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Calibrating the CsI(Tl) detectors of the GARFIELD apparatus

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Abstract

The energy and charge dependence of the light output of the CsI(Tl) detectors of the GARFIELD apparatus has been investigated for heavy ions with $5 \leqslant Z \leqslant 16$ in the energy range from 2.2 to 8.3 A MeV. The results have been compared to an analytical expression successfully used in previous calibration procedures at higher energies, and a rather good agreement was obtained between measured and calculated quantities. The resulting parameter set was successfully applied to another set of experimental data. The overall result demonstrates the validity of the above mentioned calibration procedure in a wide range of incident ion energies and masses. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

In heavy-ion physics, complex detectors based on $\Delta E - E$ telescopes are widely used [1–4] because of the large dynamical range of charge (Z) and energy (E) populated by the various nuclear reaction mechanisms. Recent progress [5,6] has demonstrated the possibility of identifying both light charged particles and heavy fragments using telescopes with only two stages: microstrip gas chambers (MSGC) as transmission detectors and CsI(Tl) crystals to stop the reaction products.

On the other hand, it is well-known that the light output of CsI(Tl) crystals depends not only on the energy deposited in the crystal but even, in a

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non-linear and not thoroughly understood way, on the atomic number and mass of the incident ion. So, the energy calibration of these detectors is not a relatively simple task such as, for example, in the case of Si diodes. That is why calibration procedures [7] have been recently developed to meet experimental situations.

The GARFIELD array [5] employs as residual energy detectors 84 CsI(Tl) crystals with photodiode (PD) readout in its forward emisphere and 96 in the backward one. The excellent value of the mean energy resolution ($\Delta E/E \simeq 3\%$: to show the quality of the resulting data a typical multiple α-source spectrum is shown in Fig. 1) found for this large amount of crystals, the checked independence of this value from the position of the incident particle, and the fact that the intrinsic light emission efficiency is the same for all crystals within the experimental error [8], prompted us to carefully deal with the energy calibration of these detectors.

Since the GARFIELD apparatus is designed to work at relatively low incident beam energy (below 15 A MeV), the main novelty of the calibration procedure described in this paper consists in the extension towards low energies (namely from 8.3 to 2.2 A MeV) of a study on the CsI(Tl) response to nuclear species in order to set up a calibration procedure formerly employed in a higher energy range (from 8.5 to 25.5 A MeV [9] and up to 60 A MeV [10]).

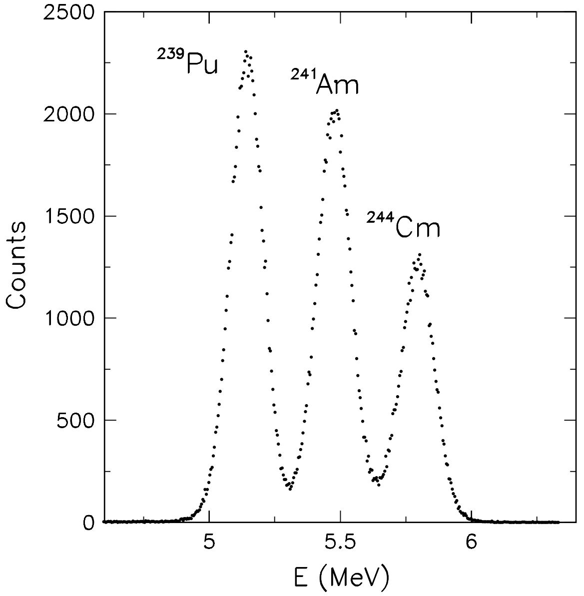

Fig. 1. Typical spectrum from a three-peaks multiple α source (^{239}Pu, $E_\alpha = 5148.8$ keV; ^{241}Am, $E_\alpha = 5478.7$ keV; ^{244}Cm, $E_\alpha = 5794.9$ keV; the reported values of E_α are the weighted mean values from the single nuclide α emissions.

2. Experimental setup

To perform an accurate energy calibration, several beams of various energies have been used as quoted in Table 1. All the beams were accelerated by the XTU Tandem of the Laboratori Nazionali di Legnaro (LNL, Padova, Italy) and impinged on a self-supporting ^{197}Au target, 70 μg cm^{-2} thick. By using a gold target, at the angles chosen for placing the crystals (see below) and for each beam-energy combination, essentially only Coulomb scattering was detected.

As already pointed out, 180 CsI(Tl) scintillators with PD readout are employed as residual energy detectors in the GARFIELD detector; the calibration procedure described in this paper deals with the four different shapes of these crystals, corresponding to the different angles in the rings of the apparatus [11]. Two crystals of each shape were placed at a distance of 15 cm from the target, at scattering angles of $\pm 13^\circ$ and $\pm 33^\circ$ with respect to the incoming beam direction; the eight detectors were labelled by numbers from “1” to “8”. Circular collimators with radii of 0.5 and 3.0 mm were placed in front of them (respectively, at $\pm 13^\circ$ and $\pm 33^\circ$), in order to roughly equalize the counting rates among the detectors.

