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INVESTIGATION OF THE PERFORMANCE OF CsI(Tl) FOR CHARGED PARTICLE IDENTIFICATION BY PULSE-SHAPE ANALYSIS

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We have studied the possibility of particle discrimination by pulse-shape analysis in CsI(Tl) scintillator. In order to investigate the limitations of that process we have analysed the time response of the scintillator for different ions at various energies. It is found that for energies lower than 200 MeV the identification is limited to charges $Z < 4$. This work also gives an understanding of these limitations.

1. Introduction

The possible use of inorganic scintillators for detection and identification of very light particles has been known for many years [1,2]. Their use gradually decreased, however, as their performance was overtaken by that of solid state detectors. However, in recent years these old techniques have had a revival of interest, particularly in the field of heavy ion physics [3–5]. The large number of detectors used in these experiments, in which it is essential to discriminate the light emitted particles, requires the use of simple and rather cheap detection systems.

The CsI(Tl) crystal has been chosen to be the basic scintillator in several detection devices [6,7] including the 140 detector modules of the 4π AMPHORA array [8].

Early studies of CsI(Tl) indicated that one could discriminate alpha particles and electrons and later studies demonstrated mass discrimination for charge $Z = 1$ [9,10] and for charge $Z = 2$ [4]. Can one anticipate to discriminate in masses heavier ions or even only to identify them in Z? In order to determine the limits of particle identification and the reasons for these limits we have undertaken a study of the time response of a CsI(Tl) crystal bombarded by different particles at various energies.

2. Discrimination by pulse-shape analysis

Storey et al. [11] were the first to study the response of CsI(Tl) scintillator to impinging particles of different type and energy. They showed that the light output of the phosphor could be described to a good approximation by a sum of two exponential functions associated with the fast and slow component, respectively:

$$L(t) = \frac{h_f}{\tau_f} \exp\left(-\frac{t}{\tau_f}\right) + \frac{h_s}{\tau_s} \exp\left(-\frac{t}{\tau_s}\right), \quad (1)$$

with the following properties:

(a) the ratio $R = h_s/(h_f + h_s)$ increases with decreasing ionisation density;

(b) τ_f has an increasing value as the ionisation density of the particle decreases;

(c) τ_s has a value close to 7 μs regardless of the nature of the particle.

The two points (a) and (b) are sufficiently separate to anticipate a pulse-shape discrimination. As soon as 1959, Owen [1] showed results for which particles were identified by using a device based on property (a). In 1961 Biggerstaff [12] published similar results obtained with a discrimination device based on property (b). All of these studies refer to the identification of electrons and particles of charges $Z = 1$ and $Z = 2$ at energies less than 10 MeV.

Recently Alarja et al. [4] used a phoswich technique (i.e. measurement of the amounts of charge in two regions of the anode pulse) which is based upon properties (a) or/and (b) and thus gives a very good identification in charge up to $Z = 4$ and in mass for $Z = 1, 2, 3$ for energies up to 100 MeV. It is clear from fig. 1 that a saturation occurs in discriminating ions of charge larger than $Z = 4$. In order to determine whether the limitation came from the rather arbitrary choice of the two integration gates, we have investigated the evolution of

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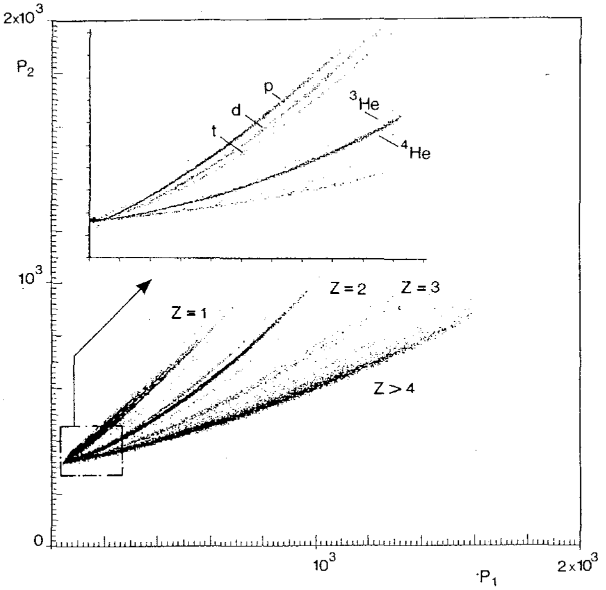

