



Response of an α source mounted in a liquid argon ionization cell and read out in full charge collection mode

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Abstract

The total charge response curve of an ^{241}Am source placed in a liquid argon ionization cell has been measured. In a pure liquid argon sample (O_2 concentration < 0.1 ppm), it can be described by a semi-empirical formula which is derived from a model formerly elaborated by Thomas and Imel. The validity of this new formula was also tested in the case of oxygen-polluted liquid argon. The agreement with the data seems to indicate that the initial ion–electron pair recombination factor is not affected when the O_2 concentration is smaller than 7 ppm. Further use of our recombination factor parameterization has been made to analyze data of liquid argon purity monitors utilizing ^{241}Am sources with a sensitivity to O_2 concentrations of ~ 0.1 ppm. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Because of their good efficiency to signal the appearance of small impurity concentrations (below 1 ppm), alpha sources are extensively used to monitor the liquid purity stability in high-energy liquid argon calorimeters. They are mounted in ionization chambers and read out in full charge sensitive mode. However, in spite of their common utilization, the charge data provided by α cells have

been so far considered as being difficult to analyze for determining absolute pollution contaminations. This fact results from two considerations: firstly, no one has ever reported any fully satisfactory model reproducing the charge curve measured with α cells in pure liquid argon when varying the charge collection electric field; secondly, some data published in the past [1] were interpreted as possibly indicating that the initial electron–ion pair recombination, which is high when dealing with α tracks in liquid argon, is altered when an additive is dissolved into pure liquid.

In this paper, we show that a semi-empirical model exists which fits the α cell charge response

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measured over a period of more than a year in a series of experiments performed in liquid argon. This model, together with an absorption factor, can also be used, as it will be shown in Section 4, to reproduce our data taken in oxygen-polluted liquid argon, indicating that no modification of the initial recombination factor takes place at low contaminations.

2. Measurements

Our α cell consists of an ^{241}Am source featuring an activity of $\sim 3 \text{ kBq}/4\pi$, which was deposited on a 30 mm diameter stainless steel disk in a central

active zone whose diameter is 15 mm. This disk, which plays the role of the cathode in our setup, faces a segmented anode composed of one central disk and an external concentric ring. The central disk, which has a diameter of 15 mm, collects the signals of drifting electrons induced by α tracks, while the external ring which is connected to the same positive HV power supply, helps in establishing a homogeneous electric field over the overall cell diameter. The liquid argon gap, which is mechanically ensured by glass fiber epoxy spacers placed on the radial periphery of the chamber, is $0.7^{+0.05}$ mm.

The central anode disk is connected via a 1.2 m 100Ω cable to the input of a charge sensitive

