Calibration of Plastic Phoswich Detectors for Charged Particle Detection

D. Fox, D. R. Bowman, G. C. Ball, A. Galindo-Uribarri, E. Hagberg, and D. Horn

AECL, Chalk River Laboratories, Chalk River, Ontario, K0J 1J0, Canada

L. Beaulieu and Y. Larochelle

Laboratoire de Physique Nucléaire, Université Laval, Ste-Foy, Québec, G1K 7P4, Canada

(August 18, 2018)

Abstract

The response of an array of plastic phoswich detectors to ions of $1 \leq Z \leq 18$ has been measured from $E/A=12$ to 72 MeV. The detector response has been parameterized by a three parameter fit which includes both quenching and high energy delta-ray effects. The fits have a mean variation of $\leq 4\%$ with respect to the data.
I. INTRODUCTION

In recent years a number of large arrays using plastic and/or CsI scintillators have been built for heavy ion experiments \[1\] - [16]. While these arrays offer a relatively inexpensive way of covering large solid angles, the nonlinear response of various scintillators as a function of the incident particle’s energy, charge, and mass poses a challenge in their calibration. To understand the nonlinear response of various scintillators, calibration data covering a wide range of projectile energy, charge and mass are required. These requirements, combined with the large number of elements in an array, make it virtually impossible to do a detailed calibration after each experiment.

Thus a procedure by which the calibration of large scintillator arrays can be achieved during or after an experiment with only a few calibration points would be valuable. The essential ingredient in such a procedure is an understanding of the scintillator response to a wide variety and energy of incident particles. Considerable work has been done in the past to understand the complex scintillator response. Birks proposed \[17\] a simple expression for the light output which took into account the quenching of light output for cases of very large energy loss. Other authors proposed expressions which also took into account high energy electrons, or “delta rays”, which escape from the primary ionization column \[18\] - [20], and recently a new model of light production by secondary electrons has been suggested \[21\] - [22]. While some authors have applied these models to their data \[23\] - [24], many others have used empirical expressions which may not be generally applicable \[4\] - [6], [10], [25] - [30].

In the present work we extend our previously published results for CsI response \[31\] by incorporating delta rays into the Birks’ formalism and applying the resulting expression to calibration data taken with plastic phoswich detectors from the Chalk River/Laval forward array \[8\]. Details of the calibration data are given in the next section. In Section II the parameterization of the light output is derived. Results with fits to the parameterization of Section II to the calibration data are discussed in Section IV. A step by step description of the procedure used to apply the calibration to data is described in Section V. Conclusions
from the present work are given in Section VI.

II. MEASUREMENTS

The CRL/Laval forward array phoswich detectors [8] consist of 0.7 mm thick fast plastic \( \Delta E \) (BC408 from Bicron Corporation) elements heat-pressed to 76 mm thick slow plastic \( E \) (BC444) elements. The photomultiplier signal is split, and integrated with two charge-to-digital converters (QDCs). The first QDC, with a gate width of 57 ns, integrates the early portion of the signal which corresponds primarily to energy lost in the fast plastic \( \Delta E \) counter. The second QDC, with a gate width of 183 ns is delayed by 210 ns with respect to the first gate. This QDC integrates a later portion of the signal which corresponds primarily to the energy deposited in the slow plastic \( E \) counter.

An example of a \( \Delta E - E \) particle identification plot is shown in Fig. 1. Ions which stop in the fast plastic \( \Delta E \) lie along the steeply rising line, or “backbone”, near the y-axis. The deviation of the backbone from the vertical is due to the tail of the fast plastic signal which extends into the delayed slow gate. Neutral particles, almost all of which interact only in the slow plastic \( E \), are visible in the inset in Fig. 1 as the straight line below the hydrogen isotopes. The nonzero slope of the neutral line is due to the leading edge of the slow signal which lies within the fast gate.

In order to measure the response of phoswich detectors from the CRL/Laval forward array, four elements of the array were mounted on a movable trolley which allowed them to be placed directly in the beam. The detectors were exposed to a series of secondary beams produced from an \(^{18}\text{O}\) beam at \( E/A=36.5\) MeV incident on two \(^{12}\text{C}\) production targets at the exit of the cyclotron at the TASCC facility at Chalk River. Six beamline rigidity settings, listed in Table I, were used to select different energies and isotopes. The production target-beamline rigidity combinations produced up to 94 calibration points per detector. A total of 41 different isotopes with \( 1 \leq Z \leq 10 \) and \( 12.0 \leq E/A \leq 72.6 \) MeV were produced. Representative \( \Delta E - E \) plots are shown in Fig. 2 for two beam rigidities. Only calibration
points with more than ten counts were used in the subsequent fitting procedure.

In order to convert the centroids of the calibration points into values proportional to the light emitted in each element of the phoswich, the QDC pedestals must be subtracted, and a correction must be applied for the cross talk of the $\Delta E$ and $E$ signals in the two QDC gates. The correction for the latter signal can be determined from the slopes and intercepts of the backbone and neutral lines. We take

$$s = L + m_b dL + b_b$$

and

$$f = dL + m_n L + b_n,$$

where $s$ and $f$ are the measured $E$ (slow) and $\Delta E$ (fast) signals, $L$ and $dL$ are the “true” $E$ and $\Delta E$ signals, $m_n$ ($m_b$) is the slope (inverse slope) of the neutral line (backbone), and $b_b$ and $b_n$ are the QDC pedestals. Solving for $dL$ the measured signals can now be related to $L$ by:

$$L = \frac{s - m_b f + m_b b_n - b_b}{1 - m_b m_n}.$$  

In this paper we describe only the calibration of the slow plastic signal. The total energy may then be obtained by determining the energy loss in the $\Delta E$ element from a table lookup based on the ion’s element number and the energy deposited in the slow plastic.

### III. LIGHT OUTPUT PARAMETERIZATION

In order to account for the observed nonlinearity of scintillator light output Birks proposed a simple expression for the differential light output $\frac{dL}{dx}$ in terms of a quenching coefficient $kB$ times the energy loss $\frac{dE}{dx}$:

$$\frac{dL}{dx} = \frac{S}{1 + kB \frac{dE}{dx}} \frac{dE}{dx}.$$
where $S$ is the scintillation constant [17]. Under this formulation, an increasing energy loss leads to greater quenching as the primary ionization column becomes saturated. The next step is to consider the effect of high energy electrons, or “delta rays”, which have sufficient energy to escape from the primary ionization column. These delta rays, whose scintillation efficiency is nearly 100% [18], will begin to dominate the light output for very heavy ions where the light output within the primary ionization column is almost totally quenched. If $F_s$ is the fraction of the energy carried by delta rays then the differential light output may be expressed as

$$\frac{dL}{dx} = \frac{S(1 - F_s)}{1 + (1 - F_s)kB \frac{dE}{dx}} + SF_s \frac{dE}{dx}. \quad (5)$$

The fraction $F_s$ may be expressed as [19,32]

$$F_s = \frac{1}{2} \ln(2m_e c^2 \gamma^2 \beta^2 / T_0) - \beta^2. \quad (6)$$

where $\beta$ and $\gamma$ are calculated from the ion velocity, $m_e$ is the electron rest mass, $T_0$ is the minimum electron energy needed to escape from the primary ionization column, and $I$ is the ionization potential of the scintillator, $I \approx 0.048$ keV for plastic scintillator. At intermediate energies $\gamma^2 \approx 1$, $\beta^2 \ll 1$, and Eq. (6) simplifies to:

$$F_s = \frac{1}{2} \left( 1 - \frac{\ln(T_0/I)}{\ln(aE/A)} \right). \quad (7)$$

where $a = \frac{4m_e}{m_0}$ and $m_0$ is the nucleon rest mass. Since $F_s$ is negative for $E/A < \frac{T_0}{a}$, Eq. (5) is integrated up to $E/A = \frac{T_0}{a}$ with $F_s = 0$. The light output may now be expressed as:

$$L = SE - SkB \int_0^{\frac{T_0}{a}} \frac{dE}{1 + kB \frac{dE}{dx}} dE - S \frac{kB}{2} \int_{\frac{T_0}{a}}^E \frac{(1 + R)^2 \frac{dE}{dx}}{2 + kB(1 + R) \frac{dE}{dx}} dE \quad (8)$$

where $R = \frac{\ln(T_0/I)}{\ln(aE/A)}$. There are three parameters in this expression: the scintillation constant $S$, the quenching factor $kB$, and the electron kinetic energy cutoff $T_0$. The quantity $S$ is measured in combination with an overall gain factor from the readout device, but the latter two parameters are, in principle, properties of the scintillator material and should be the same for each detector.
IV. RESULTS

A. $^{18}$O Calibration

The free parameters in Eq. (8) were fitted to the data described in Section II for the energy deposited in the slow plastic. The energy lost in the fast plastic was calculated using the energy-loss code STOPX [33] and subtracted from the incident energy to give the energy deposited in the slow plastic. In order to obtain satisfactory fits it was necessary to separately fit the light, $1 \leq Z \leq 3$, and heavy, $4 \leq Z \leq 10$, ions. The values for the electron kinetic energy cutoff parameter $T_0$, from the four detectors, were found to be in good agreement for the light ion fit, see Table II. The fit was then repeated with $T_0$ fixed at the average value of 2.85 keV. The results of this second fit showed a better agreement in the four values of $k B$ without significantly affecting the quality of the fit. A final pass was made with $k B$ at the average value of 8.25. Again, there was no significant effect on the overall quality of the fit. The mean difference between the fit and data is $\leq 4\%$. The light ion data and final fit results are shown in Fig. 3 for one detector.

In fitting the heavy ion data, $4 \leq Z \leq 10$, to Eq. (8) it was necessary to add a quadratic term to Eq. (3) to account for a slight curvature of the backbone for high $\Delta E$. Equation 3 becomes

$$L = s - m_b f + m_b b_n - b_b - q f^2.$$  \hspace{2cm} (9)

The additional parameter $q$ may be included in the fit, or determined independently by making the backbone pass through a punch-in point of a high $Z$ line such as the one indicated in Fig. 1. Once again, the values for $T_0$ and $k B$ were found to be in good agreement from detector to detector, see Table III. The mean difference between the fit and data is $\leq 2\%$. The results of the fits for the heavy-ion data are shown Figure 4 for one detector.

After fitting both the light- and heavy-ion data it was found that the ratio of the light ion gain factor $S_{LI}$ to the heavy ion gain factor $S_{HI}$ was $\approx 1.30$ for all four detectors; see Table IV. The ability to obtain a single detector-independent set of parameters $k B$ and $T_0$
combined with a fixed ratio for the overall gain parameters, permits the calibration of other data sets with a single calibration point.

B. Gate Tests

The sensitivity of the gains to changes in the slow gate width and delay were checked by separately varying the gate width and delay from their normal values. Figure 5(a) shows the percentage shift when the gate width was changed from the usual value of 183 ns. Reducing the gate width to 150 ns resulted in an average shift of $\approx -13.5\%$, with no apparent $Z$ dependence and less than a 1% scatter in the individual shifts. Lengthening the gate width to 210 ns produced an average shift of $\approx +11.5\%$ with a small $Z$ dependence. The effect of varying the slow gate delay from the normal value of 210 ns is shown in Fig. 5(b). For changes of $\pm 30$ ns, very small ($< \pm 1\%$) $Z$ dependence was observed. Reducing the slow gate delay to 150 ns produced the largest observed $Z$ dependence. Even in this case the observed $Z$ dependence is still small, $< \pm 2.5\%$, with the largest shifts observed for Li and Be isotopes.

Data taken with phoswich detectors can be affected by differences in timing between detectors. Since timing differences result in a small smear of slow gate delays, the data in Fig. 5(b) may be used to estimate the effect on the measured energy of poor timing between phoswich detectors. In the past we have experienced timing differences of up to 10 ns for a few of the phoswich detectors which has now been corrected. From Fig. 5(b) the effect of a 10 ns time shift can be estimated to be less than 5%.

C. $^{37}$Cl Calibration

The extent to which the values of $kB$, $T_0$, and $S_{LI}/S_{HI}$, which were obtained in Section [V.A] are applicable to other data sets was checked by calibrating a second data set with the parameter values obtained from the first data set. In the second data set, a single phoswich from the first ring of the array was placed directly into a secondary beam ranging
from Hydrogen to Argon ions produced by a $^{37}$Cl beam incident on a 50 mg/cm$^2$ C production target with a beamline $B\rho$ setting of 1.584 Tm. With $kB$ and $T_0$ fixed at 7.18 and 1.13 keV respectively, the data points for $4 \leq Z \leq 18$ were fit with just two free parameters, $S_{HI}$ and $q$. The fit results differed from the measured values by an average of 1.2%. The light ion data were then fit with $kB=8.25$ and $T_0=2.85$ keV and with the light-ion gain factor, $S_{LI}$, fixed at 1.30$S_{HI}$. The average difference between the predicted and measured centroids for $1 \leq Z \leq 3$ was 5.6%. While somewhat better fits were obtained when all the fit parameters were allowed to vary, the calibrations obtained with the $^{18}$O fit parameters are quite satisfactory for plastic phoswich detectors.

**V. APPLICATION TO DATA**

The parameterization described above in Eq. 8 is for the energy deposited in the slow plastic $E$ detector. In order to obtain the total incident energy from this parameterization it is necessary to calculate the energy deposited in the fast plastic $\Delta E$ detector. Furthermore, Eq. 8 can only be numerically inverted into a relation for energy as a function of light. The following steps are followed to produce a table of the total incident energy as a function of the light output of the slow plastic for a given ion:

1. The energy loss $\delta E$ in the fast plastic $\Delta E$ detector is calculated for the incident fragment energy $E_{inc}$.

2. Equation 8 is used to calculate the light output for the energy deposited in the slow plastic $E_{slow} = E_{inc} - \delta E$.

3. Steps 1 and 2 are repeated for a range of fragment energies. The results are used to build a table of light output as a function of incident energy.

4. The table in step 3 is inverted to give a table of the incident energy as a function of the light output of the slow plastic.

5. Steps 1 to 4 are repeated for each ion to which the calibration will be applied.

Since isotopic resolution in the phoswichs is only acheived in the calibration data through
Broseparation, normal data sets use calibrations assuming \( A = 2Z \) for \( Z \geq 2 \) and \( A = 1 \) for \( Z = 1 \). This assumption introduces an error in the fragment energy when the fragment has a different mass number than the assumed value. For example the calculated energy will be \( \approx 10\% \) less than the true energy for \(^8\)Li and \( \approx 5\% \) less for \(^{18}\)O. For comparison the slow plastic energy resolution is \( \approx 5\% \).

**VI. CONCLUSIONS**

The response of plastic phoswich detectors from the CRL/Laval forward array has been measured for a wide range of incident particles and energies. The data are well reproduced by a fit based on the light output relation of Birks with an additional term to include the effects of high energy delta rays which escape from the primary ionization column. The light output is characterized with just three parameters: the gain factor \( S \), the quenching factor \( kB \), and an electron cut-off energy \( T_0 \). The quenching factor and electron cut-off energy have been found to be constant from detector to detector. In order to achieve reasonable fits over a wide range of ions, \( 1 \leq Z \leq 18 \), it was necessary to fit the light \((Z \leq 3)\) and heavy \((Z \geq 4)\) ions separately. The inability to fit all ions with the same set of parameters may be due to pulse shape differences between the ions combined with the integration of only part of the photomultiplier signal. The mean difference between the fits and the data is \( \approx 4\% \) for light ions and \( \approx 2\% \) for heavy ions. The ratio of the gain factors for the separate light- and heavy-ion fits has been found to be a constant. It is thus possible to obtain future calibrations with a single normalization point. Tests demonstrated that changes in the QDC gates have little effect on the calibrations other than in changing the overall gain factor. The calibration procedure outlined in this paper has also been successfully applied to CsI detectors over a wide range of incident particles from \( Z=2 \) to \( 32 \).
VII. ACKNOWLEDGEMENT

This work was supported in part by the Natural Sciences and Engineering Research Council of Canada.
REFERENCES

[1] A. Baden, H.H. Gutbrod, H. Löhner, M.R. Maier, A.M. Poskanzer, T. Renner, H. Riedesel, H.G. Ritter, H. Spieler, A. Warwick, F. Weik, and H. Wieman, Nucl. Instr. and Meth. 203, 189 (1982).

[2] G.D. Westfall, J.E. Yurkon, J. Van der Plicht, Z.M. Koenig, B.V. Jacak, R. Fox, G.M. Crawley, M.R. Maier, B.E. Hasselquist, R.S. Tickle, and D. Horn, Nucl. Instr. and Meth. A238, 347 (1985).

[3] R. Bougault, D. Horn, G.C. Ball, M.G. Steer, and L. Potvin, Nucl. Instr. and Meth. A245, 455 (1986).

[4] J. Pouliot, Y. Chan, A. Dacal, A. Harmon, R. Knop, M.E. Ortiz, E. Plagnol, and R.G. Stokstad, Nucl. Instr. and Meth. A270, 69 (1988).

[5] M.M. Fowler, T.C. Sangster, M.L. Begemann-Blaich, T. Blaich, J.A. Boissevain, H.C. Britt, Y.D. Chan, A. Dacal, D.J. Fields, Z. Fraenkel, A. Gavron, A. Harmon, B.V. Jacak, R.G. Lanier, P.S. Lysaght, G. Mamane, D.J. Massoletti, M.N. Namboodiri, J. Pouliot, R.G. Stokstad, M.L. Webb, and J.B. Wilhelmy, Nucl. Instr. and Meth. A281, 517 (1989).

[6] D.W. Stracener, D.G. Sarantites, L.G. Sobotka, J. Elson, J.T. Hood, Z. Majka, V. Abenante, A. Chbihi, and D.C. Hensley, Nucl. Instr. and Meth. A294, 485 (1990).

[7] R.T. de Souza, N. Carlin, Y.D. Kim, J. Ottarson, L. Phair, D.R. Bowman, C.K. Gelbke, W.G. Gong, W.G. Lynch, R.A. Pelak, T. Peterson, G. Poggi, M.B. Tsang, and H.M. Xu, Nucl. Instr. and Meth. A295, 109 (1990).

[8] C.A. Pruneau, G.C. Ball, P. Dmytrenko, E. Hagberg, D. Horn, M.G. Steer, R.B. Walker, T. Whan, C. Rioux, R. Roy, C. St-Pierre, T.E. Drake, and A. Galindo-Uribarri, Nucl. Instr. and Meth. A297, 404 (1990).
[9] H.K.W. Leegte, E.E. Koldenhof, A.L. Boonstra, and H.W. Wilschut, Nucl. Instr. and Meth. A313, 26 (1992).

[10] D.A. Cebra, W.K. Wilson, A. Vander Molen, and G.D. Westfall, Nucl. Instr. and Meth. A313, 367 (1992).

[11] E. Migneco, C. Agodi, R. Alba, G. Bellia, R. Coniglione, A. Del Zoppo, P. Finocchiaro, C. Maiolino, P. Piattelli, G. Raia, and P. Sapienza, Nucl. Instr. and Meth. A314, 31 (1992).

[12] A. