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Section A

The mass dependence of CsI(Tl) scintillation response to heavy ions

D. Horn, G.C. Ball, A. Galindo-Uribarri, E. Hagberg and R.B. Walker
AECL Research, Chalk River Laboratories, Chalk River, Ontario, Canada K0J 1J0

R. Laforest and J. Pouliot
Universite Laval, Ste-Foy, Quebec, Canada G1K 7P4

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The response of CsI(Tl) scintillators to heavy ions is investigated as a function of E, A, and Z. In addition to the expected dependence of light output on Z and E, we observe a significant dependence on mass number. A simple parameterization of the quenching in terms of a few physical variables permits characterization of the light output for a variety of nuclear species with a single quenching constant.

1. Introduction

The inorganic crystal, CsI(Tl), has long been recognized as a potentially useful scintillator for heavy ions [1,2]. The main obstacle to its widespread use has been the nonlinearity of its response to highly ionizing charged particles. This necessitated a detailed calibration over the entire energy range for each of the nuclear species to be detected.

As a result of recent interest in particle-detection systems having a large geometric efficiency, often nearly 4π sr in solid angle [3–6], the scintillation response of CsI(Tl) to charged particles has been re-examined. While studies of quenching effects for scintillation induced by heavy ions have been made as a function of energy and atomic number [6–8], little work has been done on the possible mass dependence of this quenching. Since a good understanding of the phenomenon is not possible without a detailed study of all its contributing factors, we have measured the response of CsI(Tl) detectors to a variety of nuclear species between ^{1}H and ^{12}C as a function of atomic number, mass number, and energy (up to 37 MeV/nucleon for ^{12}C ions). Our measurements indicate that the mass dependence is a very significant effect in the calibration of CsI(Tl) scintillators for heavy ions.

2. Measurements

The CsI(Tl) detector was cylindrical in shape, 4 cm in diameter by 10 cm long, and was purchased from Bicron [9]. We used a photodiode readout system to avoid the subtle saturation effects sometimes associated with photomultiplier tubes and their divider chains. The last 4 cm of the crystal's length was tapered to mate with a 3 cm by 3 cm Hamamatsu silicon photodiode [10]. The photodiode signals were amplified by a charge-integrating preamplifier followed by a spectroscopy amplifier operated with a 3 μs shaping time. The scintillator was mounted as the E-detector of a two-component counter telescope in which the ΔE component was a silicon surface-barrier detector, 1012 μm thick. The thickness of the Si detector was obtained from measurements of weight and surface area by the manufacturer [11]. This telescope arrangement permitted the measurement of three types of calibration points for the CsI(Tl) scintillator.

i) A ^{12}C beam of 540 MeV (45 MeV per nucleon) from the superconducting cyclotron at Chalk River's TASCC facility was elastically scattered from a gold foil. We corrected for kinematics and for energy loss in the target and the silicon ΔE detector and obtained an energy of 437 MeV ± 1% incident upon the scintillator, allowing for a small uncertainty in the beam energy.

ii) "Knock-on" protons and deuterons from both ordinary and deuterated polyethylene targets were scattered forward by an 80 MeV ^{12}C beam from the MP tandem Van de Graaff at TASCC and provided light-ion calibration points up to 26 MeV for the CsI(Tl) detector. The errors in the centroids of these points were about 1% of the ion energy.

iii) Reaction products from the ^{12}C + ^{12}C reaction at 45 MeV per nucleon were detected by the Si/CsI(Tl)

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telescope at a laboratory angle of 21°. Fig. 1 shows a spectrum of the Si (ΔE) pulse height as a function of the CsI(Tl) (E) pulse height. The excellent energy resolution of the photodiode-backed CsI(Tl) detector permitted the identification of each fragment by element number and by mass number. The thickness and energy calibration of the silicon detector provided a measurement of the energy lost in the ΔE detector for each ion, and thus allowed calculation of the energy deposited in the cesium iodide at any point in the spectrum.

