Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl16

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Version of record first published: 28 Mar 2007.

Mol. Cryst. Liq. Cryst., Vol. 26, pp. 71-74

Printed in Dordrecht, Holland

Effects of the Passage of Ionizing Particles Through a Liquid Crystal

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(*Received March 8, 1973*)

Beams of ionizing particles may be detected by means of the temperature change induced in a cholesteric liquid crystal. Our estimates indicate also that it may be possible to detect an individual heavy ion with a charge perhaps as low as 6 at all speeds and a singly-charged particle near the end of its range.

The principal effect of an ionizing particle on passing through a condensed material such as a liquid crystal is the transfer of energy from the particle to the medium by excitation and ionization of the atoms of the material and the production of energetic-electrons (or delta-rays). The energy imparted to the medium appears eventually in the form of heat. The initial heat pulse along the trajectory of the particle spreads through the medium in accordance with the differential equation for the diffusion of heat. For a single-charged high-energy particle traversing a liquid crystal, the density of ion pairs along the path of the ionizing particle is of the order of 10^5 per cm or 10 per μ; thus, the mean separation between ions is about 0.1 μ. For distances large compared to the mean separation between the ions, the diffusion can be considered to proceed from a line source. The solution to the line source problem for the temperature change $u(r,t)$ at a distance r from the trajectory at a time t after the passage of the ionizing particle is

$$u(r,t) = \frac{S}{c4\pi Dt} \exp\left(-r^2/4D\,t\right) \tag{1}$$

where the the diffusivity D is

$$D = k/c\,\rho \tag{2}$$

Here the material constants are the thermal conductivity k, the specific heat c, and the density ρ. The quantity S denotes the specific-energy-loss of the ionizing particle in the medium in units of cal/gm-cm^{-2}. As the cylindrical heat pulse diffuses through the medium, the temperature $u(r,t)$ at a distance r will vary with time. The temperature change will be $1/e$ of its value at $r = 0$ for

$$r^2_{1/e} = 4\,Dt \tag{3}$$

The cylindrical heat pulse must diffuse to a distance of the order of the wavelength of light in order to detect a temperature change by optical means. For a typical liquid crystal (with $k = 3 \times 10^{-4}$ cal/sec -cm^2 - °K - cm^{-1}, $c = 0.5$ cal/gm - °K, and $\rho = 1$ gm/cc), $D = 6 \times 10^{-4}$ cm^2/sec; thus, the cylindrical heat pulse will diffuse to a distance $r_{1/e}$ of 2500 Å in about 0.26 μ sec.

Now the temperature change at the distance $r_{1/e}$ may be written:

$$u_{1/e} = \frac{S}{e\pi c\, r^2_{1/e}} \tag{4}$$

Provided that the response of the liquid crystal is fast enough, the threshold specific-energy-loss required to produce a detectable color change in the liquid crystal can be found from Eq. (4). Ennulat and Fergason[1] described a thermal imaging system capable of seeing temperature differences of 0.2°K in the scene against a background of 300°K. The temperature difference on the liquid crystal membrane is about 1.5% of the temperature difference in the scene; thus, the temperature difference on the membrane is about 0.003°K. Ennulat and Fergason have indicated that the sensitivity of the thermal imaging system might be increased an order of magnitude by improved lighting for direct viewing of the liquid crystal film. This system was based upon the extreme temperature sensitivity of the cholesteric liquid crystal cholesteryl oleyl carbonate (COC). Ennulat[2] has determined the large temperature coefficient of selective light reflection exhibited by several liquid crystalline materials. He reported that cholesteryl oleyl carbonate (COC) exhibits the highest temperature coefficient of 13% intensity change per m°C at a wavelength of 7000 Å. Based on the work of Ennulat and Fergason[1] and that of Ennulat,[2] we estimate that the threshold temperature change required to induce a detectable color change in the liquid crystal is about one millidegree.