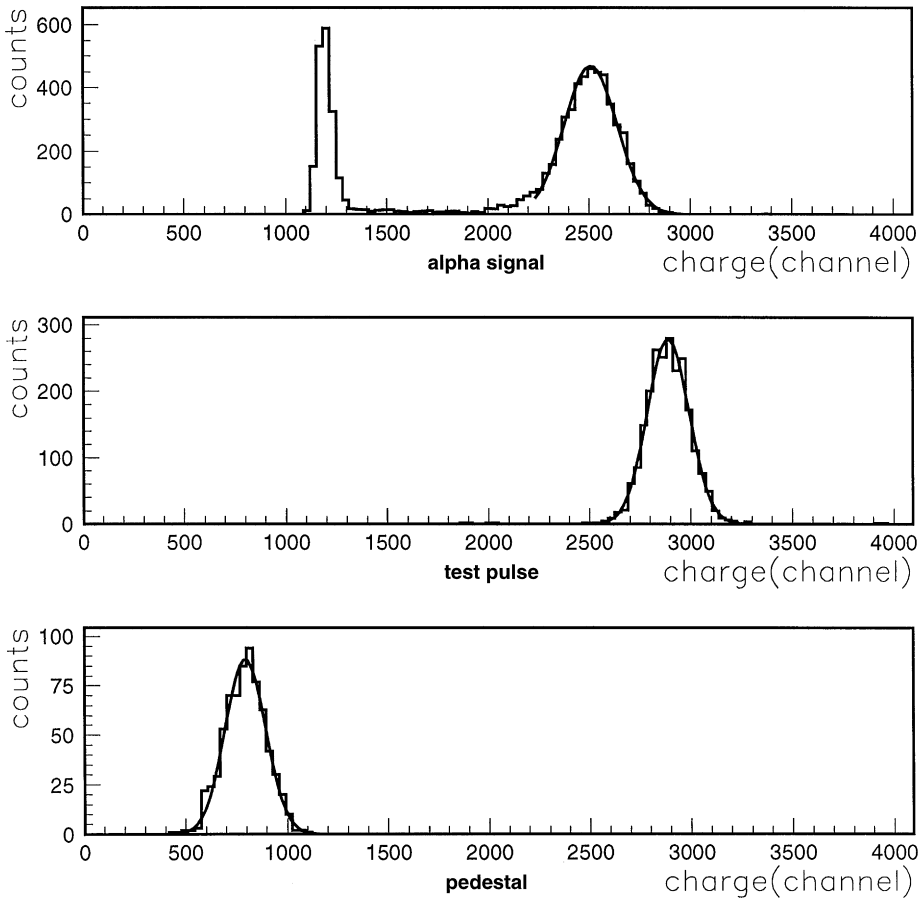


Fig. 1. Charge spectra: smooth lines are the results of Gaussian fits. On the top histogram, the tail on the left is what is left of the noise after the trigger threshold is applied.

preamplifier which is mounted with a feedback capacitor of 1 pF. The output of the preamplifier is filtered by a CR-RC shaper whose time constant is 145 ns, before being integrated in a charge-to-digital CAMAC converter over a gate of 100 ns in width which is centered on the position of the maximal amplitude of the output. The integration gate as well as the acquisition trigger threshold are delivered by a constant fraction discriminator in order to maintain a timing adjustment constant irrespective of the input signal amplitudes. To calibrate and monitor the gain of the readout chain, a generator pulse of appropriate shape (rectangular current pulse of 160 ns duration) was fed into the input of the preamplifier. Events which also include calibration triggers and random events for measuring the pedestal charge, are simultaneously recorded by means of a PC equipped with a GPIB-to-CAMAC interface.

During the measurement campaigns, the α cell is immersed in an aluminum cryostat which can contain up to 10 l of liquid argon. Special precautions were taken in the installation of the argon circuitry in order to obtain high purity liquid, i.e. typically better than 0.1 ppm of O_2 . Prior to any liquefaction operations, the cryostat is pumped over a night and then rinsed several times with clean argon gas. The argon gas, purchased in certified good purity grade (better than 3 ppm of O_2), is passed through a filtering cartridge which retains oxygen and water vapor, and is subsequently liquefied in the cold vessel of the cryostat by means of a liquid nitrogen heat exchanger.

Typical charge spectra recorded at a given electric field with this setup are presented in Fig. 1. The α charge as a function of the electric field E is derived from these data by means of the following expression:

$$Q(E) = Q_{\text{cal}} \frac{\langle \alpha(E) \rangle - \langle \text{pedestal} \rangle}{\langle \text{test} \rangle - \langle \text{pedestal} \rangle} \quad (1)$$

where Q_{cal} is the calibration factor which can be deduced from the absolute value of the collected charge we measured at 20 kV/cm: 5.53 ± 0.21 fC, in reasonable agreement with Refs. [2,3]. Fig. 2 shows the α charge values we measured as a function of the electric field. The error bars, magnified by a

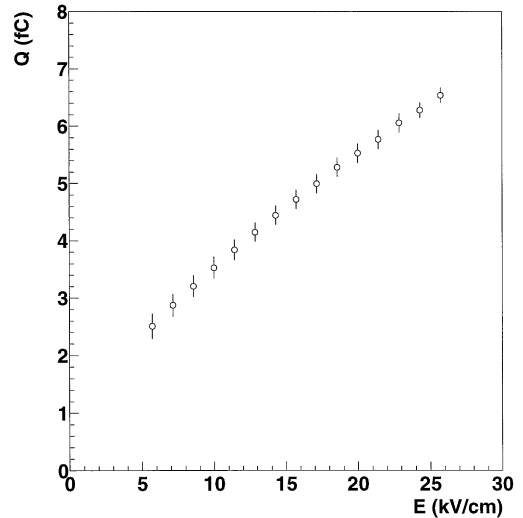


Fig. 2. α charge values as a function of the electric field. The error bars have been magnified by a factor 10 to render them visible.

factor 10 to render them visible, are typically 0.2–0.8%. All in all, 9 curves of this type were measured using approximately the same setup over a period of more than a year. Our data always showed a good reproducibility for what concerns the shape of the α charge curve. To illustrate this assertion, we present in Fig. 3 the ratio of data sets obtained from two of these experiments performed at dates separated by approximately a year.

3. Model

Ten years ago, Thomas and Imel [4] derived from the simplified transport equations of ions and electrons traveling in pure liquid argon a model of the collected charge which reads

$$Q(E) = Q_0 \frac{1}{\xi} \ln(1 + \xi) \quad (2)$$

where $\xi E = 470$ kV/cm, E is the electric field and Q_0 is the total ionized electron charge produced by an α track. In pure liquid argon, the function $(1/\xi)\ln(1 + \xi)$ describes the initial recombination of electron–ion pairs. The mean energy of an α

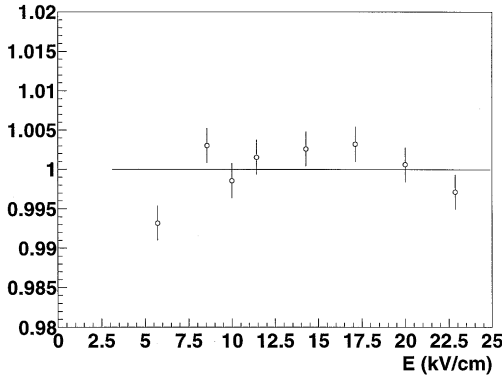


Fig. 3. Ratio of α charge values measured in two of our experiments as a function of the electric field.

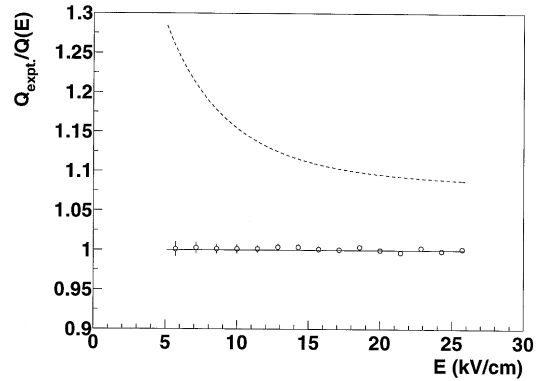


Fig. 4. α charge data compared to models. The flat curve corresponds to our model. The dashed line is the ratio of the new model over the original Thomas and Imel's one.

particle produced in the decay of ^{241}Am is 5.479 MeV [5] which, if we consider that 23.6 eV on average [6] are needed to create an electron–ion pair, yields a value of 37.1 fC for Q_0 . Although this derivation represented quite an improvement compared to Onsager's theory [7] for the description of the α charge curve, it was clearly visible in Thomas and Imel's original paper that the agreement of their model with the data of Refs. [2,8] was not perfect. Discrepancies at the level of 10–20% were manifestly present in their analysis especially at low electric field.

We suggest a slight modification of this model. Because of its good behavior in the limit of E tending to zero or infinity, we have kept Eq. (2), but ξE was allowed to be a function of E . We empirically found that

$$\xi E = a(1 - \frac{1}{2}e^{-bE}) \quad (3)$$

where $a = 416 \pm 1.4$ kV/cm and $b = 0.198 \pm 0.006$ kV/cm, provides an excellent analytic description of our data as presented in Fig. 4.

4. Model tests in oxygen-polluted liquid argon

Under the assumption that the physics processes governing the initial ion–electron pair recombination are not affected by the presence of low impu-

rity concentrations (< 10 ppm O_2), the collected charge induced by α tracks reads

$$Q'(E) = Q_0 \frac{1}{\xi} \ln(1 + \xi) \text{Abs}(E) \quad (4)$$

where $\text{Abs}(E)$ is the absorption factor which is given by the following expression:

$$\text{Abs}(E) = \frac{\lambda(E)}{d} (1 - e^{-[d/\lambda(E)]}) \quad (5)$$

in which d is the cathode-to-anode gap of the ionization cell and $\lambda(E)$ is the absorption length of free electrons drifting in the liquid. Pointing out that for oxygen, $\lambda(E)$ varies with E and the oxygen concentration p according to the following expression [1]:

$$\lambda(E) = \alpha E/p, \quad \text{with } \alpha = 14 \text{ mm}^2 \text{ ppm/kV} \quad (6)$$

one can observe that the absorption factor diminishes when increasing E , and thereby $Q'(E)$ becomes a function which is not a linear transform of $Q(E)$.

Knowing from Section 3 the expression of ξ , it is possible to derive from Q' measurements obtained in oxygen-polluted liquid argon, the values of $\text{Abs}(E)$ times a normalization factor C which may stem from a miscalibration of the read out charge, namely

$$\frac{Q'(E)}{Q_0(1/\xi)\ln(1 + \xi)} = C \text{Abs}(E). \quad (7)$$

A fit of the resulting data can be performed to extract C and the oxygen concentration p according to expressions (5) and (6). Note that if the experimental errors are small enough ($< 1\%$), a value of p significantly different from zero cannot arise from a miscalibration, i.e. $C \neq 1$, but only from a distortion of the charge curve shape.