As to the evaluation of the possible sources of error, whereas the one in light output simply consists in the inaccuracy in the determination of the position of an isolated peak in the light output spectrum and can therefore be neglected, there are three main causes of uncertainty affecting the knowledge of the scattered ion energy. They are (i) the indetermination in the energy loss in the target [12]; (ii) the indetermination in the knowledge of the effective scattering angle value, which may depend on slightly different beam alignments

Table 1
Scheme of the beams, energies and energy intervals used in the measurements

Beam	$E_{\min}$ (MeV)	$E_{\max}$ (MeV)	$E_{\min}$ (A MeV)	$E_{\max}$ (A MeV)	Energy step (MeV)
^{11}B	40	90	3.6	8.2	10
^{12}C	50	100	4.2	8.3	10
^{28}Si	70	160	2.5	5.7	10
^{32}S	70	170	2.2	5.3	10

in the different runs (the beam spot centroid may slightly vary); and (iii) the indetermination in the energy loss in the aluminized mylar covering the detectors [8]. Mark that the error in the energy of the incident beam delivered by the XTU Tandem accelerator may be neglected. Taking all these effects into account, the relative overall error is of the order of 1%.

3. Scintillation response

Having to handle a large number of detectors, the calibration procedure of the crystals must obey some requirements. First of all, it is important to use calibration functions having as large as possible physical meaning. So, the experimental calibration points, necessarily limited in isotope species and energies, are simply used to fit to the data semi-empirical expressions and the resulting curves can be reliably extrapolated in unmeasured regions of charge and energy. Moreover, the calibration formulae should contain a parametrization in terms of Z (and/or A) and E valid for all detectors: in other words, an algorithm has to be developed so that the resulting light output of all detectors is independent from the shape and differs by only one normalizing factor.

We started by adopting the expression proposed in Ref. [7]

$$L(E) = \gamma E + \beta(\mathrm{e}^{-\alpha E} - 1) \tag{1}$$

where, for a given Z, γE represents the linear contribution to the light output that dominates at high values of the energy deposited in the crystals and $\beta(\mathrm{e}^{-\alpha E} - 1)$, with α a positive constant, is the contribution which takes into account quenching effects in the induced luminescence. It must be pointed out that this formula has been already successfully tested in a large range of energy and charge values [9,10].

According to Ref. [10], the explicit expression of Eq. (1) can be written

$$L(E) = \gamma(E + E_0(\mathrm{e}^{-E/E_0} - 1)) \tag{2}$$

with

$$E_0 = d_1 Z \tag{3}$$

and

$$\gamma = d_2/Z + d_3 + d_4 Z. \tag{4}$$

$$d_i \geqslant 0, \quad i = 1, 4.$$

Expression (4) therefore allows us to obtain the light output as a function of four free parameters. The first one (d_1) represents the value of the energy to which the asymptotic linear contributions to Eq. (1) converge independently from the fragment charge (see Ref. [10] and references therein). For an homogeneous set of crystals it is expected to assume the same value. d_3 is the slope of the light output versus energy dependence for a linear response of the detector, whereas d_2 and d_4 take into account the charge dependent part of this quantity, due to quenching effects in the induced luminescence. d_2, d_3 and d_4 implicitly contain a multiplicative normalization factor which takes into account the intrinsic crystal efficiency and the relative gain of the electronic chain. Later on it will be shown that the experimental spectra (such as, for example, the $\Delta E/E$ plots) concerning different detectors can be well superimposed by simply changing this multiplicative factor.

This expression was therefore applied to fit the light output data of the CsI(Tl) detectors to be calibrated in the present experiment. Expression

(2) was fitted to the data obtained from Coulomb scattering of ^{11}B, ^{12}C, ^{28}Si and ^{32}S from the ^{197}Au target (see again Table 1 for a detailed list of the beams and energies), by using the MINUIT routine [13] to determine the four free parameters d_1, d_2, d_3 and d_4.

As pointed out in Ref. [10], a simultaneous fit of all the collected points allows to obtain the value of the light output of the considered detector. The analysis therefore started by separately fitting expression (2) to the data concerning each of the eight detectors used in the measurements; the best result (i.e. concerning the detector for which the χ^2 value reached the minimum) was obtained for the crystal labelled as "1". It can be interesting to observe that the χ^2 values concerning the other detectors varied in the maximum range of 2.1 times the value relative to the detector "1". The resulting values of the parameters are

$$d_1 = (5.31 \pm 0.05)\ \text{MeV},$$

$$d_2 = (101.03 \pm 0.49)\ \text{MeV}^{-1},$$

$$d_3 = (7.60 \pm 0.06)\ \text{MeV}^{-1},$$

$$d_4 = (0.00 \pm 0.22 \times 10^{-3})\ \text{MeV}^{-1}. \qquad (5)$$

The comparison between experimental data and calculated curves is shown in Fig. 2.

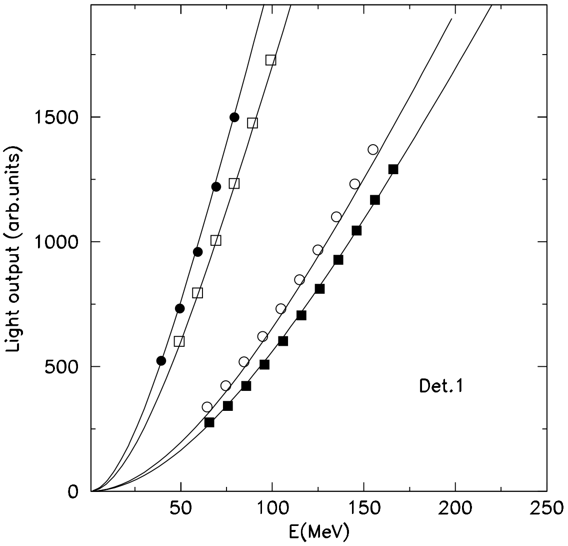

Fig. 2. Light output L of the CsI(Tl) crystal labelled "1" as a function of the incident energy for different ion species. The symbols are the data collected in the present work. Curves are the results of the fit performed using Eq. (1) and the parametrization (5).

Since our goal is to verify the overall light output response of the whole set of the detectors of the GARFIELD array, the second step consisted in fitting simultaneously the data concerning all the eight detectors, keeping fixed the parameters d_1, d_2 and d_3 (d_4 is set equal to 0): the only free parameter (fixed to 1, of course, in the case of the detector "1") was then a factor normalizing the shape of the calculated curves to the experimental points. Fig. 3 shows the results of this fit.

As already pointed out, a severe constraint on the reliability of such a kind of calibration is the possibility of extrapolating the results in unmeasured regions of charge and energy. For this reason, a series of measurements were performed with two of the previously used CsI(Tl) detectors, namely those labeled as "1" and "2". The new data consisted in ^{7}Li and ^{48}Ti ions also scattered from a ^{197}Au target, at incident energies from 25 to 50 MeV for ^{7}Li and from 70 to 150 MeV for ^{48}Ti. Results concerning ^{11}B, ^{12}C and ^{28}Si beams were used to normalize these "new" data to the "old" ones. The comparison between the data concerning ^{7}Li and ^{48}Ti and the curves calculated according to the expressions (4) and (5) shows a rather good agreement (Fig. 4): it must be of course underlined that in this figure the curves concerning ^{7}Li and ^{48}Ti data are not the result of a fit but are simply calculated according to the parameters (5) resulting from the fitting procedure of the ^{11}B, ^{12}C, ^{28}Si and ^{32}S data.

The requirements of (i) a reasonable agreement between experimental and calculated quantities and (ii) a resulting analytical expression applicable to any detector of a given set by simply scaling by a multiplicative factor are therefore fulfilled.

4. Conclusions

A calibration experiment of the CsI crystals of the GARFIELD apparatus has been performed at LNL, using the XTU Tandem accelerator to