Fig. 1. Two-dimensional map (P_1, P_2) obtained with CsI(Tl) scintillator at 15° with a 27.5 MeV/n Ar beam. P_1 and P_2 are the light outputs obtained when integrating the signal within time intervals $T_1 = 400$ ns and $T_2 = 1.2$ μs at time $t_1 = 0$ and $t_2 = 1.6$ μs. The expanded view is obtained with a higher voltage of the photomultiplier.

the time constants τ_f and τ_s of the light pulse together with their respective intensities h_f and h_s for different types of particles and at various energies. We are, however, aware that these results can strongly depend on the quality of the scintillator as well as on the photomultiplier that has been used.

3. Experimental study of the light decay of the CsI(Tl) crystal

3.1. Mechanical setup

The sample of CsI(Tl) that has been studied [13] is a cylinder of 26 mm diameter and 30 mm length which is polished and wrapped in several layers of Teflon and finally in an aluminum foil. The scintillator is optically coupled with optical grease to an RTC3461 photomultiplier for which the frequency response of the photocathode is extended to green frequencies. The front face of the CsI(Tl) crystal is covered by a reflecting foil of aluminized Mylar which is 6 μm thick. The detector is set at 15° with respect to the beam direction. The beam was a beam of argon at 27.5 MeV per nucleon impinging on a copper target.

The energy calibration is achieved by using two solid state detectors of 200 μm and 500 μm thickness which are placed in front of the CsI(Tl). The residual energy in the CsI(Tl) is easily deduced from the measurement of the energy ΔE lost in these detectors by the particle.

3.2. Electronics

The signal produced by a particle going through the scintillator was obtained from the anode output of the photomultiplier whereas the output of the last dynode was used for timing to trigger the data acquisition. The measurements were performed for different values of the high voltage to take advantage of the largest dynamical range one can achieve without saturating the signal.

The anode signal was sampled with an 8-bit flash ADC with a sampling rate of 10 MHz [14]. The signal was recorded as 255 data points at 100 ns wide intervals thus allowing to investigate the signal over a total time interval of 25 μs. All of the electronics was implemented in CAMAC. A partial integration of the pulse within a given time interval was obtained in software by adding up part of the corresponding data.

3.3. Experimental results

3.3.1. The light decay pulses

Fig. 2 shows the identification of light particles obtained with a ΔE–E telescope made of a 200 μm silicon detector and the CsI(Tl) crystal. The parameter E results from the summation of the first four channels of the flash ADC corresponding to an integration of the pulse within the first 400 ns [4]. Good particle identification is observed at all energies. In fig. 3 the evolution of the pulse shape for a pulse issued from the CsI(Tl) is shown for protons of various energies. In order to reduce the statistical fluctuations in the evolution of the

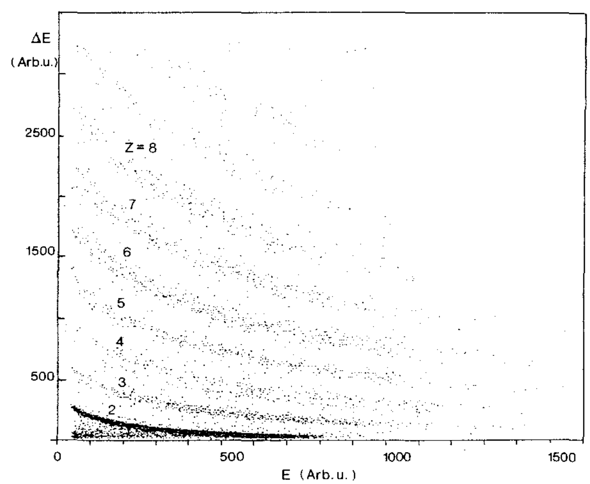

Fig. 2. Identification of light charged particles with a telescope counter composed of a thin silicon detector (ΔE) and a thick CsI(Tl) scintillator.

