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Section A

Ionization of liquid krypton by electrons, gamma rays and alpha particles

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The charge and energy resolution response of liquid krypton to electrons, γ-rays and α particles was measured with pulsed ionization chambers. The best noise subtracted energy resolution obtained with a ^{207}Bi source was found to be 3.1% FWHM for 1 MeV electrons, and 2.3% FWHM for the 5.31 MeV α particles from ^{210}Po.

1. Introduction

The ionization characteristics of liquid krypton irradiated with fast electrons, γ-rays and α particles were investigated. These studies aim at a better understanding of the properties of liquid rare gases and their use in radiation detectors for a variety of physics and astrophysics applications. Similar studies with liquid argon and liquid xenon have already been reported by us [1,2]. The availability of data on free-ion yield and energy resolution response to different ionizing radiations for the three liquids should enable the refinement of existing recombination theories. With their present limitations these theories are still unable to fully explain the experimental results on the energy resolution of liquid ionization chambers. Our experiments with liquid krypton were also triggered by the need of a more precise determination of the *W*-value, the average energy required to produce an electron–ion pair. Results on this will be presented in a forthcoming publication. In this paper we report the results on the studies of the charge and energy resolution response of liquid krypton to fast electrons, γ-rays and α particles.

2. Experimental

A parallel plate ionization chamber was used to measure the ionization yield of α particles in liquid krypton. The distance between cathode and anode was 4.7 mm. The volume of the stainless steel vessel containing the electrode structure was approximately 0.3 liter. As a radioactive source we used a combination of 0.1 μCi of ^{210}Po and 0.1 μCi of ^{207}Bi, chemically deposited on the center of the cathode plate.

For the measurements with electrons and γ-rays the ionization chamber was modified by including a grid between cathode and anode. A cathode plate with 0.1 μCi of ^{207}Bi deposited on its center was used. Typically, the distance between grid and cathode was 3.5 mm while the grid to anode distance was 2 mm. The grid was an electroformed mesh made out of nickel and had a shielding efficiency of 99%. A ratio of 2 between the collection and drift fields was used to provide 100% electron transmission.

Commercially available "research grade" krypton gas typically contains the following impurities [3]: $N_2 <$ 2 ppm, $O_2 < 0.1$ ppm, Ar < 1 ppm, $CO_2 < 0.1$ ppm, $H_2 < 1$ ppm, $CH_4 < 0.1$ ppm, $H_2O < 0.1$ ppm, Xe < 5 ppm, $CF_4 < 0.1$ ppm and other hydrocarbons less than 0.1 ppm. Before introducing it in the ionization chambers, the krypton was further purified by passing it sequentially through an Oxisorb cartridge [4], a molecular sieve trap and high temperature getters. The purification system was similar to the one used for xenon and is discussed in details in ref. [5]. From our experiments we found that krypton was much easier to purify than xenon. In fact, only one cycle of purification was sufficient to reach almost complete charge collection in liquid krypton, whereas many repeated cycles were needed for liquid xenon. We note here, however, that when we used krypton gas directly from the commercial bottle without passing it through the purifiers, the charge response measured with the combined ^{207}Bi and ^{210}Po source in a parallel plate chamber, was less than 50% of the charge collected in pure krypton.

The purified krypton gas was condensed by surrounding the test chamber with a cryogenic bath of liquid nitrogen and iso-pentane (commercially known as 2-methyl butane). The temperature of the cooling bath was 121 K, which is close to the triple point of krypton (fig. 1). At this temperature krypton has the relatively low vapor pressure of about 2 atm. As seen from fig. 1, the transition from liquid to solid for krypton at this pressure occurs within a few degrees, and care was taken to maintain a stable temperature of the bath to avoid freezing the krypton.

The pulses from the ionization chambers were analyzed with a low noise charge sensitive preamplifier, followed by a spectroscopy amplifier (Ortec 450) for amplification and shaping. The differential and integral time constants were chosen as 3 μs. For charge calibration, a voltage pulse from a precision pulse generator (BNC PB-4) was injected into the preamplifier through a known test capacitor. The value of this capacitor was measured precisely with a capacitance meter [7] and was found to be 1.08 ± 0.01 pF for most of the data measured in liquid krypton.