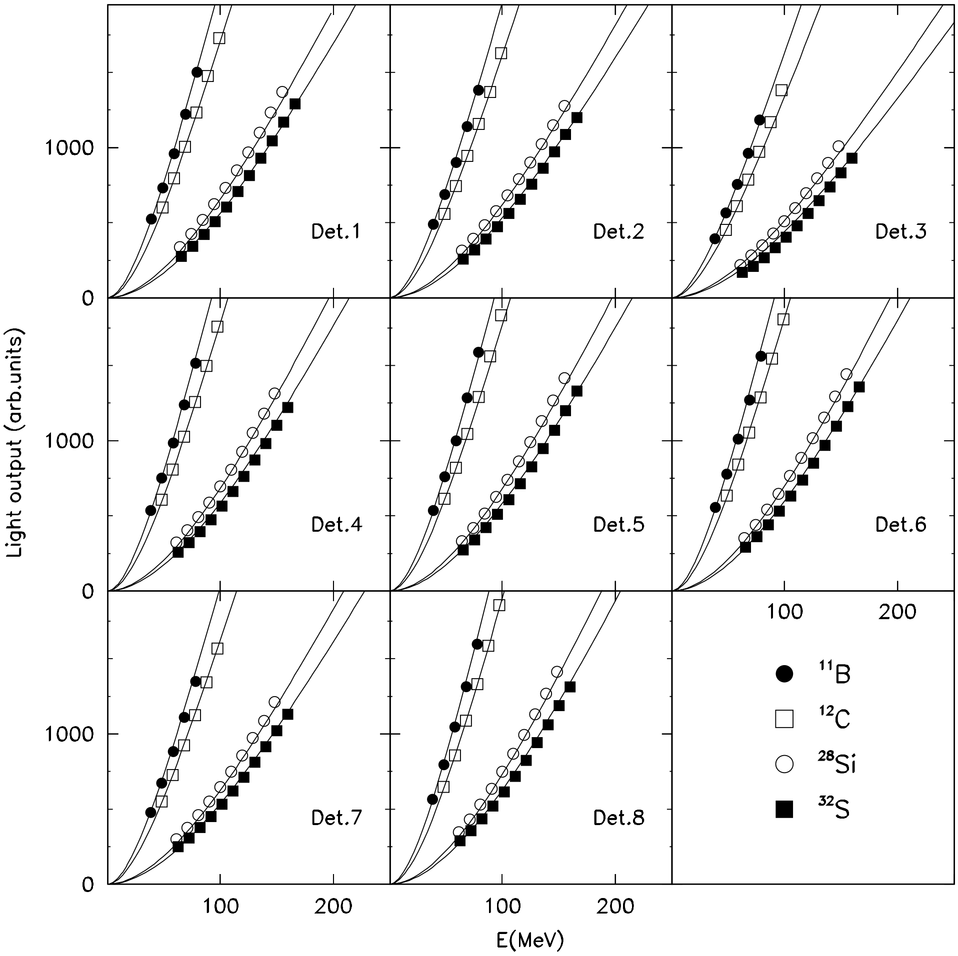

Fig. 3. Light output L of the eight CsI(Tl) crystals as a function of the incident energy for different ion species. The symbols are the data collected in the present work. Curves are the results of the calculation performed according Eq. (1) with the parametrization (5) simply scaled by a normalization factor determined through an one-parameter fit.

obtain heavy ion beams in a wide range of energy and charge. For eight CsI(Tl) crystals with PD readout, 32 points in the energy and charge range $2.2 \leqslant E/A \leqslant 8.3$ and $5 \leqslant Z \leqslant 16$ (with particular care to the low energy and low-charge regions, which are the specific operating regions of the GARFIELD apparatus), have been obtained. The method developed in Ref. [10] to calibrate the energy response of CsI(Tl) scintillators to low- and intermediate energy scattered heavy ions was successfully applied. It has been checked that the proposed formula is able to reproduce the light output response of all crystals in the apparatus by simply scaling the calibration function obtained for another crystal; moreover, the dependence of the light output from the shape of the crystal was found to be negligible. Thus by calibrating only one crystal, the calibration of all the 180 crystals of the GARFIELD apparatus can be easily obtained.

To further check its general validity, this method was applied to another set of experimental points, namely concerning ^{7}Li and ^{48}Ti beams. Without any kind of fit, a rather good result was obtained by simply using the d_i parameters obtained from the original data.

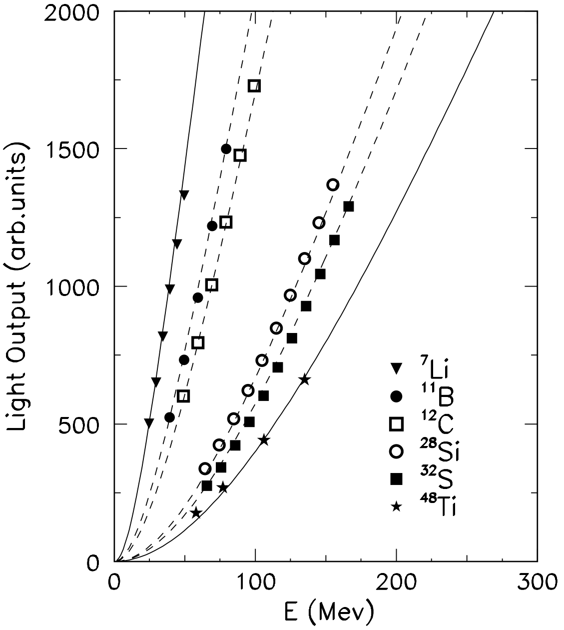

Fig. 4. Light output L for a single CsI(Tl) detector. The data were obtained in two different runs. The curves concerning the ^{11}B, ^{12}C, ^{28}Si and ^{32}S data are the results of the fit, the ones concerning the ^{7}Li and ^{48}Ti data are simply calculated according to the parameters resulting from the previous fit.

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