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SCINTILLATION LIGHT FROM LIQUID ARGON AND ITS USE IN A NEW HYBRID DETECTOR

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Scintillation light, produced by 200 MeV/c pions in a liquid argon bubble chamber/calorimeter, was measured. Results from the test device show that this signal could be used in future large bubble chambers to trigger the flash on the occurrence of an interesting event. Furthermore, this signal gives rough information about total track lengths, hence energy contained in massive electromagnetic and hadronic showers, and could complement measurements obtained by charge collection.

1. Introduction

The noble gases, in particular argon, krypton and xenon, have proved useful as scintillation detectors because of their short decay time, proportionality of light output to the particle energy dissipated over a wide range of specific ionization densities, a relatively large light output when used in conjunction with an appropriate wavelength shifter, and suitability in either the gaseous or the liquid state [1,2].

Several of the noble gases have been extensively used also as bubble chamber liquids in high-energy experiments, in particular neon and its mixtures with hydrogen, as well as pure helium and xenon, the latter being expensive and not available in large quantities. Recently, we have shown in a test device that argon also can be sensitized as a bubble chamber fluid [3], that charge collection during the bubble chamber expansion is possible [4], and that narrow bubble tracks can be produced with a laser beam [5]. From a technical and financial point of view argon has the additional advantage of being non-inflammable, that it can be cooled by liquid nitrogen, and that both liquids are abundant and inexpensive.

In the present paper we describe a new feature of our hybrid device: the technique of measuring efficiently in argon of high purity the scintillation light produced by beam particles, and that operating the flash of the bubble chamber camera does not impair the measurement of the scintillation light with the photomultiplier (the charge collection device was not installed during these tests).

We discuss briefly two potential applications of this scintillation signal: its use in triggering the flashtube when a (rare) event occurs, and in roughly determining the energy of massive electromagnetic or hadronic showers.

Our bubble chamber can also be operated with liquid argon/nitrogen mixtures. However, the scintillation intensity from argon is known to drop very rapidly with increasing nitrogen concentration [6] and, furthermore, the detector loses immediately its ability to collect efficiently free charges (calorimetry). A detailed discussion of the effects of impurities on the hybrid performance of our detector is beyond the scope of this paper.

2. Experimental technique

The liquid argon scintillation consists of a narrow-band ultraviolet continuum (130 ± 5) nm [7], due to transitions from the excited molecule Ar_2^* to the repulsive ground state. This excited molecule is created either by self-trapping of a free exciton (33%) or by recombination of a self-trapped hole and a free electron (67%). The scintillation consists of a fast component $\tau_1 = (6.3 \pm 0.2)$ns and a slow component $\tau_2 = (1020 \pm 60)$ns, having an amplitude ratio of $A_1/A_2 = 13.5 \pm 1.5$ [8–10]. The scintillation yield in liquid argon (and xenon) is comparable to the yield in NaI cristals, its dE/dx dependence of the scintillation yield is smaller [10]. Also, scintillations in the liquids have a faster time response than in NaI detectors. However, a considerable fraction of the photons emitted in the argon scintillations is absorbed by surrounding wall materials, because there are no good reflectors for ultraviolet photons.

The use of the scintillation light in the far UV poses for our bubble chamber/calorimeter two technical problems, which must be solved: firstly, the light must

pass the chamber window without large transmission losses, and secondly, the recording photomultiplier has to be protected against the flash light of the camera, which is fired shortly (milliseconds) after the passage of the particles.

The first problem can be solved by the use of a wavelength shifter (WLS), either deposited on the liquid side of the chamber window, or dissolved in the liquid itself. Since our detector is designed to operate also as charge collecting calorimeter, any poisoning of liquid argon with electronegative atoms/molecules must be avoided. Therefore, we gave preference to a coating of the window. We selected out of a multitude of WLSs, used for high energy experiments [11–13], para-terphenyl (pTP) * and vacuum evaporated it onto the window. We have chosen a 1000 nm thick layer (approximately 100 $\mu g/cm^2$), which yields a maximum gain [12]. The lifetime of the excited state of pTP is 5.5 ns, which is slightly shorter even than the main component of the scintillation in argon. For our applications, there is no need for a faster decaying WLS.

