kinetic energy of 100 MeV, the neutral pions $\pi^0$ from their decay will have large kinetic energy and large momenta. This means that the two gamma photons from the $\pi^0$ decay will not have the same energy and momenta due to energy and momentum conservation. Thus, the energy distributions of the gamma photons from decay of $\pi^0$ are broad. The distributions may extend considerably both above and below the value for stationary pions of 67.5 MeV. In general, the photons will not be emitted in opposite directions due to energy and momentum conservation. Such high-energy photons interact with matter producing very little photo-ionization. The main process is instead pair production of electron-positron (lepton) pairs [9]. Compton scattering is also an important mechanism which forms typical Compton edges in the energy spectra. The leptons created by the gamma photons inside the PMT detector produce an amplified current pulse, which is the pulse signal observed. The energies of these pulses are measured.

## 3. Experimental

The H(0) source, which is also called the muon generator [31, 32] or the meson generator, is mounted in a small vacuum chamber. In this generator, several potassium doped iron oxide catalyst samples [33, 34] form p(0) from natural hydrogen gas (99.9995% pure hydrogen, naturally containing only 0.016% D), or D(0) from D$_2$ gas (99.8%), all normally at pressures below 100 mbar. Some of the ultra-dense hydrogen formed stays on the generator upper surface. The gas pressure in the chamber during the experiments was 0.2–0.6 mbar (uncorrected Pirani gauge reading) with constant pumping, and up to 100 mbar without pumping.

The laser used to influence the H(0) phase, in just a few of the experiments shown here, is a Nd:YAG laser with pulse energy < 0.4 J at 1064 nm and pulse length 7 ns with pulse repetition rate of 10 Hz. The laser beam was focused with an f = 50 mm lens on the H(0) surface layer on top of the H(0) generator. The laser beam waist was < 20 µm as calculated for a Gaussian beam. This means a laser intensity of < 4×10¹³ W cm⁻² for a Gaussian beam [35].

In the scintillator experiments, the photo-multiplier (PMT) detector part, with a thick metal enclosure, was separated from the muon generator chamber. The scintillator used in this case was a BC-720 Fast Neutron Detector (Saint-Gobain Crystals) which is a thin plastic scintillator with additives, primarily ZnS. The neutron-generated pulse signal in the scintillator is stated by the manufacturer to have a decay time
of 200 ns. This long decay time is stated to be due to proton accelerated by fast neutron collisions in the scintillator. The signal studied now had a pulse length of a few ns and was apparently due to other fast particles. The scintillator was at a distance of 2–15 cm, usually 31 mm, from the photocathode of the PMT. The scintillator and PMT were mounted inside a light-tight thick metal container built from standard vacuum components as shown in Fig. 1. No other scintillator or converter was used in the experiments with this thin scintillator. Extinguished laboratory lighting and thick black cloth over the detector part were always used to prevent light leakage. This detector unit was moved into various positions in the laboratory.

In the converter experiments, the detector part was mounted on the vacuum chamber where the mesons and muons are formed by the H(0) generator. It was mounted at some distance from the generator as shown in Fig. 2. The front vacuum wall at the PMT part was a stainless steel plate with thickness of 0.2 mm. Outside this plate, an Al foil converter \([7, 17, 27]\) (hand compressed 20 µm thick folded pillow) and the PMT are mounted in air, in the light-tight thick metal container built from standard vacuum components. The Al converter was fastened on the PMT cathode with plastic tape. It interacted with kaons and muons and gave electron-positron pair production as in \([15]\). Extinguished laboratory lighting and thick black cloth over the detector part were always used to prevent photon leakage for example through the electrical Teflon insulated feedthroughs to the PMT.

