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Neutron – Alpha irradiation response of superheated emulsion detectors

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ABSTRACT

We report new experimental investigations of the response of single superheated emulsion detectors with small droplet (< 30 μm radii) size distributions to both α- and neutron irradiations. Analysis of the results in terms of the underlying detector physics yields a toy model which reasonably reproduces the observations, and identifies the initial energy of the α in the liquid and distribution of droplet sizes as primarily responsible for the detector capacity to distinguish between nuclear recoil and α events.

1. Introduction

The impact of any particle detector is often dependent on its ability to discriminate between detector-recorded, particle-induced backgrounds. Among the various detector types in present use are superheated liquid devices. These generally consist of either superheated emulsion detectors (SEDs): comprising distributions of micrometric liquid droplets in a gel-like medium (SDDs) or rigid polymer matrix (BDs) [1], or bulk liquid bubble chambers. Both record the acoustic signal associated with the particle-induced bubble nucleation event, as well as other non-particle acoustic backgrounds associated with environmental noise. Due to the thermodynamics of the detector response, particle sensitivity in moderately superheated devices is essentially reduced to high linear energy transfer (LET) radiations; an intrinsic low LET particle insensitivity of better than 10^{-10} has been demonstrated by γ and electron irradiations [2]. With increasing liquid superheat, this insensitivity decreases and the devices record these events also.

SEDs have been investigated for a number of radiation detection applications including nuclear, health, medical, and space physics [1,3] involving neutron, proton, heavy ion, electron and γ-ray fields. Because of their application to the direct search for astroparticle dark matter, which is critically dependent upon their ability to isolate low energy nuclear recoil events (< 100 keV) generated by elastic scattering of weakly interacting massive particles from naturally-occurring, low level neutron and α backgrounds in the materials, the question of particle response in superheated liquid devices has come under severe scrutiny and a large part of the advances in their capabilities has emerged from two experiments. In 2008, the PICASSO project using C_4F_{10} dispersed in a Gaussian droplet distribution with mean of $< r_d > = 100 \pm 25$ μm, high frequency piezo instrumentation, and irradiations effected with AmBe (neutron) and ^{241}Am and/or ^{226}Ra doping (α), reported a partial separation of the neutron-generated recoil-α acoustic event amplitude (A) distributions [4]. In 2010, the SIMPLE project independently reported [5] a full separation of the two power distributions in irradiations of separate devices, using C_2ClF_5 with a Gaussian droplet distribution of $< r_d > = 30 \pm 7.5$ μm, a low frequency electret microphone, U_3O_8 α-doping and neutron irradiations with either AmBe or epithermal neutrons from the Portuguese Research Reactor (PRR) [6], which was attributed to the difference in proto-bubble formation. In 2011, PICASSO presented "new insights" into the detector response, this time with the same SEDs but based on the recorded event acoustic energy [7] obtained by squaring the waveform of each transducer signal and integrating over its duration, which also identified the difference in recoil-α proto-bubble formation as the determining factor for the separation of the two response distributions. Experimentally, however, only a partial separation between the recoil-α events was again obtained, and only in the case of ^{226}Ra α-calibrations. The difference between the results of the two projects has since remained unresolved [8].

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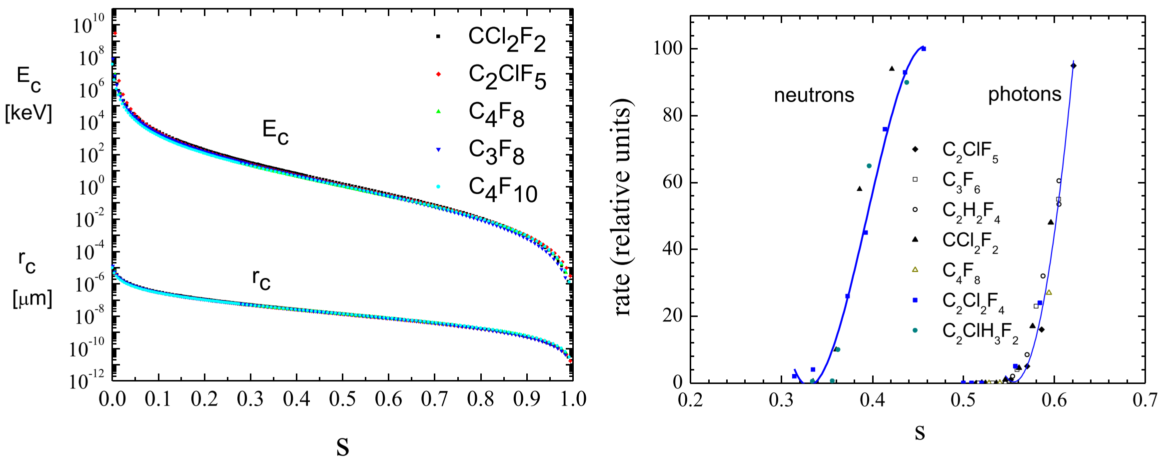

(a) (b)

Fig. 1. (a) Universal behavior of E$_c$ and r$_c$ in terms of s; (b) γ and neutron irradiation responses of various superheated liquids, which in s fall on single curves (adapted from Ref. [21]).