The energy-loss calculations were performed with the code STOPX, based on the stopping power parameterizations of Littmark and Ziegler [12]. Of the methods, iii), used chiefly for ions with atomic numbers 2, 3 and 4, was sensitive to errors in the energy-loss calculation. For example, a 1% error in the energy deposited in the silicon detector for a 165 MeV ^{7}Li ion would result in a 1.5% shift in the energy assigned to the 121.2 MeV CsI(Tl) calibration point. However, three things should be noted about this source of error. Firstly, the shifts would be systematic, preserving to first order the relative positions of the calibration curves for $Z = 2$, 3 and 4. Secondly, the reference points determined from i) and ii) for $Z = 1$ and 6 were included in the same fit as the values from iii) and found to be consistent (see section 3). Finally, the energy losses for $Z = 2$, 3 and 4 ions with specific energies above 5 MeV per nucleon are well known. Stopping-power compilations (e.g. Hubert et al. [13]) typically differ by less than 1% from those of ref. [12] in this range of mass and energy. The calibration points obtained by these three techniques are indicated in fig. 2.

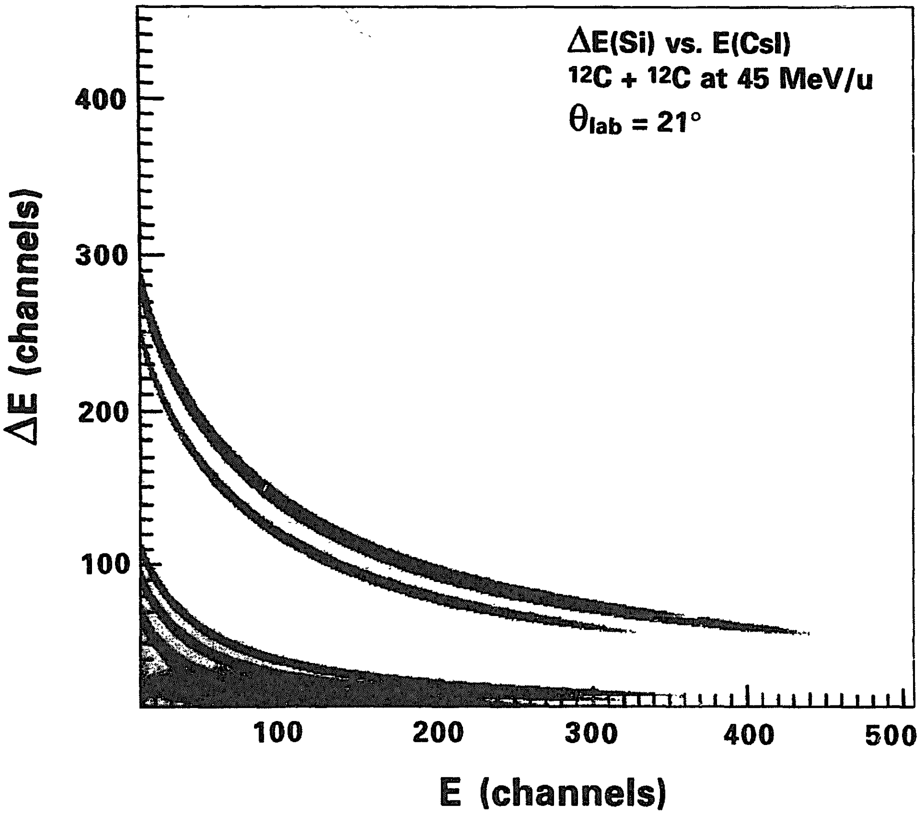

Fig. 1. Pulse height of Si ΔE detector as a function of CsI(Tl) E detector light output for products from the reaction of 45 MeV/nucleon ^{12}C ions with a ^{12}C target. The detector was positioned at 21° with respect to the beam axis. Both pulse heights are expressed in uncalibrated channel numbers; in this representation, the energy deposit implied by a given E channel depends strongly upon the nuclear species detected. Note the excellent energy resolution and the clear isotopic separation. Four groupings of ions, corresponding to the isotopes of elements 1 to 4, are apparent. All three hydrogen isotopes (lower left) are readily visible, as are ^{3}He, ^{4}He and ^{6}He. However, the two higher groupings, $^{6-8}$Li and ^{7,9}Be show their heaviest isotopes only faintly, since they are weakly produced in this reaction. The "tail" of degraded E pulse height (readily visible in connection with the more energetic protons and alpha-particles) originates from incomplete energy deposition caused by scattering or nuclear reactions inside the cesium iodide crystal. In this spectrum, the "tail" intensity associated with alpha-particles is approximately 1% of the total identified yield of alpha-particles; that for protons is about 8% of the total proton yield.

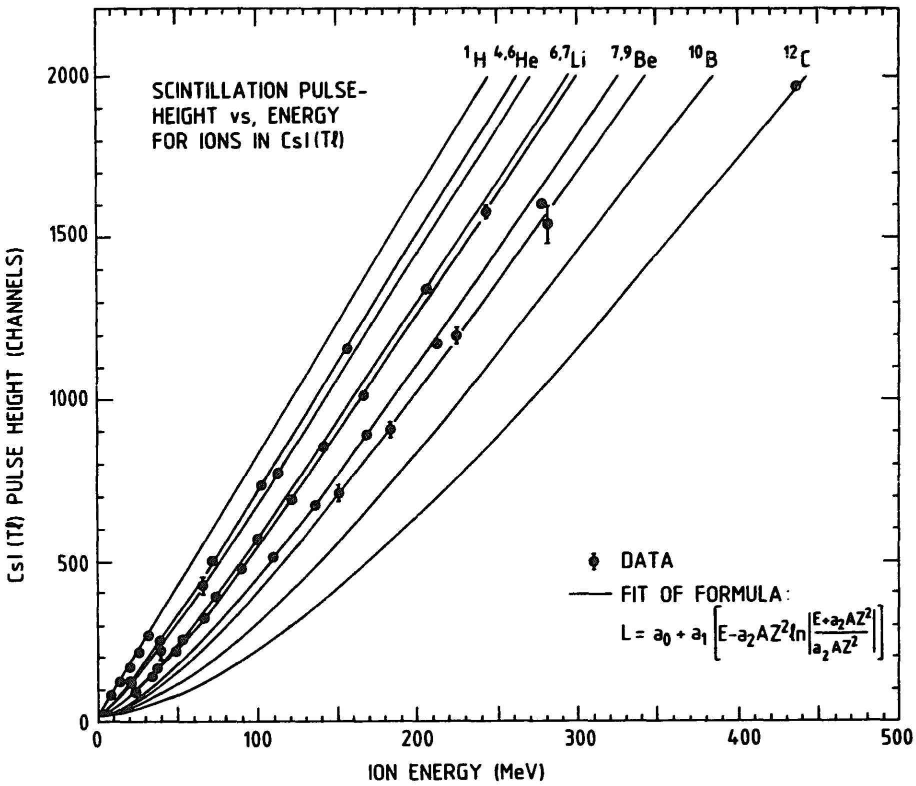

Fig. 2. Calibration points for the CsI(Tl) scintillator obtained in this measurement. The curves are the result of a least-squares fits to eq. (3) of the text. Data for the ions ^{2}H, ^{3}H and ^{3}He agree equally well with their respective curves, but have been omitted from the figure for clarity of presentation. Uncertainties in the observed channel number and ion energy are typically smaller than the size of the plotted points. See Table 1 and the text for a more detailed discussion of the uncertainties.

3. Discussion

The quenching of light output from charged particles in organic and inorganic scintillators has been associated with the specific energy loss, $\mathrm{d}E/\mathrm{d}x$, of the ion. For example, Birks [14] proposed that the differential light output, $\mathrm{d}L/\mathrm{d}x$, has the form:

$$\frac{\mathrm{d}L}{\mathrm{d}x} = \frac{S(\mathrm{d}E/\mathrm{d}x)}{1 + [\mathrm{kB}(\mathrm{d}E/\mathrm{d}x)]} \tag{1}$$

where S is the scintillation efficiency and kB the quenching factor (Birks' constant). For energies above a few MeV per nucleon, the approximation,

$$\mathrm{d}E/\mathrm{d}x \simeq cAZ^2/E \tag{2}$$

is valid, where c is a proportionality constant. In that approximation, analytic integration of the differential light output over the range of the ion gives:

$$L = a_1\left\{E - a_2AZ^2 \ln\left|\frac{E + a_2AZ^2}{a_2AZ^2}\right|\right\}, \tag{3}$$

with

$$a_1 = gS \tag{4}$$

and

$$a_2 = ckB, \tag{5}$$

where g is the gain factor from the electronics. Eq. (3) combined with a zero-offset term, a_0, from the experiment's electronics, can then be used to fit the experimental pulse heights.