The PMT was an Electron Tubes 9128B with single electron rise time of 2.5 ns, electron transit time of 30 ns, end-window cathode, and linear focused dynode structure. PMT high voltage was 1600 V. A preamplifier (Ortec VT120) with bandwidth of 10–350 MHz and gain of 20, and a pulse-shaping amplifier (Ortec 440A) with shaping time of 0.5 µs were used. The signal from the amplifier was analyzed by a 2048 channel multi-channel analyzer (MCA) (Ortec EASY-MCA-2k with Maestro software) for the MCA spectra normally within a 250 s measuring period.

The electron energy scale of the detector was calibrated by using the beta emission from a \(^{137}\)Cs probe (37 kBq, Gammadata, Uppsala, Sweden) either outside the metal wall of the detector enclosure or close to the PMT body without metal enclosure. Thus, the photocathode was not involved in the signal generation and the electrons passing into the PMT from the outside started the signal generation and amplification process in the PMT. The detector is only sensitive to charged particles entering or being formed inside the PMT. The muons formed by the decay of the mesons are penetrating \([36]\). Plots of the square root of the number of counts against MCA channel number (approximate Kurie plot) show zero signal cutoff due to \(^{137}\)Cs at 170 channels using the preamplifier with gain 200. With \(Q = 512 \text{ keV for } ^{137}\text{Cs}\), this provides a calibration of 3.0 keV/channel. With a preamplifier of nominal gain 20 instead, this would correspond to 30 keV per channel. However, a better calibration of this preamplifier using a gain of 8 in the main amplifier corresponds to 46 keV/channel (recalculated to gain 1), and a calibration using a gain of 1 in the main amplifier correspond to 47 keV/channel (more uncertain due to the small number of channels used). Thus, 46 keV per channel with gain 1 in the main amplifier and with the gain 20 preamplifier is used here. This calibration is used up to 70 MeV which is an extrapolation. However, the uncertainty in the
energy deposition from the gamma photons into the leptons in the PMT is arguably a larger uncertainty factor, and the observation of particle energies approaching 100 MeV is certain.

4. Results

The main neutral kaon decay processes which produce muons and gamma photons are [8–11],

\[ K_S^0 \rightarrow \pi^0 + \pi^0 \rightarrow 2\gamma + 2\gamma \rightarrow n (e^+ + e^-) \] (1)

\[ K_S^0 \rightarrow \pi^+ + \pi^- \rightarrow \mu^+ + \mu^- \rightarrow i(e^+ + e^-) \] (2)

\[ K_L^0 \rightarrow \pi^0 + \pi^0 + \pi^0 \rightarrow 2\gamma + 2\gamma + 2\gamma \rightarrow m (e^+ + e^-) \] (3)

\[ K_L^0 \rightarrow (\text{metal}) \rightarrow K_S^0 \rightarrow \pi^0 + \pi^0 \rightarrow 2\gamma + 2\gamma \rightarrow n (e^+ + e^-) \] (4)

\[ K_L^0 \rightarrow (\text{metal}) \rightarrow K_S^0 \rightarrow \pi^+ + \pi^- \rightarrow \mu^+ + \mu^- \rightarrow i(e^+ + e^-) \] (5)

Neutrinos are also formed but omitted here. The decays differ for \( K_L^0 \) and \( K_S^0 \) by the emission of six or four photons, respectively, which is here used to discriminate between them. The muonic channels Eqs. (2) and (5) provide evidence for the neutral kaons. Eqs. (1) and (4) with 4 gamma photons show evidence for the short-lived neutral kaon \( K_S^0 \). Eq. (3) with 6 gamma photons provides evidence for the long-lived neutral kaon \( K_L^0 \). As described further below, three different gamma photon peaks are observed, which correspond to two, four and six gamma photons, thus providing evidence for both \( K_S^0 \) (four gamma photons) and \( K_L^0 \) (two and six gamma photons).

The two gamma photons from each neutral pion decay do not generally move in opposite directions as they would do if the pion was at rest in the lab system. This is caused by the momentum of the neutral pion \( \pi^0 \) which is of a size similar to that of the gamma photons. Further, the photons do not in general have an energy of \( 135/2 = 67.5 \) MeV due to the large kinetic energy of the neutral pion. Thus, the energy and momentum conservation results in different directions for the initial pion and the resulting two gamma photons.