Para-terphenyl has a slightly opaque appearance in visible light. Therefore, we coated only two D-shaped parts (135 cm^2 total) of the window, leaving a centre stripe of 4 cm width pependicular to the beam direction uncovered to allow track photography (fig. 1). This enables us to relate quantitatively the number of particles passing through the liquid and registered as tracks on film, to the amplitude of the scintillation signal (or the number of scintillation counts).

As yet no attempt has been made to improve the light output by covering the WLS with an antireflection coating. Magnesium fluoride (MgF_2) could be used, which is transparent for light down to 115 nm [12]. Such a coating could enhance the mechanical resistance of pTP. However, the electronegativity of MgF_2 as compared to pTP is not yet known at cryogenic temperatures.

There is a high absorption of the scintillation light by the stainless steel walls and by the scotchlite. However, at present it has not been necessary to improve the reflectivity, since the recorded scintillation signal is high enough for the envisaged applications.

Only readily available materials were used for our feasibility test. We mounted a Philips XP 2020 photomultiplier (PM) above the camera outside the vacuum tank of our detector, ~90 cm away from the liquid (fig. 2). The PM has a 44 mm diameter sensitive cathode and covers a solid angle of 1.9×10^{-3} sr. A blue filter (H 320a, from MTO Paris) is attached to the front of the PM as protection against the light from the flashtube. To improve the situation further, a high-pass yellow filter (DT gelt 104/234, from Balzers) is mounted in front of the annular flashtube and the camera lens. In addition, should it become necessary, the high-voltage of the PM could be gated open for the beam spill of the accelerator (~80 μs basewidth) and turned off before the flash is fired ~ 1 ms later, thus avoiding any saturation effects of the photocathode and the current integrator by unwanted photons. The scintillation light, amplified by the PM, is transmitted to a charge sensitive ADC. The ADC values, together with the scaler signal from coincidence counters in the beam line in front of the detector, are read out via CAMAC to an Hewlett-Packard computer.

For bright-field photography of the tracks we used

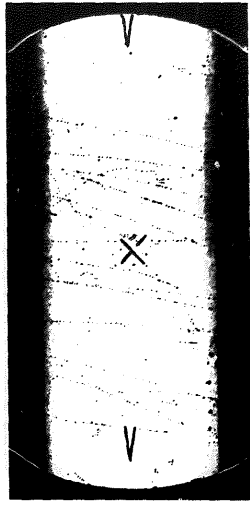

Fig. 1. Photo of 200 MeV/c pion tracks in argon. The chamber window is partially covered, upstream and downstream with the wavelength shifter and is therefore not transparent in these regions.

* $C_{18}H_{14}$ [14,15] manufacturer Merck.

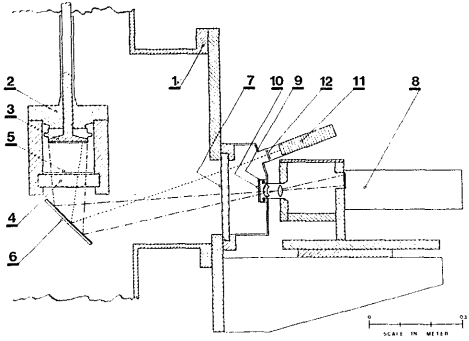

Fig. 2. General layout of the detector: (1) vacuum tank, (2) chamber vessel, (3) expansion piston, covered with scotchlite, (4) chamber window, (5) wavelength shifter, (6) mirror, (7) vacuum tank window, (8) camera, (9) annular flash, (10) yellow filter, (11) photomultiplier, (12) blue filter.