Calibration points with energies above 4 MeV per nucleon and sufficient statistics to determine channel number to a precision of ± 4 units were fitted to eq. (3), giving $a_1 = 8.145 \pm 0.036$, $a_2 = 0.326 \pm 0.003$, and $a_0 = 28.0$ with a standard error of 5.9 channels, or 0.7 MeV. The measured points included in the fit are listed in table 1, along with the channel numbers calculated with the resulting calibration coefficients. The fit was unweighted by uncertainties, except in the sense that statistically uncertain points were excluded as described above. Fig. 2 shows the calibration curves superimposed on the full set of data. It is evident from fig. 2 that when the linear term becomes very large with respect to the logarithmic term, i.e. $E \gg a_2AZ^2$, the calibration curves become approximately parallel. In this limit, the total quenching at fixed energy is proportional to AZ^2.

Table 1
Calibration points for the CsI(Tl) detector at 21°

Ion	Energy [a] [MeV]	Data [channels]	Channel calculated with fitted coefficient
^{1}H	8.6	87.8±0.1	88.9
	14.3	129.2±0.1	134.0
	20.1	175.1±0.2	180.5
	26.0	221.8±0.5	228.4
	31.9	268.6±0.1	275.6
^{2}H	15.4	142.2±0.1	136.6
	20.7	180.7±0.2	178.0
	25.9	223.6±0.1	218.9
	65.6	525.0±3.0	537.7
^{3}H	15.0	130.9±0.3	127.9
	32.7	273.5±0.3	265.7
^{3}He	26.1	172.9±0.6	175.7
	51.6	369.7±0.5	363.8
	74.4	549.2±0.7	538.5
	116.3	868.3±1.1	866.1
^{4}He	20.9	123.3±0.3	129.8
	39.0	254.2±0.3	254.9
	71.4	505.5±0.5	495.4
	102.0	740.0±0.3	730.4
	156.8	1155.7±0.7	1159.2
^{6}Li	24.4	99.3±1.5	102.1
	37.2	167.5±2.4	168.3
	53.1	260.4±2.1	261.3
	73.5	390.7±2.0	391.1
	100.1	575.3±2.0	571.1
	141.3	851.0±3.9	863.6
^{7}Li	34.3	141.8±1.8	143.2
	48.8	221.1±1.2	222.1
	66.5	329.0±1.4	328.2
	90.0	478.4±1.1	479.7
	121.2	690.4±1.8	692.3
^{7}Be	109.5	515.6±3.3	508.0
	135.9	674.1±3.5	673.6
	168.8	890.0±3.3	889.7
^{12}C	436.8	1967.2±0.1	1968.1

[a] See section 2 for a discussion of uncertainties in energy.

3. Conclusion

We have measured the scintillation response of CsI(Tl) crystals to energetic heavy ions as a function of energy, atomic number, and mass number. We find a significant mass dependence in the response; for example, in the 10 MeV per nucleon range, ^{7}Be and ^{9}Be have pulse heights differing by about 10% for the same incident energy. Integration of the standard quenching formula gives (in addition to the zero-offset of the electronics) an expression containing two coefficients, one proportional to the scintillation constant, the other proportional to the quenching constant. Fits of this expression to the measurements are achieved with values of the two constants that do not depend on Z, A or E. Contrary to previous findings, we conclude that for CsI(Tl) detectors a few calibration points will suffice to cover an extended range of mass, energy, and atomic number. The technique requires linear light-to-pulse-height conversion, as afforded by PIN photodiodes, uniform scintillation efficiency, and uniform light collection. Furthermore, in applications where a ΔE detector provides adequate isotopic information, this calibration is reliable for ions suffering quenching effects of 50% or more. This result opens the way for the use of CsI(Tl) as a practical high-resolution heavy-ion detector.

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