The kaon decay processes in Eqs. (4) and (5) take place in contact with the metal parts around the detector and especially in the Al foil pillow converter used in some of the experiments. Each gamma photon with energy of the order of 70 MeV can create numerous lepton pairs, since each such pair requires only 1.02 MeV for its production. The number of leptons in each pulse will vary mainly with the number of neutral pions decaying, resulting in a crude spectrum in the PMT with photpeaks for each set of pions (primarily two and three sets as in Eqs. (1) and (3)). There exists also another decay channel (12%) for \( K_L^0 \) [10]

\[ K_L^0 \rightarrow \pi^0 + \pi^+ + \pi^- \rightarrow 2\gamma + \mu^+ + \mu^- + \ldots \rightarrow m (e^+ + e^-) + i(e^+ + e^-) + \ldots \] (6)
In this process, a signal corresponding to just one neutral pion $\pi^0$ will probably be observed by the detector employed. A similar signal from just one $\pi^0$ may also be obtained from charged kaons $K^\pm$ [10] (21%), so it is expected to observe three equally spaced photopeaks, indicating the gamma photons from one, two or three neutral pions $\pi^0$. This is confirmed below, with peaks centered close to 19.2 MeV, $19.2 \times 2 = 38.4$ MeV, and $19.2 \times 3 = 57.6$ MeV energy observed by the PMT detector. Thus, evidence for both types of neutral kaons is obtained.

The method of detection used is selective: charged mesons will not easily pass through the stainless steel enclosure of the PMT, and the PMT detector only reacts to charged particles. Thus, the charged particles must be formed inside the detector enclosure. The energy calibration of the PMT as described above uses a beta (electron) emitter outside the PMT, so the photocathode is not involved in the signal generation. This means that neutral particles which can penetrate into the detector enclosure and form charged particles there will be detected preferentially. This is the detection process needed for identification of neutral kaons, being either short-lived or long-lived, and also for neutral pions, which create leptons in the interaction of the gamma photons with the detector structure. The final signal observed is due to charged leptons formed or released inside the PMT. These leptons induce secondary cascades in the multiplier dynode structure when a high voltage is applied over the PMT.

4.1. Muon and kaon detection with scintillator

The results presented in this section are found with the thin scintillator detector separated from the meson generator chamber. It is at a distance of less than 2 m from the generator in air. Thus the particles reaching the detector have penetrated 2 mm of stainless steel in the vacuum chamber wall and a similar thickness of stainless steel in the detector enclosure. The signals observed are mainly spontaneous and decrease in time for weeks after formation and deposition of H(0) in the generator. Also signals caused by laser impact in the generator can be observed, but due to the short pulse length and low laser repetition rate of 10 Hz, also in these cases the main part of the observed signal is due to spontaneous processes in H(0). However, the pulsed laser impact in the generator chamber causes recognizable energy spectrum effects even when the detector part is separated from the generator by up to 2 m of air and 4 mm of steel, as shown below. This proves that the signal is not due to any other sources outside the apparatus. The spontaneous signal (i.e. a signal that is not directly related in time to an external stimulus) is influenced by the prior or concurrent laser use, thus also the spontaneous signal is from the inside of the apparatus. A typical signal using the thin scintillator BC-720 is shown in Fig. 3. There are three different signal contributions apparent in this figure: 1) the dominant muon signal at low energy which was studied in previous publications [7, 17], 2) a slightly lower signal at intermediate energy and 3) an even less intense signal at high energy above 1 MeV. The high energy signal will be studied further in the next section. It is there shown to be due to neutral kaon decay. An intermediate energy signal was concluded in experiments inside the vacuum chamber [27] to be due to charged particles. Here, however only muons and long-lived neutral kaons can penetrate the steel walls and reach the detector outside the chamber, to create leptons in the detector part. The black spectrum in Fig. 3 shows the signal remaining
after running the laser for a few minutes. This process decreases the kaon signal, both at high and intermediate energy, after partial destruction of the H(0) in the generator. This effect shows once more that the signal observed is due to spontaneous sources inside the apparatus which can be influenced by the laser, not due to any external or cosmic sources.