To validate this procedure, we analyzed the charge data obtained in two contamination experiments for which 3.5 and 7 ppm ($\pm 10\%$) of oxygen was admixed with pure liquid argon. The oxygen was mixed with argon in the gaseous phase. It was introduced in a portion of the argon circuitry located sufficiently far away from the cryostat to avoid undesired condensation or retention on the surface of the cold pipes. Then, the oxygen–argon mixture was forced into the cryostat by circulating (and condensing) for a few minutes some pure argon gas through the circuitry section in which the oxygen was introduced. To let the liquid attain a homogeneous composition, the setup was left on its own for more than 5 h before taking any data.

The results presented in Fig. 5 confirm the method. The fits provided 3.5 ± 0.2 and 6.7 ± 0.3

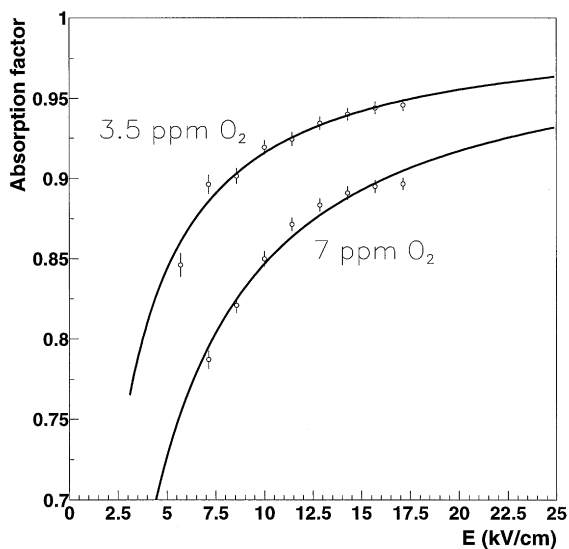


Fig. 5. Absorption factor in oxygen-polluted liquid argon as a function of the electric field with $d = 0.7$ mm.

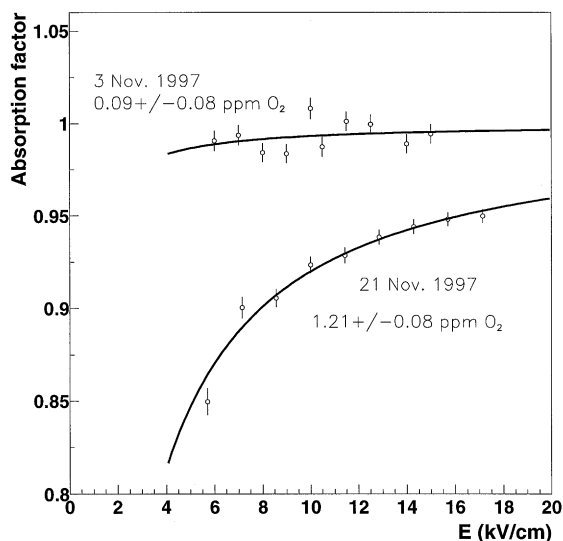


Fig. 6. Absorption curves measured at CERN in the test cryostat of the ATLAS liquid argon end-cap calorimeter.

ppm of oxygen in good agreement with the contamination values quoted above and a global normalization coefficient C of 0.997 ± 0.005 .

It is also possible to fix in the fitting procedure the oxygen concentration values which are known with a precision of 10%, and thereby to determine the favored value of the pollution coefficient α used in expression (6). The value we found is 14.3 ± 1.4 mm² ppm/kV which is twice as precise as the measurement reported in Ref. [1].

To further prove the validity of the method and at the same time to demonstrate its utility, we applied it to analyze the data recently acquired at CERN with a liquid argon purity monitor built in collaboration with the university of Mainz [9]. This monitor utilizes an ²⁴¹Am source mounted in a 2 mm gap ionization cell. It was developed to survey the argon purity in a cryostat which will enclose the future electromagnetic end-cap calorimeter modules of ATLAS [9] during test periods. Fig. 6 presents the absorption curves measured soon after filling the cryostat and 18 days later. One clearly observes a degradation of the liquid purity which seems to be compatible with an oxygen (or air) leak. Note that the sensitivity of this technique is better than 0.1 ppm O₂.

5. Conclusion

We have accurately measured the charge response curve of an ^{241}Am source mounted in a liquid argon ionization cell. We found that our measurements can be described by a semi-empirical formula inspired from a former study carried out by Thomas and Imel [4]. We also tested this formula on oxygen-polluted data and found that the measurements seem to rule out any alteration of the initial ion–electron pair recombination factor for low contaminations contrary to what was suggested in Ref. [1]. This new parameterization has been proved to be valid in extracting the absorption curve from the data of ^{241}Am -source-based purity monitors in order to determine the O_2 contamination of liquid argon with a sensitivity of approximately 0.1 ppm.

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