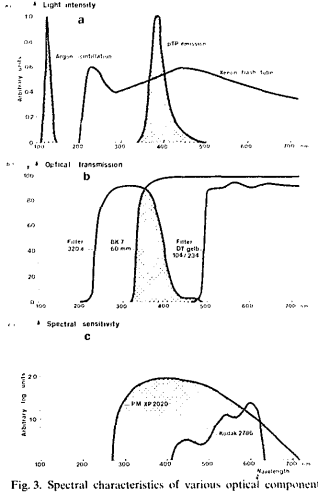

Fig. 3. Spectral characteristics of various optical components (see text).

customary high-contrast, high-resolution, low-sensitivity film (Kodak microfine 2786).

Fig. 3 shows the spectral characteristics of the various optical components. Fig. 3a gives in arbitrary units the scintillation light in liquid argon and the light shifted by polycristalline pTP [11]. The light distribution of the xenon flashtube is smoothed [16] for an average electrical power (20 J, produced by the discharge of 3 μF at 3700 V), the 1/e-width of the light pulse being ~ 2 ms.

Fig. 3b shows the optical transmission of the two filters and of the chamber and vacuum tank windows (BK7, from Schott), thickness 35 and 25 mm, respectively.

Fig. 3c gives, in arbitrary logarithmic units, the spectral response of our PM and film.

3. Experimental results

3.1. General performance

Two bubble chamber runs were made with the described set-up (~ 30 days), with cooldowns to 120 K and complete warming to ambient temperature. There was no obvious problem with differences in thermal contraction of the WLS and the chamber window: no change in the macroscopic appearance of the WLS was found. During these runs the charge collection device [4] was not installed. Therefore it could not yet be checked if there is any poisoning of the liquid by microscopic particles or molecules from the WLS. This poisoning

would result in increased electron attachment, if pTP is electronegative, and could spoil the chamber's operation as calorimeter. The argon purity was $\sim$99.9999% (specification of the manufacturer: contamination with $O_2 < 0.1$, $N_2 < 0.3$, $H_2 < 0.001$, $CH_4 < 0.005$, $H_2O < 1$ ppm).

The yellow filter in front of the annular flash tube and the photographic lens reduces slightly the light output, and hence its reception in the camera. The reduction in optical density on film arises from the cutaway region between 410 and 500 nm, since our film is not sensitive below 410 nm nor above 630 nm. As expected from fig. 3, the flash voltage had to be increased by $\sim 10\%$ when the filter was used. The light intensity was chosen to give in bright-field illumination a background density of $d \sim 1.0$.

The transmittances of both the chamber window and the blue filter limit the spectral range of the light seen by the PM eventually to the band extending from 300 nm to 450 nm. The maximum sensitivity of the PM being at (400 ± 30) nm, there is a comfortable overlap with the operational region of the pTP enhancing the sensitivity of the detector. With a constant incident particle flux and the flash not fired, the ratio of signal heights, measured with and without the blue filter, was $\sim 1:1.5$.

When the bubble chamber flash was fired with 20 J, and the PM was operated at 2.4 kV, the small overlap of the transmission curves of the two filters caused an undesirable PM signal of $\sim 120 \mu A_{peak}$. This value is in reasonable agreement with the light emission and its reflection from the scotchlite into the PM. Major uncertainties in this estimate arise from the sharp drop of reflection from scotchlite with increasing angle of incidence and the variation of this angle across our detector. Under the above conditions, the recovery time of the PM was ~ 50 ms. However, the base-line of the integrated signal used to feed the ADCs was still some-