The signal at intermediate energy is observed at relatively high intensity in the experiments. One example is shown in Fig. 4. There the total signal corresponding to neutral kaons at intermediate energy is of the order of 100 s\(^{-1}\). This large signal size excludes once more that the signal is due to cosmic or other external sources. The black curve in Fig. 4 shows the signal a few days earlier, before long-time preparation in D\(_2\) gas which gave a large amount of D(0) in the apparatus. Kurie-like plots (square root of intensity against particle energy) here generally show a good linear variation with energy. This indicates a muon signal and shows a constant cut-offs at 1.1 MeV on the PMT energy scale (Fig. 5). This indicates a pulse size corresponding not only to one muon (as described in previous publications \([7, 17, 27]\) with a 0.52 MeV cutoff) but an energy corresponding to two simultaneously detected muons. This agrees with a decay process of short-lived neutral kaons as in Eqs. (2) and (5) \([8, 9]\). The two almost simultaneously formed muons (certainly both appearing within the 500 ns shaping time of the amplifier) will result in double the pulse size in the PMT relative to the one muon case studied previously \([7, 17]\). This explains the behaviour at intermediate energies found in Fig. 5. The long-lived kaon oscillation to short-lived kaons means that each long-lived neutral kaon decays to one positive and one negative muon with 69% probability \([8–11]\). This detection process forms a large signal contribution due to the metal enclosure of the detector as described above. If short-lived neutral kaons are formed at the meson generator, they will decay rapidly and there is little signal in the detector. With no oscillation to a short-lived neutral kaon, a long-lived neutral kaon should form a pair of charged pions with 12% probability which decay to muons and one charged pion with either positive or negative charge with 66% probability. These decays also form muons. These small differences between the processes for 1. long-lived neutral kaons oscillating to short-lived (69%) or 2. (not oscillating (66 + 12 = 75%)) cannot be observed in the results found. The kaon interaction with the steel walls close to the detector makes it highly likely that short-lived kaons are formed there from the long-lived kaons. The probability that a long-lived neutral kaon will decay by itself inside the detector volume (52 ns decay time passing through the detector) is much smaller than the probability of decay as a short-lived neutral kaon (0.1 ns decay time) after oscillation due to the metal walls. Unfortunately, this oscillation probability does not appear to be known from theory or experiment but from the present results it appears to be of the order of 0.1 or larger.

This neutral kaon signal increases with the amount of D(0) in the generator, and it increases by heating of the generator and by D\(_2\) admission. The most striking observation is that the kaon signal increases with time (of the order of days) using D\(_2\) gas at high pressure (many mbar) in the generator, with one example in Fig. 4. Further, this signal is slowly decreased by laser impact on the generator, in the time range of minutes to hours with an example in Fig. 6. Thus, the structure of D(0) which forms most neutral kaons is created by self-organization in the D(0) material but it is destroyed by the (probably subsidiary) effects of
the impacting laser, possibly by gamma photon emission from the laser-induced nuclear processes. This special structure is concluded to be the small molecules H$_3$(0) and H$_4$(0) [37].

The detection of neutral kaons does not depend on the special properties of this scintillator. The same type of spectra as in Figs. 3 and 4 can be found also with a metal converter in the setup used in the next section. Thus, the detection of neutral kaons described here is due to kaon decay in dense materials followed by almost the same detection mechanism of the muons generated as reported for muons previously. A coverage of the scintillator end with a PE box does not reduce the neutral kaon signal at intermediate energy while the normal muon signal at low energy decreases as expected. A removal of the scintillator from the detector tube strongly decreases both the muon and the kaon parts of the signals. Thus, the kaon signal is due to both the metal wall and the scintillator: the kaons decay to pions in the walls around the PMT, and the pions finally form electrons and positrons in the scintillator and in the PMT tube. Thus, neglecting neutrinos and gamma photons,

\[ K^0_L \rightarrow (\text{metal wall}) \rightarrow K^0_S \rightarrow \pi^+ + \pi^- \rightarrow \mu^+ + \mu^- \ (\text{scintillator}) \rightarrow i(e^+ + e^-) \]

is the main signal generating process as in Eq. (5).