Other researchers have since contributed to the issue of particle response, principally however with respect to neutron-generated nuclear recoil and γ events [9,10]. Das et al. recently reported [11] recoil-α response studies using CCl_2F_2, a low frequency condenser microphone, a bimodal Gaussian distribution of small droplet sizes (58% $<r1>\sim 3\pm 1$ μm, 42% $<r2>\sim 25\pm 5$ μm), and irradiations with neutron (AmBe) and a solid α source (^{241}Am) – the latter which, in contrast to the usual emitter-doping, was positioned outside the SED gel. Analysis of the data via the acoustic signal energy demonstrated an inversion of the recoil - α response amplitudes, accompanied by a significant overlap of the two distributions.

The detectors of each experiment differ in various aspects: superheated liquid and concentration, droplet sizes, gel composition and stiffness, size and volume of detectors, operating temperatures and pressures, instrumentation, signal acquisition and analysis. We here examine the response issue in small ($r_d < 30$ μm) droplet size distribution SEDs, towards providing an improved understanding of the involved mechanics for general use in future SED implementations. Section 2 summarizes the bubble nucleation physics underlying SED performance. Section 3 describes new experiments using single SEDs with several droplet size distributions and modified gel stiffness, and discusses the results. Section 4 elaborates on the particle-superheated liquid interactions, and introduces a simple model of the SED response which is seen to reproduce well the experimental results. The difference in number of proto-bubbles created by recoil target ion and α's, the initial energy of the α in the liquid, and the differences in droplet size distributions, are identified as the basis for the particle response. A summary of conclusions is given in Section 5.

2. Irradiation response

The general physics of detector operation, based on the "thermal spike" model of Seitz [12], has been described by various authors [13–21] (and references therein). The process consists of several stages beginning with the incident particle energy deposition in a small ($\sim 3\times 10^{-4}$ μm^3) volume of the liquid, creating ionization electrons which generate a localized, high temperature region (the "thermal spike"). The resulting sudden vaporization of the region and its expansion generates a shock wave in the droplet, in which the temperature and pressure within the shock enclosure initially exceed the critical temperature and pressure of the liquid: there is no distinction between liquid and vapor, and no bubble. As the energy is transmitted from the thermalized region to the surrounding medium through shock propagation and heat conduction, the temperature and pressure of the fluid within the shock enclosure decrease and the expansion process slows [17]. As the temperature and pressure continue decreasing to their critical values, a vapor-liquid interface is formed which may generate a proto-bubble of submicron critical radius $r_c = 2\sigma(T)/\Delta p$ of the vapor state at which the pressure difference ($\Delta p = p_v - p_l$, with v=vapor, l=liquid) overcomes its surface tension σ. If this is not achieved, growth is impeded by interface/viscous forces and conduction heat loss, and the proto-bubble collapses; otherwise, the droplet evaporation generates an expanding gas bubble, accompanied by a pressure wave. The time scale for proto-bubble creation is sub-nanosecond; complete droplet evaporation occurs over milliseconds.

Only 2–6% of the total energy release appears acoustically. The acoustic energy release is given by [22]:

$$E = A^2\tau = -\frac{4\pi\rho_l}{3c}\frac{r_b^6}{\tau^3}, \tag{1}$$

from which the acoustic power is

$$K = A^2 = \frac{4\pi\rho_l}{c}\frac{r_b^6}{\tau^4}, \tag{2}$$

where ρ_l is the liquid density, c is the speed of sound in the liquid, $r_b = r_b(\tau)$ is the bubble radius, τ is the expansion time of the bubble, and A is the signal amplitude.

Proto-bubble formation occurs if the particle energy deposition (E) satisfies [12]:

$$E \geq E_c = 4\pi r_c^2\left(\sigma - T\frac{\partial\sigma}{\partial T}\right) + \frac{4\pi}{3}r_c^3\rho_v h_v - \frac{4\pi}{3}r_c^3\Delta p \tag{3}$$

and

$$dE/dx \geq E_c/L_c \equiv LET_c, \tag{4}$$

where T is the SED operating temperature, $\rho_v(T)$ is the vapor density, and $h_v(T)$ is the heat of vaporization. The E_c/L_c is the critical deposited energy density required for proto-bubble nucleation, with $L_c = \Lambda r_c$ the effective ionic energy deposition length, and Λ an empirical liquid-dependent parameter. Both E_c and r_c, when displayed as a function of the reduced superheat $s = (T - T_b)/(T_c - T_b)$ with T_c, T_b the critical and boiling temperature of the liquid at a given pressure [21] respectively, are seen to provide "universal" curves for different liquids (Fig. 1(a)). Similarly, the response of the SEDs to a given irradiation type lie on "universal"