3. Results and discussion

Krypton gas contains small amounts of the radioactive isotope ^{85}Kr that has a half-life of 11 yr. It decays by beta decay with an endpoint energy of 670 keV and releases an average energy of 250 keV. We observed approximately 500 decays/s/cm^3 in liquid krypton. The spectra obtained with the ^{207}Bi and ^{210}Po sources were dominated in the low energy region by this background.

3.1. Electrons and γ-rays

The ionization of liquid krypton by ^{207}Bi internal conversion electrons and γ-rays was studied with a gridded ionization chamber. The energy spectrum of ^{207}Bi was measured repeatedly with chambers of different geometries, to confirm the reproducibility of the data. The maximum drift field applied was 16 kV/cm, after which breakdown occurred. Fig. 2 shows some of the results. In all of the spectra, the rightmost peak is the test pulse. Its width of 15 keV FWHM corresponds to the electronic noise. Due to the beta decay of ^{85}Kr, the low energy lines from ^{207}Bi in the range 550 keV to 570 keV were not visible at low fields and appeared only as a small enhancement at high fields. For drift fields above 2 kV/cm, the 976 keV K-conversion electron line was clearly distinguishable from the higher energy line, produced by 1048 keV L-conversion electrons and 1064 keV γ-rays. In liquid xenon such a

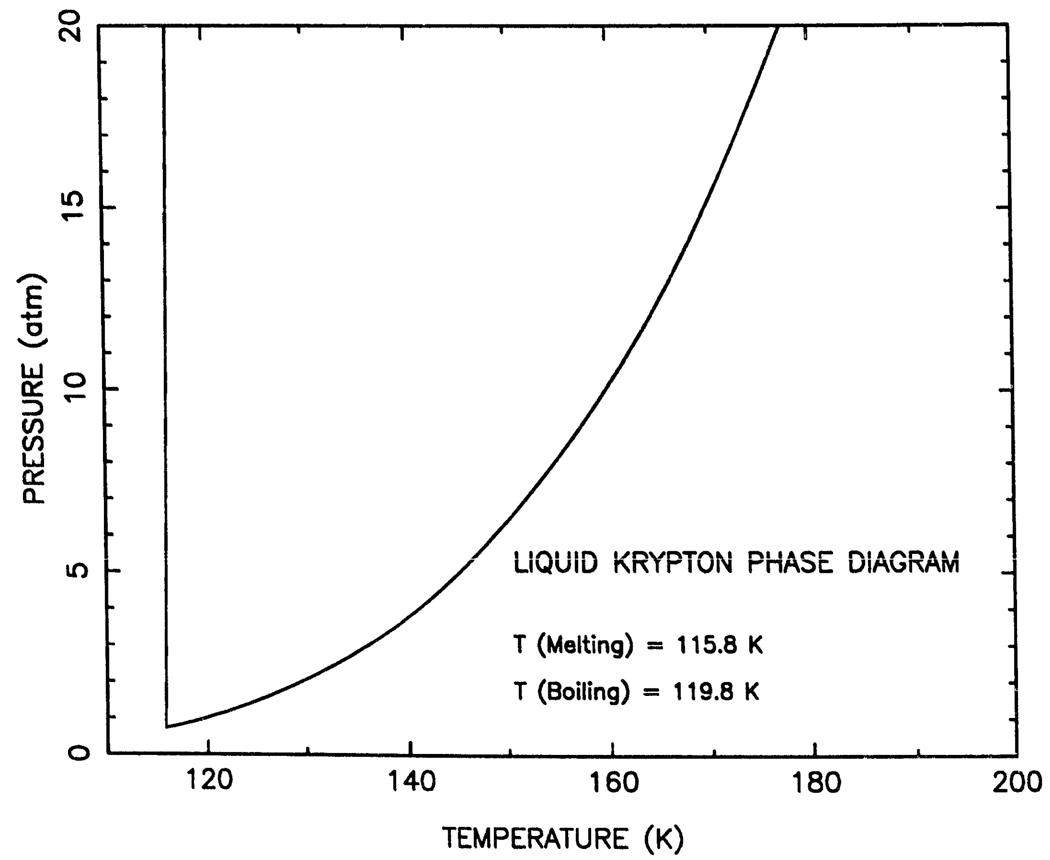

Fig. 1. Liquid krypton phase diagram. [6]

separation could only be achieved at much higher fields, indicating the better energy resolution response of liquid krypton.

The peak location and the width of the observed lines were determined by a least square fit with Gaussian functions to the data measured at each field. The data set which had the least electronic noise was analyzed. Fig. 3 shows the field dependence of the noise-subtracted energy resolution of the 976 keV electron as well as that of the combined 1048 keV and 1064 keV lines. The best energy resolution obtained with liquid krypton was 3.1% FWHM at 1 MeV. In comparison, the energy resolution measured by us in liquid xenon and in liquid argon was 4.5% FWHM [2] and 2.7% FWHM [1], respectively, at the same energy and similar electric field strength. The results with liquid krypton confirm our suggestion that the degradation of the energy resolution of a liquid ionization chamber is connected with the density of the liquid and the production of δ-electrons. The higher the density, the shorter the range of δ-electrons. Recombination fluctuations in the number of carriers liberated by low energy δ-electrons influences the total collected charge and hence the resolution.

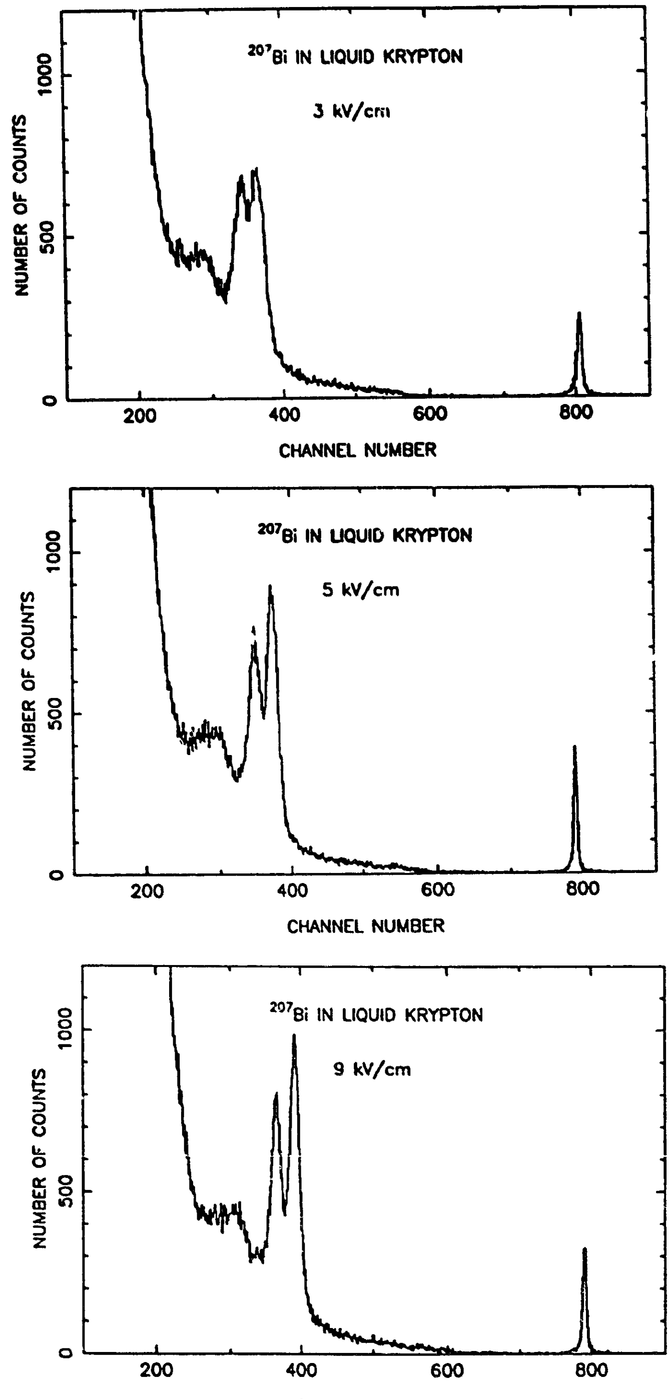

Fig. 2. Energy spectra of ^{207}Bi in liquid krypton at different drift fields. The rightmost peak corresponds to the testpulse.

3.2. *α particles*

To study the ionization yield of α particles in liquid krypton, the parallel plate geometry was used. The energy spectrum of ^{210}Po 5.31 MeV α particles was measured at different electric field strengths, in the range between 0.05 kV/cm to 20 kV/cm. Fig. 4 shows the ^{210}Po spectrum measured at 12 kV/cm. The rightmost peak is again the calibrating test pulse. At low electric fields the alpha peak was visible only as a small enhancement on top of the large background from ^{85}Kr. Since the source was a combination of ^{207}Bi and ^{210}Po, the 976 keV electron line from ^{207}Bi was also observed, given the short range of these electrons compared to the drift gap size. The energy resolution was, however, very poor due to the absence of the shielding grid.

Fig. 5 shows the electric field dependence of the collected charge, Q, normalized to the total number of electron-ion pairs liberated by a 5.31 MeV α particle, Q_0. For comparison, data obtained with the same source in liquid xenon are also shown [8]. For the normalization we used the W-value of 15.6 eV for liquid xenon [9], and our experimental value of 18.4 eV for liquid krypton [10]. The characteristic nonsaturation feature of the ionization yield of heavily ionizing particles in a dense medium was observed, as previously reported for liquid xenon and liquid argon [8]. Even at the highest applied field of 20 kV/cm, only about 15% of the total liberated charge was collected.

The noise subtracted energy resolution of the 5.31 MeV α particle peak is shown in fig. 6 as a function of the drift field. For comparison, data obtained in liquid xenon with the same source are also shown. The best energy resolution obtained in liquid krypton was 2.3% FWHM at 14 kV/cm, better than that for liquid xenon. The field dependence of the energy resolution is similar for the two liquids. The lower value in liquid krypton at high fields is explained by the reduced

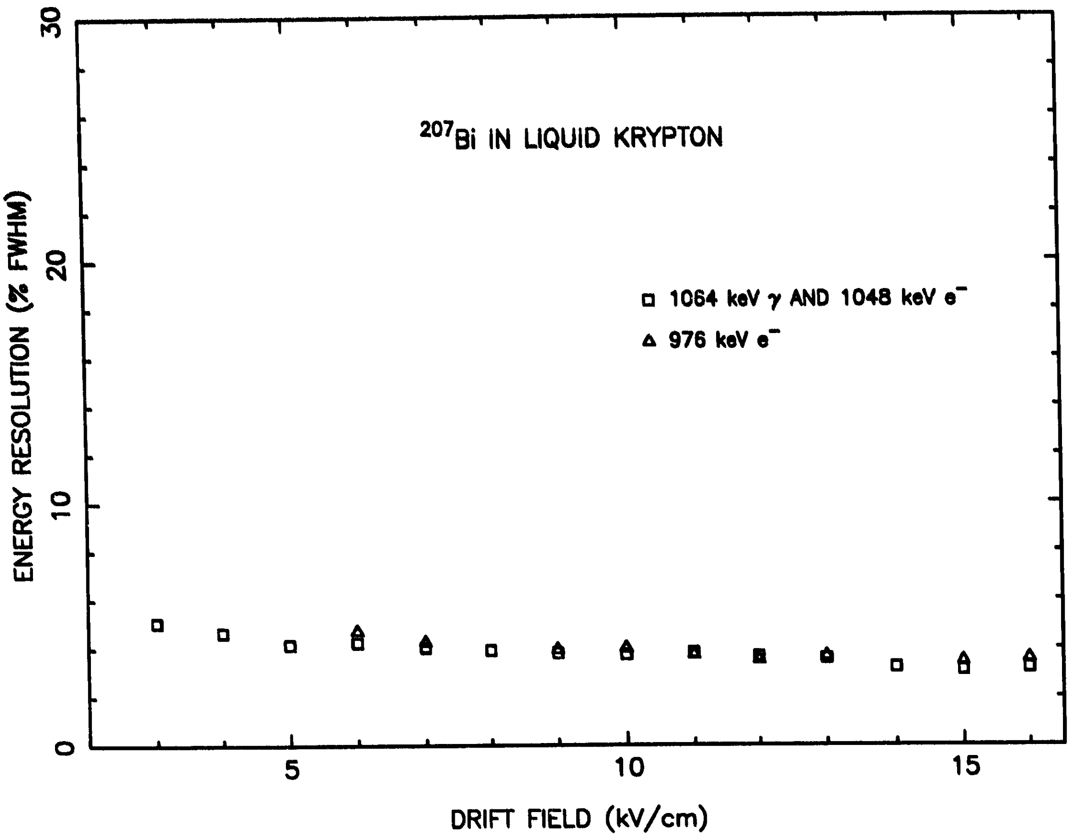

Fig. 3. Noise subtracted energy resolution of the combined 1048 and 1064 keV lines (□) and the 976 keV line (△) vs the drift field.

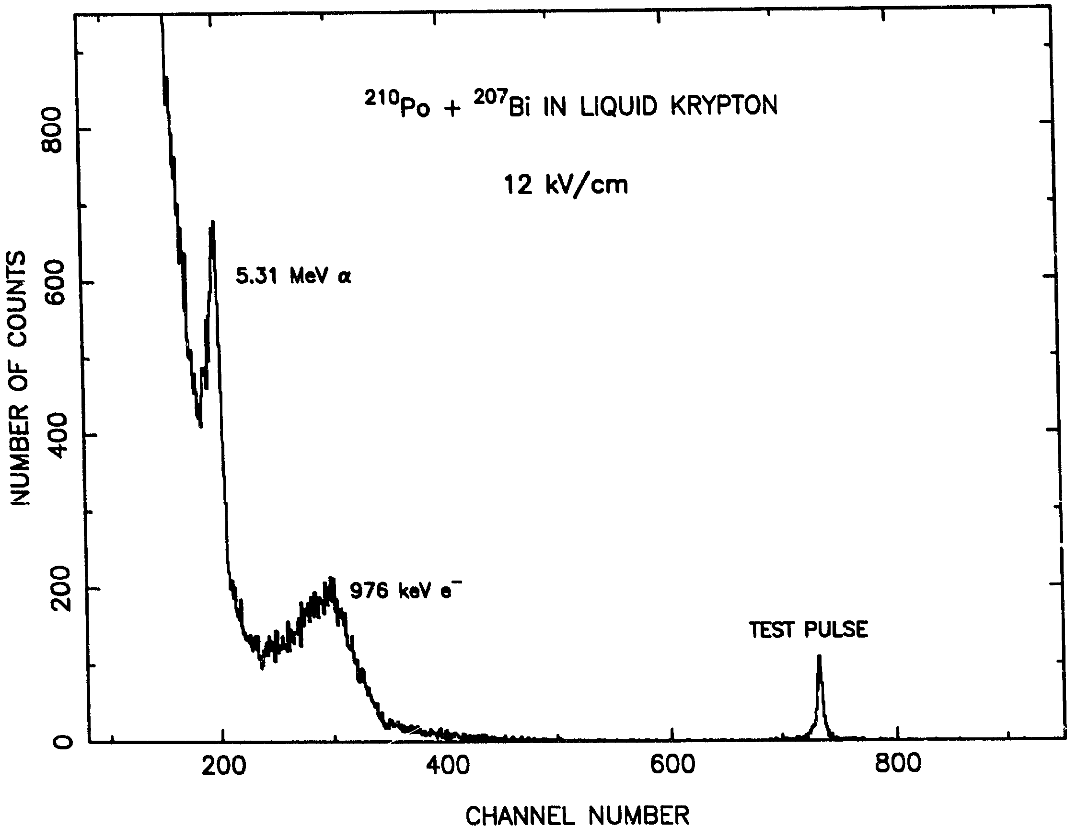

Fig. 4. Energy Spectrum of ^{210}Po + ^{207}Bi in liquid krypton at 12 kV/cm. The peak at the extreme right is the test pulse distribution.

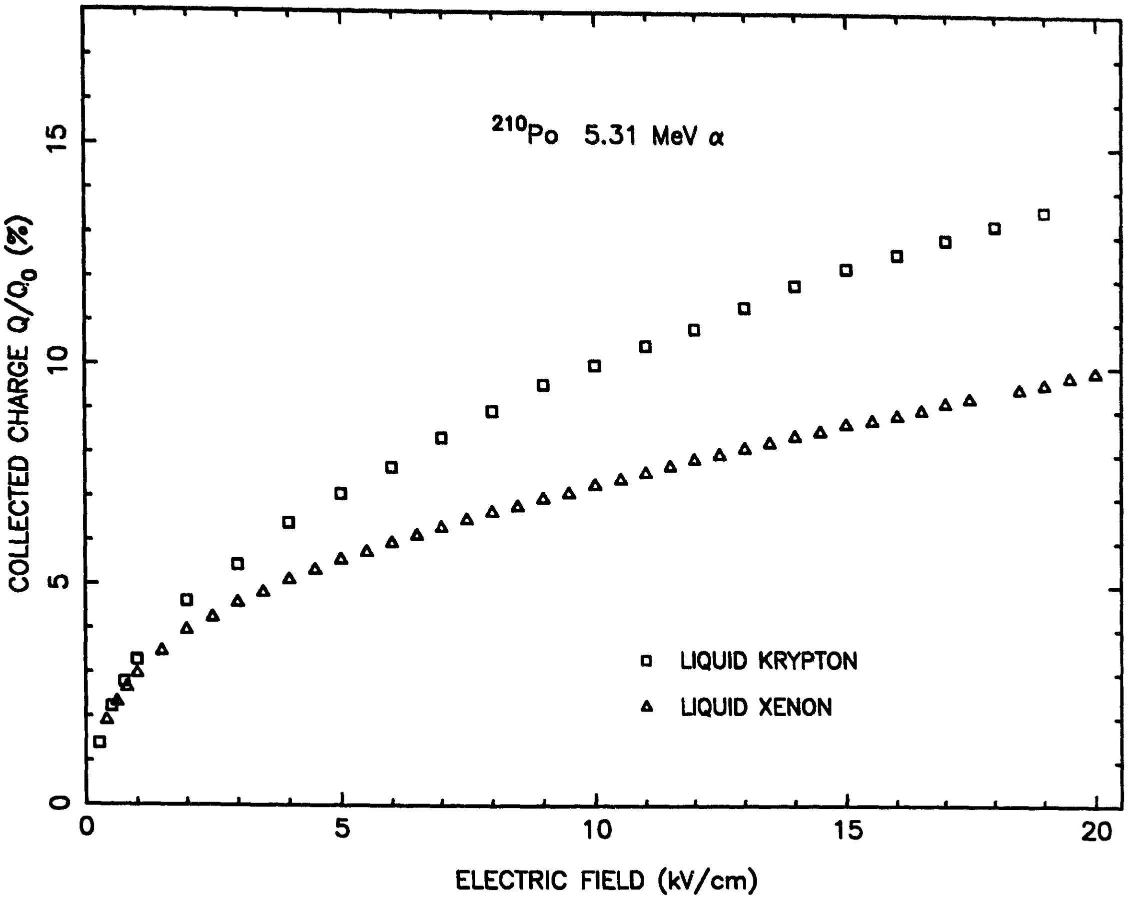

Fig. 5. Collected charge (Q / Q_0)% vs electric field for ^{210}Po in liquid krypton (□) and liquid xenon (△).