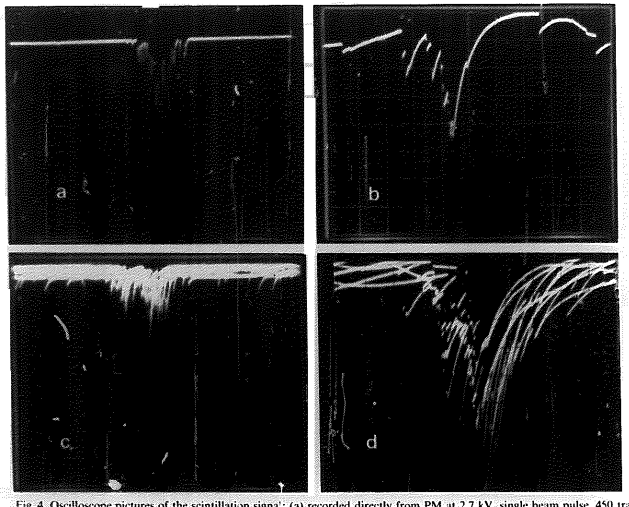

Fig. 4. Oscilloscope pictures of the scintillation signal: (a) recorded directly from PM at 2.7 kV, single beam pulse, 450 tracks; 1000 mV/div, 50 μs/div; (b) recorded after integration PM at 2.4 kV, single beam pulse, 45 tracks; 100 mV/div, 100 μs/div; (c) recorded directly from PM at 2.4 kV, 10 beam pulses, 45 tracks each; 500 mV/div, 50 μs/div; (d) recorded after integration at 2.4 kV, 10 beam pulses, 45 tracks each; 100 mV/div, 50 μs/div.

what raised, which would make it necessary to gate the high-voltage of the PM or the current integrator during the discharge of the flash tube, when even repetition rates higher than 1 Hz are attempted.

Typically, flashtubes in bubble chambers are fired some 0.5 to 10 ms after the passage of particles, the delay depending essentially on the desired bubble diameter (size of the chamber and optical resolution), whereas the individual scintillation signals are collected within nanoseconds, the precise time depending mainly on the duration of the beam spill.

We did not find any difference in the amplitude of the scintillation signal when the bubble chamber was expanded or not. This implies that in liquid argon at our relatively slow expansions sono-luminiscence effects do not occur, which had been previously observed at very rapid expansions (produced by ultrasonic techniques) in Freon 11 ($CCl F_3$) [18]. No influence of mechanical vibrations on our results have been found either.

In our set-up, we had to photograph the tracks and to detect the scintillation light through the same window. In any larger detector, one would probably decouple these functions by using separate optic ports.

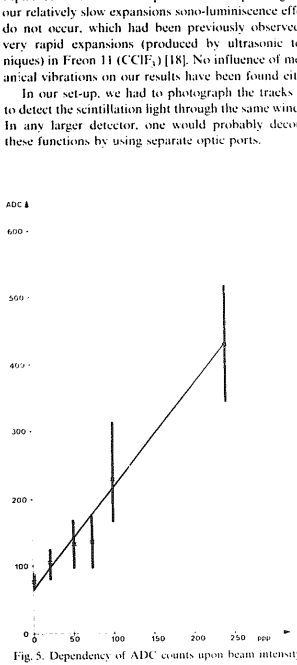

Fig. 5. Dependency of ADC counts upon beam intensity, PM at 2.25 kV.

3.2. Scintillation intensity

The 200 MeV/c pion beam from the CERN SC has a spill duration of ~ 40 μs fwhm and a base width of ~ 80 μs. The intensity distribution inside this pulse is gaussian-like and has a 60 ns microstructure. The main features of the beam pulse are reflected in the scintillation signal (fig. 4a). The repetition rate of the accelerator is 183 s.

The beam intensity was monitored by coincidence counters in front of the detector. Their gain was adjusted such that there was a one-to-one correspondence between counts and visible tracks in the bubble chamber. The long-term stability of the beam intensity was better than about ± 1%, however it varied from pulse to pulse by approximately ± 30% r.m.s., as seen on photos. The maximum number of particles during these tests passing through the chamber was 250 / burst.

Most of the results were obtained at a repetition rate of 1 s. For technical reasons, our measurements so far have not been taken simultaneously with the bubble chamber pictures.