### 4.2. Gamma photon detection with metal converter

In the so called converter type of experiment, the PMT detector part is mounted on the vacuum apparatus which contains the meson generator, as shown in Fig. 2. The vacuum wall in front of the PMT part is a steel plate of 0.2 mm thickness. Thus, the particles pass through the 0.2 mm steel plate to the Al foil converter at the PMT cathode as shown in Fig. 2. This converter [17] is used to form electrons and positrons by pair production from muons (as in [7, 15, 17, 27]) but here it is also used for lepton pair production from the gamma photons created by the decay of neutral kaons as shown in Eqs. (1), (3) and (4). The signals observed are spontaneous, no inducing field or particles are used. To observe the large energy signal, the preamplifier used has low gain, normally G = 20. Typical experimental results with two of the main peaks observed are shown in Fig. 7. These peaks are in the energy range up to 70 MeV for electrons using the calibration 46 keV/channel, which was described in the experimental section. The energies found are thus very large and show directly that decaying particles with large masses like kaons are involved and that an efficient process has transferred energy to the leptons which enter the PMT. The interpretation of these results is that long-lived neutral kaons $K^0_L$ are emitted from the generator. After entering the stainless steel plate facing the PMT part and partial transformation at the steel plate to short-lived kaons $K^0_S$, they decay to neutral pions $\pi^0$ which then form high-energy gamma photons. These gamma photons produce several lepton pairs (electron-positron pairs) at the PMT detector. Of course, these complex processes may produce a varying appearance of the peaks due to the exact direction of the kaons entering the detector part. A reasonable calibration for the efficiency of this setup can however be found from the results in Fig. 7, if the two main peaks are interpreted as due to two and three neutral pions each, from the processes in Eqs. (3) and (4). This means that each neutral pion with at least 135 MeV energy on average deposits 19.2 MeV as electron energy in the detector (19.2×2 = 38.4 MeV, 19.2×3 = 57.6 MeV for the other peaks). This will be discussed below.
A typical low-energy distribution is shown in a logarithmic plot and a square-root (Kurie-like) plot in Fig. 8. The prior use of the laser decreased the kaon signal level. The distribution in Fig. 8 does not show a clear beta-like shape, which distinguishes this kaon-type signal from the normal muon signal observed in the same system at lower energy [7, 17, 27]. Beta-like signals were observed in the scintillator experiments described above. Thus, a broad energy distribution exists for the leptons from the decay of neutral pions, as expected. The typical zero cutoff energy in Fig. 8 is around 19 MeV. This corresponds to one gamma photon from one neutral pion coming from the process in Eq. (6). The reason for the distribution is likely that several particles (lepton pairs) are formed from each photon with variable energy in the range around 70–100 MeV.

These high-energy signals are not quenched at a gas pressure of the order of 10 mbar in the chamber. The pressures used are indicated in the figure captions. Charged mesons like charged kaons and pions are quenched at such pressures. This shows that the signal here is caused by neutral particles, thus neutral kaons as was concluded from the gamma photon spectra.

