A system for determining the purity of liquid krypton used in the NA62 rare kaon decay experiment at CERN was developed based on a small time projection chamber. The lifetime of drifting ionization electrons from absorption of 511 keV gamma rays in liquid krypton was measured to assess the purity. The setup was tested with krypton obtained directly from the NA62 calorimeter and with krypton purified from commercial sources.
I. INTRODUCTION

The liquid krypton (LKr) ionization calorimeter (LKRC) plays a key role in the photon veto and particle identification systems for rare kaon decay measurements done at the CERN experiment NA62 [1]. Detailed descriptions of the LKRC can be found in [2, 3]. The active volume is longitudinally segmented by 127 cm-long beryllium-copper ribbons which form an octagonal grid of 13248 \( \times \) \( \times \) cm\(^2\) individual towers facing the beam direction. The cylindrical cryo-vessel contains about 9 m\(^3\) of LKr. Boil-off gas passes through filters before being re-condensed in the LKRC by an argon cooler, ensuring continuous recirculation.

Due to the transitory occurrence of small leaks in the LKRC system during the period 2016–17, it became necessary to replenish the Kr supply using commercially obtained gas which is typically available with purity at the ppm level. However, for operation in the LKRC purification of the Kr gas at the ppb level is required and measurement of the electron lifetime is desirable before it is transferred to the LKRC.

The principal electro-negative impurities in such systems are usually oxygen and water. During the development and commissioning phase of the LKRC, the maximum electron drift time was measured under normal operating conditions (with 3 kV applied to the anodes) to be 3 \( \mu \)s [4]. The electron lifetime was found to be >300 \( \mu \)s [3] which is sufficient for NA62 operations.

To determine the ionization electron lifetime in the LKRC and in LKr purified from commercially sourced Kr, a new purity monitoring system was developed. The system is based on the use of a small (32 cm\(^3\)) time projection chamber (TPC) installed in a cryogenic vessel containing about 2 l of LKr. The device allows measurement of the attenuation of ionization charge as a function of the drift time and applied electric field, and, therefore, can be used to determine the electron lifetime in LKr.

This report describes the cryogenic and purity measurement systems, and the purity measurements made with gas sampled from the LKRC and with newly purified Kr. The following sections cover the cryogenic system (II), the detection apparatus (III), and the measurements performed (IV).

II. PURIFICATION AND CRYOGENIC SYSTEMS

The cryogenic setup and the procedures used to purify and condense LKr are described in [5]. Briefly, filtered Kr gas was condensed inside the LKr vessel with a heat exchanger (HEX) linked to a cryocooler. The filters used to purify commercially supplied Kr gas were the same as in the LKRC recirculation system: two Sertronic type N gas purifiers in series. In the filters, the feed gas passes through a special catalyst which traps oxygen, while water and carbon dioxide are adsorbed on a molecular sieve bed. The principal

\[1\] http://www.sertronic.com/gas-purifiers/sertronic-purifiers/neutral-gas-purifier/
impurities removed are $\text{O}_2$, $\text{CO}$, $\text{CO}_2$, and $\text{H}_2\text{O}$. A single stage coaxial pulse tube cryocooler was used as a cooling source to liquefy Kr. The cooling power of the cryocooler (with a 3 kW compressor) at 120 K is approximately 55 W. The temperature of the cold head was controlled at 119 K during condensation and then at 119.8 K during stable operation. Figure 1 shows an assembly drawing of the vacuum insulated LKr vessel with the TPC, HEX, and the radiation entrance window. The inner LKr vessel cryostat is covered in 20 layers of multi-layer insulation. Prior to measurements described in Sec. IV, the LKr vessel was baked at 60 C for 3 weeks by running a current through a temporarily applied heating tape and pumping vacuum to a level $p < 2 \times 10^{-7}$ mbar.

The HEX cold head of the cryocooler cannot be heated above 60 C and the MPPCs described in section III cannot be heated to more than 80 C.
III. DETECTION APPARATUS

The TPC detector system, previously used in the measurements on liquid xenon [6], was modified for the present measurements of electron lifetime in LKr. As discussed below, avalanche photodiodes (APD) were replaced by Multi-Pixel Photon Counters (MPPC) to provide triggering for the ionization drift time measurement and preamplifiers were installed on the anodes. As shown in Figure 2, the TPC features ground potential anodes, a shielding grid (25 µm dia. wires, spaced 3 mm apart) separated from the anodes by 3 mm, a field cage, and a negatively biased cathode plane with a $3 \times 3 \times 3.6 \text{ cm}^3$ drift volume. Charge was collected on a central 1 cm dia. electrode (A1) or on a $3 \times 3 \text{ cm}^2$ outer electrode (A2). An electric drift field up to 1.5 kV/cm could be applied between the cathode and the shielding grid separated by 3.6 cm; the positive electric field between the anodes and grid was maintained at twice the drift field value. The field cage consisted of nine wires with a spacing of 3 mm strung around the four walls of the chamber; the voltage was distributed by 100 MΩ resistors.

![Figure 2](image_url)

**FIG. 2** – Schematic of the TPC. Left: End view showing the central (A1) and outer (A2) anodes and locations of the MPPC light sensors. Right: Side view showing the drift region with anodes, grid, cathode, and field cage wires; 511 keV gamma rays from annihilation of positrons emitted by a $^{22}\text{Na}$ source enter through the cathode from the left.

As indicated in Figure 3, eight windowless Hamamatsu VUV4-MPPC were assembled to view the prompt 150 nm scintillation light from LKr through the field cage wires. The signals from two groups of four MPPCs were summed and sent to external room temperature post-amplifiers (MPPC1 and MPPC2). Prior to the installation of the MPPC light sensors, the TPC was washed with isopropanol in an ultrasonic cleaner at a maximum temperature of 60°C. The completed detector system was then installed in the cryostat. A $^{22}\text{Na}$ positron

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3 Hamamatsu model S13371-6050CN-02 VUV Multi-Pixel Photon Counter.
annihilation source (activity $2.5 \times 10^5$ Bq) was used to create energy deposits in the TPC for electron drift time measurements as indicated in Figure 4. 511 keV photons produced from positron annihilation at the source were detected in the TPC in coincidence with an external NaI(Tl) crystal detector of dimensions 12.7 cm dia. and 12.7 cm long. A source collimator and the crystal were aligned in a brass support cylinder aimed at the central anode (A1) position, previously determined relative to the cryostat entrance window shown in Figure 1. The coincidence between energy-selected 511 keV photo-peak events measured
FIG. 4 – Schematic diagram of the measurement system (not to scale). A $^{22}\text{Na}$ positron annihilation source emits back-to-back 511 keV gamma rays detected by the TPC and a NaI(Tl) detector. The TPC central anode (A1), grid (g), cathode (C), and MPPCs are indicated.

Taking into account the energy needed to produce an electron-ion pair $W = 20.5 \pm 1.5$ eV \cite{8}, and assuming charge collection efficiency 80 % of the saturation value at 0.8 kV/cm, and 80 % grid transparency, an A1 anode signal of about 2.5 fC was expected for a 511 keV photon undergoing absorption by photo-electron emission. The anode signals were read out with adjacent N-Channel JFET (BF862) amplifiers situated in the LKr (see Figure 5) and connected by coaxial cables to room temperature post-amplifiers located outside the cryostat.

The readout system is outlined in Figure 6. The signal from the NaI(Tl) detector was split to allow high and low level discriminators used to select the 511 keV photo-peak events. The signals from the NaI(Tl) detector, MPPCs, and anodes were read out using a CAEN...
FIG. 5 – Schematic of the cold preamps (see text).

DT5725 14-bit 500 MS/s FADC. The FADC was connected through a USB port to a laptop computer running the MIDAS [9] data acquisition system.

IV. MEASUREMENTS

Initial measurements were performed at the CERN Cryolab and, after qualification, the apparatus was transported and reassembled adjacent to the LKRC in the NA62 experimental area. Prior to measurements, the LKr vessel and connecting piping were baked-out as mentioned in Sec. [1] and purged to remove any residual gas; then, the vacuum insulation space between the outer and inner regions was evacuated.

Measurements were made with boil-off gas from the LKRC with no additional filtering. Figure [7] shows the charge distribution on the TPC anode A1 triggered by coincidence of the MPPC and NaI(Tl) signals for the full 16 µs drift time window at a drift field of 0.83 kV/cm. A Gaussian fit to the 511 keV photoelectron peak gave a resolution $\sigma = 7.3 \%$.

The average light signal varies in amplitude due to the solid angle acceptance of the
MPPCs which is maximum at the center of the TPC. After selecting the 511 keV charge peak, the observed energy resolution based on the light signal at the central 1 µs drift time slice was $\sigma = 13\%$. Since the light and charge signals are anti-correlated in LKr \[10\], the charge signal increases and the light signal decreases with increasing electric field. Combining the signals as discussed in \[11\] resulted in improved resolution of $\sigma = 4.3\%$ as indicated in Figure 8. The correlation angle in the charge vs. light plot was $18^\circ$.