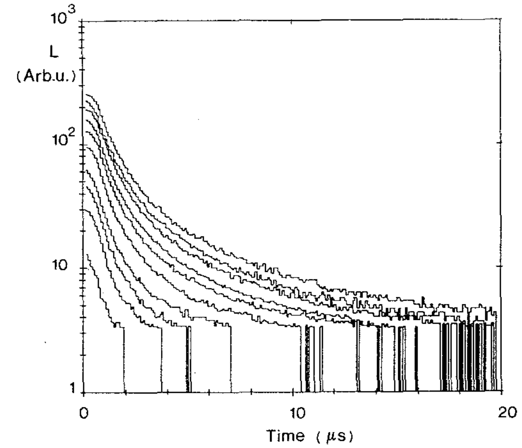

Fig. 3. Scintillation decays of CsI(Tl) for protons of various energies ($6 < E < 40$ MeV).

signals, each curve has been obtained as the average of several signals in an energy bin 2.5 MeV wide. These results indicate that the relative intensity of the slow component increases as a function of energy and that the fast pulse decay is slower as the energy increases.

3.3.2. Fitting conditions

Each of these decays has been fit by eq. (1). One example is given in fig. 4. The general trend is well reproduced. However, the following points should be noted:

– The precision on the time constant associated with the slow component is poor at low energy. Indeed the intensity is low and the conversion dynamics does not allow a precise analysis. Storey [11] gives a value of 7 μs whereas in a recent work Grassman [15] fits up to 4 μs for the pulse delivered by 5.5 MeV alpha particles without using any decay constant for the slow component. Shamowskii [16] gives a value of 4.5 μs for τ_s for 5 MeV alpha particles. For low energy alpha particles we deduced a value of 3.5 ± 1 μs from the fitting procedure whereas at higher energies a value of the order of 5 μs is deduced. This value is confirmed for all masses associated with charge $Z = 1$. We chose to use a constant value for τ_s of 4 ± 1 μs.

– The pulse height at $t = 0$ is overestimated by the fit. The use of a second exponential function in the fast component and taking into account the rise time of the signal could improve the fitting results. However, the observed rise times, of the order of 40 ns for excitations by β and even faster for excitations by α, are too short to yield an accurate determination of such effects. Grassman [15] proposes a fit of the light decay by β excitation with two fast components $\tau = 0.24$ μs and $\tau = 0.7$ μs. Lyapidevskii's work [17] gave evidence of a very fast component ($\tau \sim 6$ ns) whose intensity and spectral composition depend on the activator concentration. However, in the present work we have considered it satisfactory to interpret the CsI(Tl) luminescence with only one fast component which depends on the ionisation density of the particle and with a constant slow component decay of 4 μs.

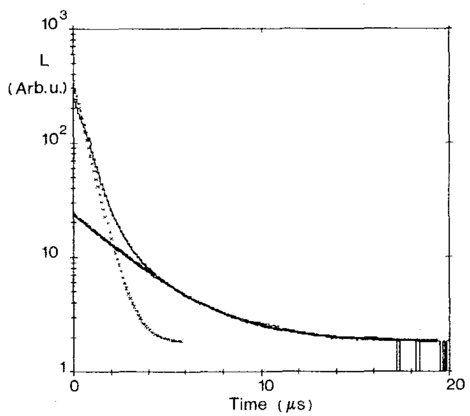

Fig. 4. Scintillation pulse of CsI(Tl) after α excitations (95 MeV). The pulse is fitted with two exponential functions, giving $\tau_f = 800$ ns and $\tau_s = 4000$ ns.

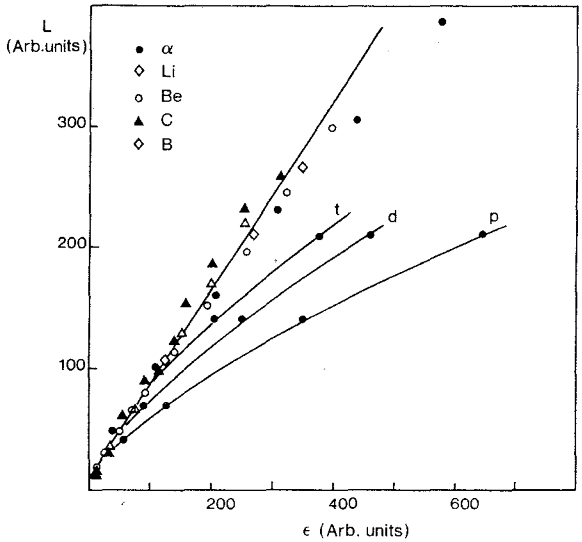

Fig. 5. Total light output L $(= h_s + h_f)$ vs $\epsilon = E_0^{3/2}/(A^{1/2}Z^{2/3})$ where Z, A, E_0 are the ion atomic number, mass number and energy of the particle, respectively.

3.3.3. Results of the fits

The results of the fitting procedure give values of the parameters τ_f, h_s and h_f.

It should be noticed that the total light yield L is then expressed as $L = h_f + h_s$. The variation of L as a function of energy shows trends which have been known for a long time [19,20]. All of these data for $Z > 2$ fall on a single straight line when the parametrization pro-

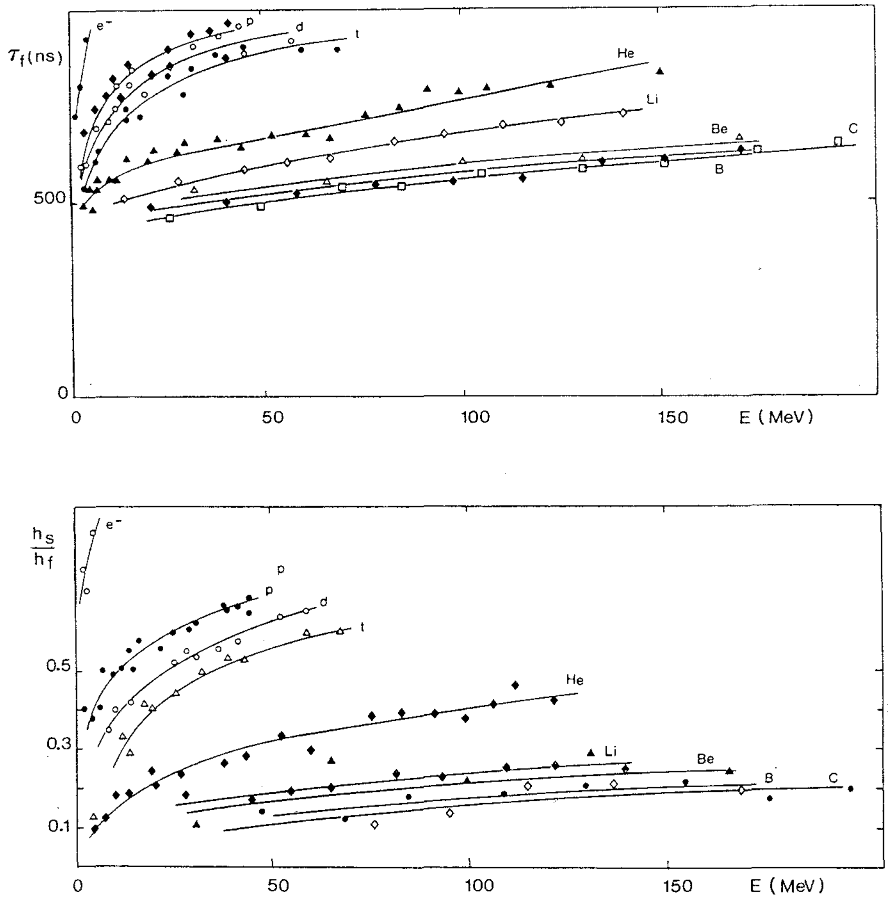

Fig. 6. Variation of the fast decay time τ_f and the intensity ratio h_s/h_f vs energy of different particles.

posed for CsI(Tl) and NaI(Tl) by Womack [21] is used. This is corroborated at much higher energies and for heavier ions by Salamon [22]. In fig. 5 L has been plotted versus $\epsilon = E^{3/2}/(A^{1/2}Z^{2/3})$. This linearisation – which seems to be a simple method to calibrate scintillators for ions of high Z – justifies a posteriori the approximation of the decay of the CsI(Tl) into a sum of two exponential functions.

The experimental values of τ_f as well as the ratio h_s/h_f are reported in fig. 6 for different ions at various energies. It is interesting to notice the likeness of the two families of curves for which so far no explanation has been proposed. They give evidence to two essential features:

- τ_f and h_s/h_f increase with decreasing density of ionisation [18];
- both parameters saturate for $Z \geq 4$ (and even $Z \geq 3$ for h_s/h_f).

3.3.4. Consequences for particle identification

From these results a bidimensional detection map can be simulated by integrating the exponential functions as defined above within two different time regions P_1 and P_2. A small time gap (see fig. 7b) alters the quality of the separation whereas a larger gap (see fig. 7c), which theoretically would lead to a better separation, is actually not desirable as it involves integrations on low amounts of charge in the pulse thus generating large statistical fluctuations. A compromise consisting of using time intervals of 400 ns and 1200 ns with a 1000 ns gap in between (fig. 7a) is a suitable solution and justifies the empirical choice of ref. [4] (see fig. 1).

In fig. 8 the variations of τ_f and h_s/h_f have been reported as a function of the total light output $L = h_s + h_f$ rather than as a function of the energy of the ions. This allows a comparison of the pulse shape taking into account their total intensity. These curves infer that ions of charge $Z \geq 4$ cannot be identified in the energy range of interest ($E < 200$ MeV).

As far as ions of charge $Z < 4$ are concerned, it is interesting to understand what is the main process involved in the particle discrimination. To this end two simulations have been performed:

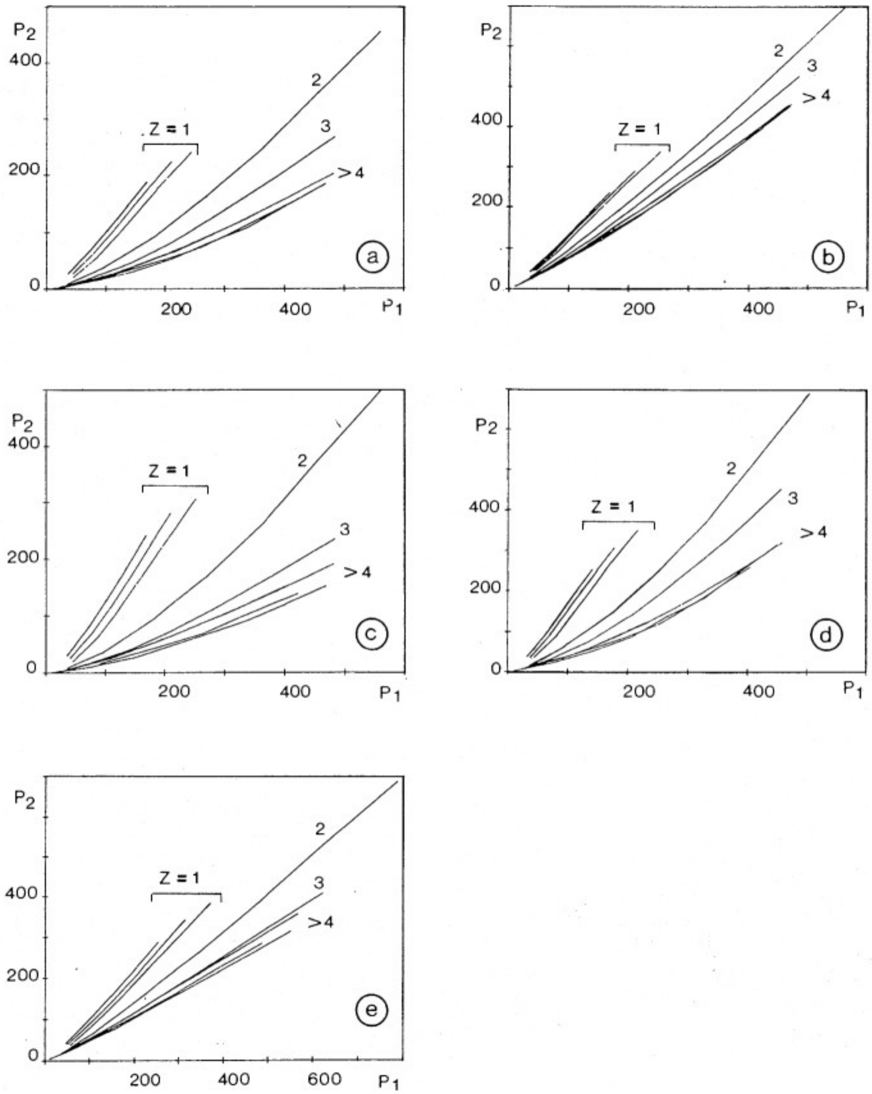

Fig. 7. Two-dimensional simulations of particle identification with the scintillator studied here. P_1 and P_2 are the light outputs obtained when integrating the signal within different time intervals T_1 and T_2. (a) $T_1 = 400$ ns at time $t_1 = 0$, $T_2 = 1$ μs at time $t_2 = 1.6$ μs. (b) Same conditions as in (a) but $t_2 = 400$ ns. (c) Same conditions as in (a) but $t_2 = 4.4$ μs. (d) Same conditions as in (a) but $h_s = 0$. (e) Same conditions as in (a) but $\tau_f = 500$ ns.

- The first simulation (fig. 7d) assumes that the light decay only consists of the fast component ($h_s = 0$). The identification is then due to the variation of τ as a function of the density of ionisation of the ions. The quality of the separation between the lines corresponding to different particles is similar to the separation actually obtained from measurements.
- The second simulation (fig. 7e) assumes that τ_f does not depend on the ion type or energy ($\tau_f \sim 500$ ns). The identification only comes from variations in the ratio of the intensities of the two components. The discrimination is not as good as obtained previously. It follows from this study that the variations of τ_f and h_s/h_f with the density of ionisation both play a role but at different levels in the discrimination process.

4. Conclusion

The study of the time response of a CsI(Tl) scintillator to ions of different type and energy has shown that the light decay can be reasonably well fit by two exponential functions whose intensity ratios and decay constants depend on the type and energy of the detected particles. A decay constant of 4 μs has been

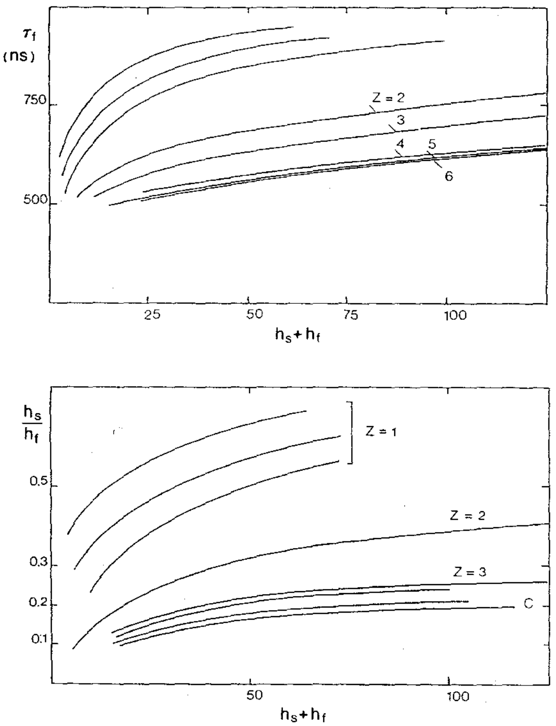

Fig. 8. Variation of τ_f and h_s/h_f vs total light output $L(=h_s+h_f)$.

measured for the slow component regardless of the type or energy of the ions. The decay constant associated with the fast component depends on the density of ionisation at least for ions of charge $Z<4$. This dependence is the essential feature which allows discrimination of particles by pulse-shape analysis for charges $Z<4$ in the energy range of 0–200 MeV.

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