By changing the conditions at the generator it is also possible to observe further high-energy features. In Fig. 9, a small amount of Ga metal is added on the muon generator surface. The liquid Ga metal absorbs H(0) and forms a larger amount of H(0) on the generator. This results in a visibly stronger white plasma with impinging laser pulse. In the top panel Fig. 9(a), a typical photopeak with Compton minimum is observed, at an edge corresponding to 67 MeV thus close to the expected average gamma photon energy (135/2 = 67.5 MeV). This peak corresponds well to a pair of photons with 135 MeV total energy, which creates the peak just below 67 MeV and the peak at 63.5 MeV which may be close to the Compton edge. This means that the gamma photopeak can be observed for the neutral pion decay. This photopeak has also been reproduced without Ga using 20 mbar H₂ pressure. By moving the generator to a slightly lower position, shown in Fig. 2 (thus introducing more material in the path to the detector), the peak at 58 MeV from Fig. 7 is found together with the photopeak in Fig. 9. This peak at 58 MeV corresponds to three pions. A similar effect may be observed for the lower energy 38 MeV (two pions) peak in Fig. 7, where both a relatively sharp photopeak clearly indicating gamma photons and a broader peak are shown.

The changes in peak structure for example between Figs. 7, 9 and 10 are apparently due to changes in the kaon distributions to the detector, due to variations in the location and structure of the emitting H(0) material inside the generator. If more information about the scattering of the kaons is needed for the design of kaon detectors, more specific experiments can be performed.

An important non-intuitive result is shown in Fig. 10, providing further proof for the signal generation process. Two spectra are shown, one with and one without the usual Al converter between the steel plate and the PMT. In the case without converter the signal is very low and does not show any high-energy particles. With the Al converter in place, the signal is high and shows a typical photopeak at 38 MeV as in Fig. 7, attributed to four gamma photons from $K^0_S$ as in Eqs. (1) and (4). It is apparent that intense showers of leptons enter the PMT or are formed in it. This creates the intense pulses observed at the anode output of the PMT. If the signal pulses would be due to photons entering the PMT instead, the
signal in Fig. 10 would be higher with the Al converter removed (not blocking the entrance to the PMT), not a factor of > 300 lower without converter as found here. Thus, the Al converter interacts with the kaons and forms the neutral pions and finally the gamma radiation and the lepton pairs observed.

It is also possible to distinguish between gamma photons originating at the muon generator and in the steel plate and the Al converter in front of the PMT. Due to the large distance between the generator and the detector, the number of gamma photons reaching the PMT should be decreased by a factor < 4 when the PMT is moved away 10 cm (to the double distance). In Fig. 11, it is shown instead that the signal decreases a factor of 90 or more by this change in PMT position. This indicates that the gamma photons are formed at the steel plate in the wall or in the converter at the PMT by particles generated in the steel plate by neutral kaons. If these particles from the steel plate are very short-lived neutral pions $\pi^0$, the loss in signal by moving the PMT away 10 cm will be very strong. The angular coverage of the converter relative to the steel plate decreases strongly through the 10 cm move, and even more important the neutral pions will decay long before they reach the converter, emitting gamma photons which have just a small probability to reach the converter or the PMT. Thus, the gamma photons observed are formed close to the detector, not at the generator. The particles which can reach the steel plate from the generator are (possibly) charged kaons and long-lived neutral kaons $K^0_L$. The long-lived neutral kaons oscillate at the steel plate to form short-lived neutral kaons $K^0_S$ which decay to neutral pions inside the detector housing. The pions decay to gamma photons which produce lepton pairs inside or just outside the PMT. This experiment in Fig. 11 thus shows all the important steps in the signal generation.

5. Discussion

The most striking evidence for the formation and decay of the short-lived neutral kaons $K^0_S$ is the large particle energies (around 70 MeV) observed with the metal converter in the PMT detector part, when it is attached to the vacuum apparatus thus close to the generator. That such high-energy features exist at all is remarkable and convincing evidence for spontaneous formation of neutral kaons. The photopeaks observed indicate gamma photons. The energy spectra are not constant in the form shown for example in Fig. 10 as can be seen from the other figures showing the converter experiments, Figs. 7–9 and 11. They vary during an experimental run, with low signals at the start of the day before H(0) has accumulated in the generator. The gas pressure and the history of H(0) deposition in the generator are important factors for the signals obtained. Thus, it is easily observed in the experiments that the signal is not due to any (highly unlikely) factor like some type of spontaneous neutron activation of the Al foil converter (which was indeed easily exchanged as a check with no change in performance). These signals are neither caused by cosmic processes of any kind since they change in a reproducible and predictable way with the conditions in the H(0) generator.