For a liquid crystal with a specific heat of 0.5 cal/gm-°K = 1.3×10^{13} MeV/gm-°K, an optical diffusion radius of 2500 Å, and a threshold temperature of 1 m°, the threshold ionization-energy-loss is about 70 MeV/gm-cm^{-2}. This value is about 35 times the minimum value of the ionization-energy-loss for a singly-charged particle.[3] Since the ionization-energy-loss increases with the square of the charge Z of the particle, the threshold value of 70 MeV/gm-cm^{-2} is about equal to the minimum ionization loss for carbon ions ($Z = 6$). Thus, the above calculation indicates that it may be possible to detect an individual heavy ion with a charge perhaps as low as 6 at all speeds. Since the ionization-energy-loss of a charged particle near the end of its range is more than 100 times larger than the minimum value, the above calculation indicates also that it may be possible to detect a single-charged particle near the end of its range. Jalaluddin and Husain[4] have suggested earlier that a liquid crystal may be used as a single particle detector. Their proposal is based on the use of a weakly twisted cholesteric liquid crystal in combination with an external electric field which is triggered off by the passage of an ionizing particle.

We have investigated also the possibility of detecting beams of ionizing particles by means of the temperature change induced in a liquid crystal. In its simplest form, a single element of the liquid crystal beam detector consists of a coating of liquid crystal on a sheet of suitable material such as metal or glass. The liquid serves as an indicator of the temperature rise induced in the metal (or glass) by the passage of the ionizing particle. If we neglect heat losses from the metal (or glass), then the time-integrated flux density I of ionizing particles required to produce a temperature increase ΔT in the metal (or glass) with a specific heat c is

$$I(\text{particles/cm}^2) = \frac{c\Delta T}{S} \tag{5}$$

For a heavy metal such as bismuth, lead, gold, or platinum, the specific heat is about 0.030 cal/gm-°K (= 7.9×10^{11} MeV/gm-°K). The time-integrated flux density of particles required to produce a temperature rise of one millidegree in such a heavy metal is

$$I(\text{particles/cm}^2) = \frac{7.9 \times 10^8}{S\,(\text{MeV/gm-cm}^{-2}\text{ metal})} \tag{6}$$

For a beam of singly-charged minimum ionizing particles, $S \simeq 2$ MeV/gm-cm^{-2}; hence, $I \simeq 4 \times 10^8$ particles/cm^2. The particle flux density J required for an irradiation time of one second is 4×10^8 particles/cm^2-sec. Primary beams from many particle accelerators surpass this flux density of 4×10^8, and some secondary beams do reach this level. Some secondary beams at the Los Alamos Meson Physics Facility (LAMPF) are expected to exceed this flux density. The liquid crystal beam detector may have important applications to the diagnostics of secondary particle beams.

TABLE I

Irradiation Time Required to Induce a Detectable Color Change in the Liquid Crystal Beam Detector by a Beam of Minimum-Ionizing Singly-Charged Particles at a Flux Density of 10^8 Particles/cm^2-sec.

Material	Specific Heat at 25°C c(cal/gm-°K)	Threshold Irradiation Time, t(sec)
Al	0.215	28
Bi	0.0292	4
Cu	0.092	12
Au	0.0308	4
Pb	0.0305	4
Pt	0.0317	4
Quartz	0.188	25
Crown Glass	0.161	21
Flint Glass	0.117	16

Acknowledgement

One of the authors (D.N.) would like to acknowledge the hospitality of the Aspen Center for Physics, where a portion of this work was done. This work was supported in part by the Atomic Energy Commission.

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2. Ennulat, R. D., *Mol. Cryst. and Liq. Cryst.* 13, 337 (1971).
3. For typical values of the specific-energy-loss *S* as a function of particle speed, see, for example, Rich, M. and Madey, R., Range-Energy Tables, University of California Radiation Laboratory Report UCRL-2301 (March 1954).
4. Jalaluddin, A. K. and Husain, Hashmat, *Proc. Nucl. Phys. Sol. State Phys. Symp.* 2, 527 (1971).