To estimate the electron lifetime, the drift time was segmented into 16 1 µs regions and the amplitudes of the 511 keV peaks were determined by fitting the peak regions with a Gaussian in the presence of functions representing the Compton edge and background. Figure 9 shows the amplitude of the 511 keV photopeak as a function of drift time for data taken with Kr gas taken directly from the LKRC. The attenuation was estimated to be $\Delta A/A(0) = (-6.6 \pm 5.8) \times 10^{-4}/\text{cm}$ corresponding to a lower limit on the electron lifetime $\tau_e > 2.7$ ms (90\% c.l.\[12\]) using the observed drift velocity $v_d = 2.3 \text{ mm/}\mu\text{s}$ at electric field $E = 0.83 \text{ kV/cm}$. Using the average of the atomic electron attachment cross sections available for LAr and LXe compiled by Doke \[13\] at this electric field, we estimated an equivalent O$_2$ (or H$_2$O) contamination of < 0.1 ppb for the system measuring gas from LKRC.

In other measurements, commercially obtained Kr gas$^4$ was passed once through the

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$^4$ Krypton 5.0 from supplier Linde AG with the following maximum component of impurities: H$_2$O $\leq 2$
FIG. 7 – Energy distribution from the charge measurement for all drift times at electric field \( E = 0.83 \text{ kV/cm} \); a Gaussian fit to the 511 keV photoelectron peak is shown (see text).

FIG. 8 – Combined charge and light energy distribution for central drift times at electric field \( E = 0.83 \text{ kV/cm} \); a Gaussian fit to the 511 keV photoelectron peak is shown (see text).

filters and then condensed in the LKr vessel. With no electric field applied to the TPC cathode, the rate of MPPCs hits was found to be 7 kHz\(^5\) due primarily to the presence of \(^{85}\text{Kr}\); this rate is consistent with an expected \(^{85}\text{Kr}\) contamination of \(10^{-11}–10^{-10}\) \(^{14}\). Figure 10 shows the amplitude of the 511 keV photoelectron peak as a function of drift time for data taken at electric field \( E = 0.83 \text{ kV/cm} \) with condensed Kr from commercially supplied Kr gas passed through the filters; the limit obtained on the electron lifetime was \(\tau_e > 1.9 \text{ ms} \) (90\% c.l.) and the equivalent \(\text{O}_2\) (or \(\text{H}_2\text{O}\)) contamination was estimated to be 

\[ \begin{align*}
\text{ppm} , \, \text{O}_2 & \leq 0.5 \text{ ppm}, \, \text{HC} \leq 0.5 \text{ ppm}, \, \text{N}_2 \leq 2 \text{ ppm}, \, \text{Ar} \leq 1 \text{ ppm}, \, \text{CF}_4 \leq 1 \text{ ppm}, \, \text{Xe} \leq 1 \text{ ppm}, \, \text{CO}+\text{CO}_2 \leq 1 \text{ ppm}, \, \text{H}_2 \leq 1 \text{ ppm}.
\end{align*} \]

\(^5\) The detection threshold was estimated to be 100 keV to be compared with the \(^{85}\text{Kr}\) beta decay endpoint energy of 687 keV.
FIG. 9 – Charge signal photo-peak amplitude (keV) vs. drift time (channels) in 1 µs slices at electric field $E = 0.83$ kV/cm for condensed Kr gas from the LKRC. Each channel is 4 ns.

< 0.2 ppb. Since the attenuation is reduced further at higher fields, it is clear that these levels of impurity contamination have a negligible effect on the operation of the LKRC at its nominal field of $E = 3$ kV/cm.

V. CONCLUSION

A system for measuring the ionization electron lifetime, and consequently, the purity of LKr was developed. The attenuation of drifting ionization was measured in a small-time projection chamber triggered by scintillation light detected by MPPCs in coincidence with signals from a NaI(Tl) crystal observing back-to-back 511 keV annihilation photons from a $^{22}$Na source. Electron lifetimes $\geq 2$ ms were observed in gas samples from the NA62 LKr calorimeter and from commercially supplied Kr gas bottles after filtering, more than satisfying the requirements for operation of the NA62 experiment.

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FIG. 10 – Charge signal photo-peak amplitude (keV) vs. drift time (channels) in 1 µs slices at electric field $E = 0.83$ kV/cm for condensed filtered Kr gas from bottles. Each channel is 4 ns.

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