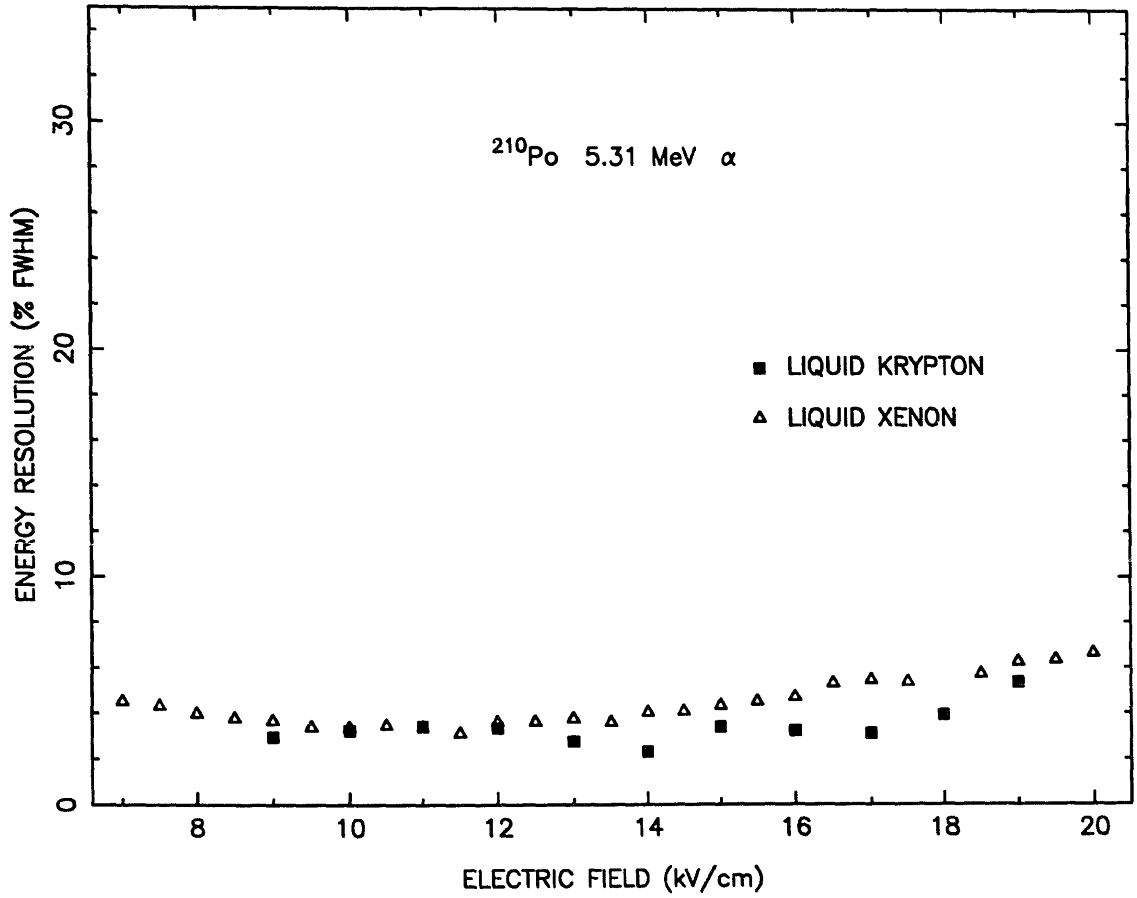

Fig. 6. Noise subtracted energy resolution vs electric field for ^{210}Po in liquid krypton (■) and liquid xenon (△).

effects of recombination along the δ-electron tracks, as already pointed out in section 3.1.

4. Conclusion

The energy spectrum of ^{207}Bi internal conversion electrons and γ-rays and ^{210}Po α particles was measured for the first time in liquid krypton, at various drift fields. Compared to liquid xenon, liquid krypton was found to be easier to purify and to have a better energy resolution, despite the lower ion yield. The best noise subtracted energy resolution obtained with the ^{207}Bi source was found to be 3.1% FWHM for 1 MeV electrons, and 2.3% FWHM for the 5.31 MeV α particles from ^{210}Po. Results on the *W*-value of liquid krypton will be presented in a forthcoming publication.

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