The signal at energies below the photopeaks in the converter experiments may to a large part be due to lepton showers from pair production. It is likely that these leptons are formed by highly energetic photons from decay of neutral pions with energies of the order of 50–130 MeV. The interaction of such gamma photons with the metal converter and other structures close to the PMT will form numerous lepton pairs
through pair production. This is the most important energy loss process for such gamma photons, even if Compton scattering also exists. The photopeaks may be due to pairs of photons from the same neutral pion or from single photons close to the maximum energy, while the remaining signal will be due to unrelated photons from different pions. Gamma photons backscattered from the structure surrounding the PMT may also contribute to the signal level between the peaks via lepton pair formation.

The energy calibrations in the converter experiments indicate that two pions or four gamma photons (2×135 MeV) form a total lepton shower energy of 38 MeV. This corresponds to an energy efficiency of 38/270 = 14% (or estimated 38/540 = 7% when the kinetic energy of the neutral pions is available for pair production). This 7% value agrees with the expected pair production probability of a few % loss in energy for 68 MeV gamma photons [38]. A low energy efficiency is expected for pair production outside the PMT due to the low lepton collection efficiency. Of course, when a considerable number of the leptons as here are formed inside the PMT the fraction lost will be smaller and this will results in a high observed efficiency. The high efficiency here may be due to a strong pair production depending on the large kinetic energy of the neutral pions.

The formation process of kaons from the ultradense condensate of hydrogen is well understood theoretically, with the overall experimental mechanism proved in several publications [1, 2, 3, 4, 17, 39]. This mechanism is proved from the energy cycles in section 2 in good agreement with baryon annihilation [5, 6].

It would also be interesting to determine the sensitivity of the neutral kaon detection. The detection process depends on the so-called oscillation or regeneration process, where the long-lived kaon $K^0_L$ is transformed to the short-lived kaon $K^0_S$. This process depends on the interaction of $K^0_L$ with matter and varies with the velocity of the kaons [9] and the density and thickness of the material. In the present experiments, the velocity of the kaons is relatively low, of the order of 100 MeV from their formation process, in contrast to some experiments where around 100 GeV/c momentum was used [40]. Thus, it does not seem possible to compare such results directly. Theoretical calculations of kaon regeneration appear to be disputed [41]. Thus, the detection efficiency of the kaons cannot be determined at present. It appears however to be relatively high > 0.1.

In the discussion of radiation hazards for living tissue, neutral kaons are often treated like ionizing radiation, while in fact they interact neither electromagnetically nor strongly with matter and thus are penetrating through solid materials and living organisms without much harm. They do not appear to be involved in nuclear reactions similar to neutrons. The oscillation from $K^0_L$ to $K^0_S$ is however observed in the experiments, and this produces continued decay to neutral pions and gamma quanta. This might appear to be a contradiction to the small radiation effects stated. It is suggested here that the oscillation from $K^0_L$ to $K^0_S$ only takes place in contact with heavy nuclei (like in the metal walls around the detector) and thus that this oscillation process is not very important for neutral kaons entering living tissue. Further studies are certainly needed.
6. Conclusions

