COMPRESSED XENON GAS NEAR ITS CRITICAL POINT AS AN IONIZATION MEDIUM

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Abstract

This paper studies the properties of compressed xenon gas near its critical point as an ionization medium.

I. INTRODUCTION

As part of an effort to study 0ν ββ decay of ^{136}Xe, a compressed xenon drift chamber has been developed. In such a chamber, the ability to drift ionization over large distances without attenuation, stability with time, and excellent energy resolution are essential.

Xenon is an attractive candidate for use as an ionization detection medium. Its low cost in large volumes gives it an advantage over solid-state detectors. Its large atomic number (Z=54) and density (when compressed or condensed) give a high stopping power for γ-radiation. The low average energy required to produce an electron-ion pair (w=21.9 eV measured for xenon gas, 15.6 eV for liquid)[1] and small Fano factor (0.13 measured for gas, 0.04 predicted for liquid)[2,3] allow good energy resolution. The expected intrinsic energy resolution is 2 and 4 keV FWHM at 1 MeV in liquid and gaseous xenon, respectively.

Thus, high density xenon spectrometers have a detection efficiency similar to NaI(Tl) crystals of the same size and an energy resolution comparable in theory to that in Ge(Li) detectors. However, the best energy resolution results in liquid xenon[4], 34 and 54 keV FWHM for the 570 and 1064 keV photo-peaks of ^{207}Bi, respectively, fall considerably short of the Fano factor predictions. It appears that the resolution is limited by some process other than Poisson fluctuations.

In this report we describe results obtained from a dual gridded ionization chamber filled with highly purified gaseous xenon operating near its critical point where the density, ρ_C = 1.09 g/cm^3, approaches that of the liquid phase. This thermodynamic regime has not previously been studied in xenon.

II. APPARATUS AND EXPERIMENTAL PROCEDURE

The detector consists of two gridded ionization chambers[5] of different size, with a common signal collection anode. The cylindrical sensitive volumes (between the grid and cathode) are 2.7 and 5.0 cm in height, respectively, and 11.4 cm in diameter; the anode to grid spacing is 0.64 cm in both detectors. Two field shaping rings are required in the larger detector (D2), and only one in the smaller detector (D1); the rings are annuli 1.27 cm high. The grids are composed of an electroformed nickel mesh spot welded onto a washer with a 10.2 cm diameter aperture. The mesh wires are 28.2 μm thick spaced 282 μm between centers.

Charge collection characteristics were studied using ^{207}Bi internal conversion electron sources electroplated on the center of each cathode. Drifting the same amount of ionization over two different distances within the same chamber allowed the direct measurement of any charge attenuation due to the presence of electronegative impurities.

The detectors are contained in a cylindrical, 4.5 liter stainless steel vessel which has copper gasket seals. Electrical feedthroughs are mounted on the top flange of the chamber for the electrical connections and mechanical supports for the electrodes. The vacuum system comprises sorption pumps for roughing and a triode-ion pump to achieve less than 10^{-10} torr in the vessel and gas-handling system. The entire system is simultaneously evacuated and baked at ≥ 300°C for three days prior to use. The measured outgassing rate, using these preparations, was < 10^{-12} torr·liter/sec.

Research grade xenon was purified using two hot metal getters. The gas was transferred cryogenically, condensed into the chamber and allowed to reach room temperature prior to a run. The pressure, determined by the ambient temperature[6] was measured using a transducer with a piezoelectric sensor. The operating pressure for many of the measurements made was approximately 62 atm (1.4 g/cm^3) at 19.0°C. This is near, but above the critical point of xenon (ρ_C=1.09 g/cm^3, P_c=57.5 atm, T_c=16.6°C).

Negative high voltage for the electrodes was supplied from a single power supply through an external resistive divider chain with capacitive filtering. The anode current resulting from the motion of ionization electrons was integrated using a room temperature, charge sensitive pre-amplifier mounted directly on the chamber. The pre-amp pulses were shaped, amplified and fed into a MCA and the spectra were stored in a computer for charge collection and energy resolution measurements. The calibration of the whole readout chain was made with a high stability test pulse generator coupled to the gate of the first stage FET of the pre-amp. The pre-amp input capacitance was approximately 93 pf for both detectors and corresponded to approximately 19 keV FWHM of electronic noise.

III. RESULTS

We chose the 976 keV K-internal conversion electron line of ^{207}Bi for our charge collection and energy resolution

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studies. In order to precisely determine the peak position and energy resolution for a given line, a least squares fitting routine was employed. Calibration of the energy deposited in the xenon was accomplished using the known energy of the lines of ^{207}Bi and the corresponding peak positions in the pulse height spectra. The relation between the pulse height and the energy of the line for the two detectors was linear to less than 1%. Presently the measured energy resolution of the 976 keV electron line for a given detector is obtained by subtracting, in quadrature, the measured electronic noise from the width of the peak in the energy spectrum.