Since the direct signal from the PM decays in a few nanoseconds, and the beam pulse has a substructure of 60 ns, which means up to ~ 1000 subpulses, these signals were not compatible with the use of the ADC. Therefore a feedback current integrator with a linear response over 100 μs was built, which integrated the PM current pulses before they started to decay. A 60 ns gate to the ADC was delayed to be near the maximum of the integrated current. For one accelerator pulse, the original and the integrated PM signals are shown in figs. 4a and 4b, respectively, and in figs. 4c and 4d the corresponding signals, when ten accelerator pulses were superimposed on the oscilloscope. For the conditions of figs. 4b, c, d ~ 45 tracks were visible on each bubble chamber photo.

Systematic measurements were made for ADC readings as function of particle intensity. As expected, a linear behaviour was found, which had a noise level of about fifty ADC channels (figs. 5 and 6). The errors given in these graphs are r.m.s. deviations from a mean value, obtained each from at least 40 particle bursts. These errors are mainly due to:

a) variations of the number of particles in the spill, as was verified by counting straight tracks on film (the ± 30% r.m.s. deviations account for about half of the error bars),

b) the position of the tracks in the chamber, and

c) the varying distribution of the particles within the spill.

The latter effect causes a jitter of the maximum integrated current (fig. 4d), relative to the timing of the ADC gate, which accounts for another appreciable part of the errors. These errors are expected to be about an order of magnitude smaller in the envisaged applica-

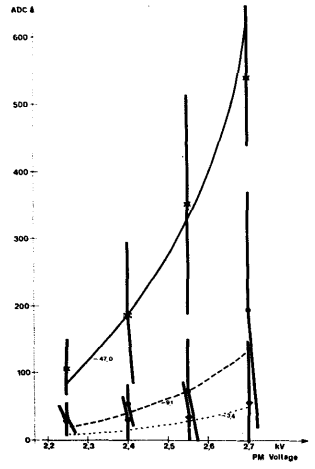

Fig. 6. Dependency at ADC counts upon PM voltage. With blue filter, particle flux as parameter. Solid line: gain of PM, normalized at experimental point of highest flux and 2.4 kV (big circle); dashed and dotted lines: gain of PM, scaled for lower fluxes.

tions: there, the scintillation pulses from the various tracks of an interaction are created at the same time, and the time spread of the pulse is only determined by the different distances of the tracks from the recording PM, as well as the decay time of the scintillation pulse and the WLS.

Fig. 6 shows the dependency of ADC readings on the PM voltage, with particle intensities as parameter. The lines are the gain curves of the PM, normalized at a PM voltage of 2.4 kV and the highest beam intensity. The experimental values fit these curves well. The error bars at the high PM voltage and high intensity points are somewhat smaller than elsewhere, because the current integrator reached saturation during some of the particle pulses.

For the highest beam intensity the ADC values are slightly lower, when the bubble chamber flash was fired shortly after the beam pulse: this left the base line of the current integrator at a higher level for the following beam spill.

When the blue filter was removed, but particle flux and PM voltage were kept constant, the scintillation signal increased by approximately 35%. This result can be explained best by using the WLS spectrum for polycrystalline pTP of ref. [11] (rather than refs. 12 or 14), and the cut-off by the blue filter towards large wavelengths.

A rough estimate of the number of photoelectrons $N(\mathrm{PE})$, to be detected by our PM, can be based on the assumptions used in Table 1.