Expected signatures of neutral kaons especially of the short-lived neutral kaon $K_S^0$ have been identified. This complements the previous observations of long-lived neutral kaons $K_L^0$ from their 52 ns decay time constant. Particle energy measurements with scintillators identify the process of decay of $K_S^0$, finally producing two muons after the initial decay of $K_S^0$ to two charged pions. This process is the most probable process for decay of $K_S^0$ with 69% probability. Particle energy measurements with Al converters identify the process of decay of neutral pions to high-energy gamma photons (following the initial decay of $K_S^0$ to two neutral pions, which has 31% probability). A peak corresponding to four gamma photons is proof for $K_S^0$, while a peak corresponding to six gamma photons provides proof for $K_L^0$. The verification of all three types of kaons generated from H(0) is completed. The relatively simple device used here has the power to observe neutral kaons which are generated at up to $10^{14}$ s$^{-1}$ from the novel nuclear fuel H(0). Such kaons are difficult to observe with other methods since they are neutral. The next important step is to measure and understand the interactions of the neutral kaons with matter and living matter, for annihilation energy processes and radiation safety in such processes.

Declarations

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Conflict of interest statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

References


Figures

Figure 1
Photo of the separate PMT (photo multiplier) part with location of PMT indicated, as used for the thin scintillator experiments. Thin scintillator (Saint-Gobain BC-720) is seen with enclosure opened. The preamplifier is seen on the feedthrough in the outer flange at the top-left corner of the upper panel.

Figure 2

Vertical cut through apparatus used for the converter experiments, not to scale. The vacuum separation between the chamber and the detector part is an 0.2 mm thick stainless steel plate mounted between two rubber o-rings in the flange at the main chamber. Note the Al converter between the steel plate and the PMT. The laser is used in just a few experiments.
Figure 3

Neutral kaons give two muons. Typical MCA energy spectra with thin scintillator BC-720. Spectrum in black is the same run after running the laser, with decreased signal of both kaons and muons. Setup in Fig. 2 with prior D$_2$ gas admission. Experiment duration 2500 s.
Figure 4

Large signal of neutral kaons, with twice the energy of muons in the range above 500 keV. Setup in Fig. 2 with prior $D_2$ gas admission. Spectrum in black is an earlier experiment a few days before $D_2$ gas admission. Experiment duration 2500 s. Count rate of neutral kaons of the order of 100 $s^{-1}$. Thin scintillator BC-720.
Figure 5

Twice the muon energy for the neutral kaons. There are two parts of the curve which show an approximate Kurie behavior. The part corresponding to muons is shown in the top panel, and the one corresponding to kaons is shown in the bottom panel. 10 mbar D$_2$ gas. Scintillator BC-720.
Figure 6

Effect of laser on neutral kaon signal. The kaon signal falls slowly during minutes and hours after the laser is turned off. Scintillator BC-720. 10 mbar D$_2$ gas.
Figure 7

Photopeaks corresponding to two \((38 \text{ MeV} \approx 2 \times 19.2 \text{ MeV})\) and three \((58 \text{ MeV} \approx 3 \times 19.2 \text{ MeV})\) neutral pions. Converter spectra using apparatus in Fig. 2. Preamplifier with gain 20. 19 mbar H\(_2\) and air, and laser on in (a) and 14 mbar H\(_2\) gas in (b).
Figure 8

Logarithmic plot and approximate Kurie plot for the signal at relatively low energy with apparatus in Fig. 2 with Al converter. After laser experiment. Cutoff close to 19 MeV. Preamplifier with gain 20. 3 mbar H₂ gas.
Figure 9

Photopeak at 63.5 MeV with Al converter. Ga metal added at the generator surface using apparatus in Fig. 2. The photopeak is observed at 0.2 mbar H₂ pressure in (a) with generator in top position (at level with detector) and in (b) with generator 2 cm lower.
Figure 10

Photopeak at 38 MeV $\approx 2 \times 19.2$ MeV corresponding to two neutral pions. Al converter. Preamplifier with gain 20. 14 mbar H$_2$ gas. Approximately $10^4$ counts s$^{-1}$ with converter, spontaneous signal.
Figure 11

Effect of distance between steel plate and PMT with Al converter. With 10 cm added distance, all high-energy particles formed in the steel plate decay before they reach the PMT. Preamplifier with gain 20 at 7 mbar H$_2$ gas, showing a photopeak at 38 MeV.

**Supplementary Files**

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