The transparency of the grids in the present chamber to the drifting ionization electrons was was optimal when the collection electric field (E_c) between the anode and grid was at least 3.5 times the drift electric field (E_d) between the grid and the cathode for both detectors. This is nearly twice as large as that predicted[5] for a grid of wires instead of a mesh.

Figure 1 displays the dependence of the collected charge and energy resolution of the 976 keV electron peak on E_d in both detectors. Using 21.9 eV as the *w*-value in gaseous xenon and an absolute charge calibration that was performed, we estimate that we are collecting approximately 98% of the total expected charge at E_d=1.5 kV/cm, where the curves have sufficiently saturated. This fraction is consistent with complete charge collection since the overall systematic uncertainty in the absolute charge calibration is 4% (not shown in the figure). At about 1.3 kV/cm the energy resolution has a value of 20.0 ± 1.0 keV FWHM for the 976 keV peak at 62 atm (1.4 g/cm^3) in both detectors. The errors bars are due to statistical uncertainties in the data and systematic uncertainties in the applied electric fields.

The measured relation between electronic noise subtracted energy resolution for the conversion electron peaks of ^{207}Bi and their energy indicates that the energy resolution scales as $1/E^{1/2}$ to other energies. The extrapolated energy resolution at 2480 keV, the endpoint of ^{136}Xe $\beta\beta$ decay, is 1%.

Since the two detectors are consistent in their collected charge and energy resolution for all electric field values studied, we conclude that there is no evidence of attachment to electronegative impurities in our experiment. Furthermore, no systematic change in collected charge or energy resolution was observed over the entire 7 month period of data taking. These facts indicate a very clean chamber with a low residual outgassing rate and an efficient and reliable xenon purification system.

Similar results were obtained in a significantly different detector. In Fig. 2 we show a ^{207}Bi spectrum taken in 0.9 g/cm^3 (58 atm) xenon in a small prototype that was previously developed. The grid-anode and grid-cathode spacings were 0.5 and 1.3 cm, respectively. The cathode and grid were 6.4 cm in diameter, while the anode was 2.5 cm in diameter. The grid had an aperture of 2.0 cm over which 63.5 μm diameter wires spaced 635 μm apart were spot welded. Since the grid was made with wires of circular cross-section, a field ratio of 2.0 was sufficient for this detector geometry.

The lines in the pulse height spectrum of Fig. 2 are mostly due to K-shell internal conversion electrons or their summing

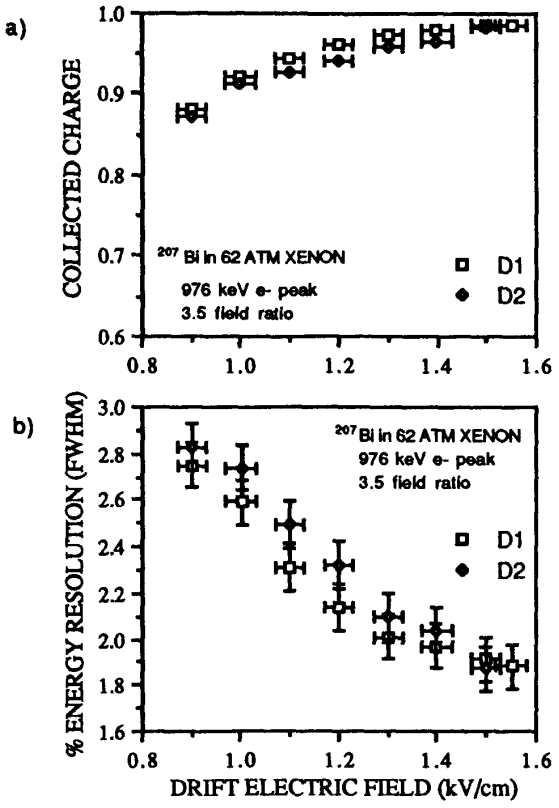

Fig. 1. a) Fraction of collected charge expected and b) electronic noise subtracted energy resolution (FWHM) as a function of E_d in both detectors.

with the K-fluorescence x-rays or Auger electrons. The peaks corresponding to the full nuclear transition are asymmetrical with a low energy "bump" and/or tail. This is due to the detection of the L-conversion electron and/or incomplete charge collection from γ events. The peak due to test signals from the electronic pulser is at the far right and measures the noise due to electronics (~6keV FWHM for the 20 pf input capacitance of this prototype system). The electronic noise subtracted energy resolution (FWHM) measured for the 976 keV peak of ^{207}Bi in this spectrum was 16.6 ± 1.0 keV (1.7%) at an applied drift electric field of 3.0 kV/cm. The stability of the prototype chamber was also excellent.

IV. DISCUSSION

The largest factor contributing to the broadening in energy of the pulse height peaks was the measured electronic noise. Effects due to the source, impurities, ballistic deficit, inefficient grid shielding and/or transparency, and electron-ion recombination were examined. Only the last phenomenon appeared to be having an effect; there was a slight improvement in the energy resolution as we increased E_d

beyond 1.5 kV/cm. However, in previous studies done in the smaller prototype, we were able to reach drift electric fields of >3.0 kV/cm, with only a slight improvement in energy resolution above 1.3 kV/cm.

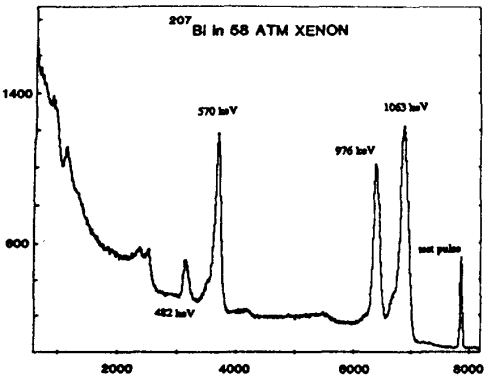

Fig. 2. ^{207}Bi pulse height spectrum in 0.9 g/cm^3 of xenon gas at 3.0 kV/cm for the small prototype previously developed. The noise subtracted energy resolution of the 976 keV electron peak is 17 keV FWHM. The FWHM of the test pulse peak is 6 keV.

Another approach to studying the effects of recombination on the energy resolution is to lower the density of the xenon gas. This should reduce the amount of recombination. This specific type of investigation has not been performed using liquid xenon. The gas density was gradually lowered from 1.40 to 0.49 g/cm^3, during which the electronic noise subtracted energy resolution and charge collection were measured at a field ratio of 3.5 and a drift field of 1.3 kV/cm. The results are presented in Figure 3 for D1. We see that at a density of 0.49 g/cm^3 the energy resolution improved to 11.7 ± 1.0 keV FWHM for the 976 keV electron peak. However, there was no indication of a systematic increase in the average collected charge.

We expect an improvement in energy resolution to be accompanied by an increase in the amount of charge collected from the ionization process. We searched for systematic effects that might cancel this expected enhancement but found none. Clearly the intrinsic resolution in our chamber is not solely determined by simple Poisson statistics. We will designate our result, 12 keV FWHM at 976 keV, to be the intrinsic energy resolution of our detector.

V. CONCLUSIONS

Our data suggests that xenon near its critical point is an important addition to the presently available high resolution radiation detector media. We have demonstrated both the ability to drift ionization electrons over large distances without attenuation and stability with time. The energy resolution of the 976 keV K-conversion electron peak of ^{207}Bi was measured to be 20 keV FWHM in 1.4 g/cm^3 (62 atm) of xenon, independent of the distance over which the charge drifts. These facts indicate that attachment to electronegative impurities is not a problem.

An additional effect was observed as the density of the xenon gas was lowered from 1.4 to 0.5 g/cm^3; the energy resolution improved without an increase in the average charge collected. This fact contradicts both intuition and previous assumptions of the effects of recombination. The intrinsic energy resolution obtained for the 976 keV K-conversion electron peak of ^{207}Bi in this work was 11.7 ± 1.0 keV (1.2%) FWHM in xenon gas at a density of 0.5 g/cm^3 (52 atm). While still a factor of 3 worse than the Fano limit, this result is the best reported thus far in xenon by over a factor of 4.

VI. REFERENCES

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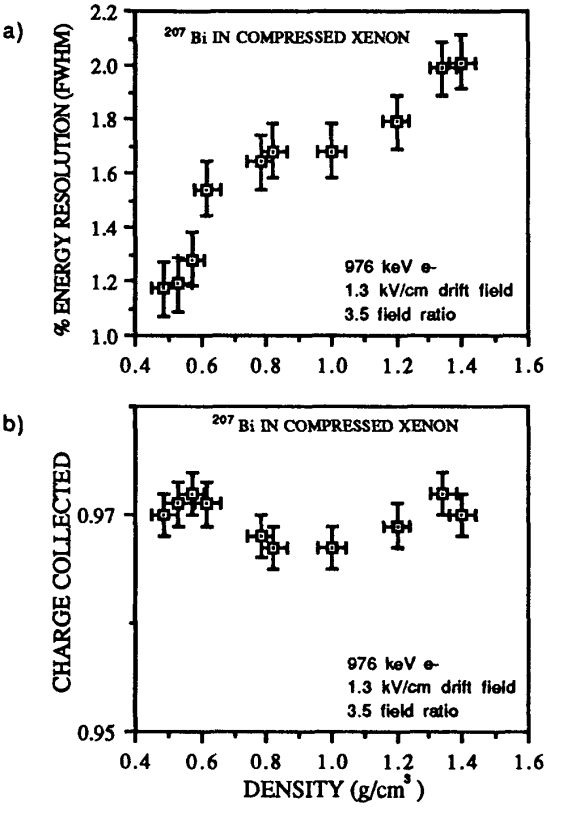

Fig. 3. a) Electronic noise subtracted energy resolution and b) collected charge as a function of the xenon gas density.