Then we obtain for a single track prior to amplification by the PM

$N(\mathrm{PE})/\mathrm{track} \simeq 1.$

Table 1

$(\mathrm{d}E/\mathrm{d}x)_{\mathrm{total}} = 2$ MeV g^{-1} cm^2,	total energy loss of minimum ionizing particles
$d = 1.0$ g/cm^3,	density of liquid argon at 135 K
$(\mathrm{d}E/\mathrm{d}x)_{\mathrm{sc}} \lesssim 0.04(\mathrm{d}E/\mathrm{d}x)_{\mathrm{total}}$,	energy loss of α-particles from Am-decay going into scintillation [17]; no better estimates for liquid argon available
$E_i = 9.5$ eV,	energy of photons from scintillation
$N_{\mathrm{incident}}/N_{\mathrm{emitted}} \lesssim 1$,	ratio of incident to emitted photons of WLS, estimated from:
	(a) energy of emitted photons $E_e = 3.2$ eV [11], or $E_e = 2.9$ eV [12]
	(b) isotropic reemission of photons
	(c) transmittance of WLS to its own fluorescence light [14], but not for incident photons
$\Delta R \simeq 25\%$,	reflection losses on 6 glass surfaces
$L_m = 16$ cm,	maximum track length in bubble chamber
$L_e \simeq L_m/2$,	effective track length in chamber for scintillation, due to reduced area of WLS on window ($S = 135$ cm^2)
$A = 1.9 \times 10^{-3}$ sr,	solid angle from each point of a track to the PM surface
$Q_{\mathrm{PM}} = 25\%$ (manufacturer) or $= 12\%$ [12],	quantum efficiency of PM at 390 nm
$G = 7 \times 10^7$,	gain of PM at 2.4 kV

and get after amplification 1.7×10^7 electrons. If we assume further, that a scintillation pulse produced by one particle, has an overall duration of less than 60 ns (microstructure of the beam spill $\gtrsim 60$ ns, decay time(s) of scintillation $\gtrsim 6$ ns, lifetime of excited state of WLS ~ 5.5 ns), then this results in a PM anode current of $\sim 180\ \mu$A.

On the other hand, we measure on the oscilloscope (capacitance of the cable ~ 10 pF, connector ~ 20 pF, impedance at anode of PM 4.7 kΩ), an average pulse height of 500 to 1000 mV, with a pulse width of 300 ns (one time constant). This corresponds to $\lesssim 200\ \mu$A, in order of magnitude agreement with our theoretical estimate.

4. Conclusions and outlook

Our test detector was filled with liquid argon of high purity. In spite of the very restricted solid angle of the PM, we observed scintillation pulses produced by minimum ionizing particles. At present, the level of sensitivity corresponds to ~ 25 cm track length, a performance which can be considerably improved in any new detector by a better geometric layout. We demonstrated that during bubble chamber operation the detection of the scintillation signal is compatible with the light pulse of the flashtube.

The compatibility of pTP with argon purity requirements for charge collection will be investigated in our next tests when the decrease of scintillation in the presence of high electrical fields [19,12] will be studied. Because of its relatively small size and geometrical layout, our detector is not suited for systematic investigations of the reabsorption of the far UV light in liquid argon.

The scintillation light pulse can be reliably used as a fast trigger signal for the bubble chamber camera, when an event with more than a preselected number of particles or track lengths occurs. In any future large detector of this type, several optic ports could be equipped with PMs: then the current pulse, produced by scintillation light, could be fed into a computer. Its amplitude would give information on energy contained in heavy electromagnetic and hadronic showers, thus complementing the results from a charge collection device. It can also trigger a gate between a charge sensitive amplifier and a double differentiating amplifier of suitable shaping time constant to collect total charge. This would allow a drastic reduction in microphonic noise and effects from the change of capacitance arising from bubble chamber expansions [4], particularly when long beam spill times are involved. There is a comfortably long time gap between the arrival of the scintillation light at the PM and the arrival of the first free electrons. The light needs only 33 ps/cm plus the scintillation time constants of argon with 6.3 ns and of the WLS with 5.5 ns, whereas the electrons, moving in an electrical field of ~ 2 kV/cm towards the charge collection electrode, need $\sim 5\ \mu$s/cm. Furthermore, the scintillation signal could be used to trigger a laser beam [5] almost simultaneously with the event, which in turn could produce a string of bubbles, which have the same size as the bubbles of the particle tracks from an event, thus marking an interaction of interest, and providing at the same time a fiducial line, which is subject to the same liquid and bubble movement as the tracks from the event.

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