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Acoustic response of nuclear recoils in bubble chambers

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Abstract. The bubble chambers of the PICO collaboration use the acoustic signal generated from nucleations to classify nuclear recoil events from alpha decays in the bulk fluid. The success of these detectors in probing the potential WIMP-proton cross section comes in part from the low energy threshold that can be achieved. This nucleation threshold, based on the Seitz model, is dependent on fluid type, pressure, and temperature. At higher thresholds bubble nucleation does occur but with a significant loss in the measurable acoustic signal. To investigate this, the acoustic response of bulk nuclear recoil events was measured as a function of pressure and temperature and found to depend exponentially on both parameters.

1. Introduction

Bubble chambers maintain liquid Freons in a superheated state allowing ionizing radiation to nucleate a bubble if enough energy is deposited within a critical radius. For nuclear recoils, alphas, and potentially WIMP dark matter, the energy threshold and critical radius are well described by the Seitz model [1]. In addition to the visible bubble a correlated acoustic signal is generated. The bulk of the emitted power in this acoustic signal is generated within the first $\mathcal{O}(10)$ μs when the bubble is in the inertial growth phase [2].

The travel distance of a recoiling fluorine nucleus is much smaller than that of a alpha particle which leads to a comparatively quieter acoustic signal generated from nuclear recoils than from alphas particles. The acoustic power (AP) can therefore be used to discriminate between nuclear recoils and alpha particles [3, 4].

2. Queen's University test chamber

Queen's University operates right-side-up test chambers for rapid testing of novel detector materials and fluids. The Freon is contained in a 14 mL quartz vessel surrounded by a bath circulating warm water. The setup includes two cameras (Bassler acA720-290gm) for recording the bubble position, a lead zirconate titanate piezoelectric transducer for the acoustic signal, and a fast differential pressure transducer (Dytran 2005v) to measure the pressure rise when the bubble is created. The pressure in the quartz vessel is adjusted through a LabView-controlled hydraulic cart and bellows accumulator. When the bellows are expanded, the pressure decreases and the warm Freon in the quartz vessel becomes superheated. The transfer lines and bellows are cooled with a chilling unit (Jubalo 600F) to prevent spontaneous nucleations in these regions when expanded. When a bubble is nucleated, a trigger generated by the rise in pressure is sent to compress the chamber which condenses the bubble. The Freon used in this measurement was a mixture of approximately 15% $C_3F_8/(C_3F_8 + C_4F_{10})$.

3. Acoustic response

A ^{252}Cf neutron source was used to generate bulk nuclear recoils in the detector. Data sets were taken by scanning through expansion pressures at three different temperatures. After basic data quality cuts, bulk events are selected based on the magnitude of their pressure rise which separates bulk from wall and multi-bubble events. The start time of the event, T_0, is based on the amplitude of the acoustic trace being greater than a simple noise-dependent threshold. The acoustic response $\mathcal{R}$ is defined as the difference in the discrete Fourier transform (DFT) of the acoustic trace after T_0 summed over a specific frequency range (e.g. 15–60 kHz) minus the DFT of a pre-trigger sampling of the noise. The acoustic response is calculated for each event and averaged across the entire data set at that specific pressure and temperature.

The acoustic response for data sets including three isothermal scans through pressure (35°C, 42°C, 47°C), shown in Figure 1, decreases exponentially with increasing pressure. Plotting this data as a 3D surface reveals that the temperature increases exponentially with temperature, yielding an overall response that takes the form:

$$\mathcal{R} = a_1 \exp(-a_2 \mathrm{P}) \exp(a_3 \mathrm{T}), \tag{1}$$

for the expansion pressure P, temperature T, and where a_i are constants determined from a fit of the data.

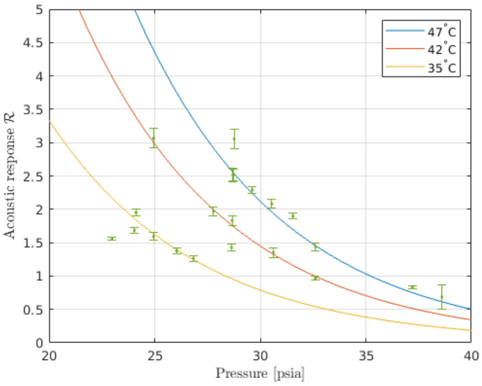

Figure 1. Acoustic response $\mathcal{R}$ as a function of pressure for data sets with temperatures including 35°C (yellow), 42°C (red), and 47°C (blue).

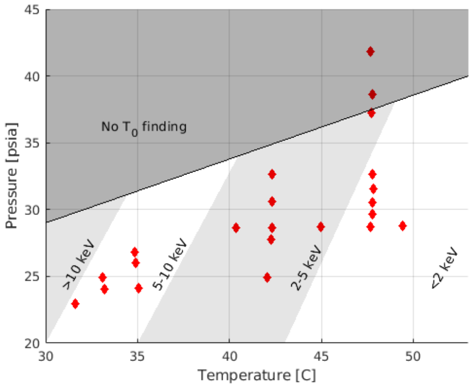

Figure 2. Acoustic response data sets (red diamonds) at varying pressure and temperatures along with corresponding Seitz threshold boundaries (white and light grey). The dark grey region indicates where acoustic signals are no longer measurable.

The scaling factor a_1 is highly dependent on the coupling of the piezo to the quartz vessel. The values of a_2 and a_3 are found to be constant across the frequency range from 70–170 kHz. Once a_i are known for a detector setup, Equation 1 can be used to predict the acoustic response for possible operating pressures and temperatures. A similar exponential response is also seen in other detectors and fluids, albeit with differently-fitted a_i.

The effect of both expansion pressure and temperature dependence on $\mathcal{R}$ in reaching specific energy thresholds in the Queen's University test chamber while maintaining adequate acoustic signals can be seen in Figure 2. The data sets used in Figure 1 are shown as red diamonds, and Seitz threshold boundaries are drawn as white and light grey bands across the pressure and temperature space. The dark grey region labeled “No T_0 finding” denotes where the acoustic signal generated by a nucleating bubble becomes lost below the piezo noise. While bubbles still nucleate in this region, T_0 cannot be calculated, and therefore AP discrimination cannot be performed.

From Figure 2, it can be seen that good acoustic signals at low thresholds ($\lesssim 5$ keV) are easily attainable, while higher thresholds ($\gtrsim 10$ keV) become more difficult. Limitations in expansion pressures (typically a few psia greater than atmosphere) and vessel heating/transfer line cooling abilities begin to restrict the available operating conditions in these higher threshold regions. While seemingly not so severe in the 15% mixture used in the small test chamber for this study, cooling becomes much more difficult in pure C_3F_8 where temperatures below -20°C need to be maintained.

4. Conclusion

The acoustic response of bulk nuclear recoils were measured in a small test chamber using a ^{252}Cf neutron source. A functional form of the response was found to depend exponentially on pressure and temperature. The next generation of large-scale bubble chambers like PICO-500 will need to operate with energy thresholds $\gtrsim 10$ keV to avoid the background generated from the coherent elastic neutrino-nucleus scattering of ^{8}B solar neutrinos. While results presented here are specific for a small test chamber, understanding the trends in pressure and temperature on the acoustic response of bulk nucleations is useful to inform potential operating conditions and thermal design in order to reach these higher thresholds while maintaining AP discrimination.

Acknowledgments

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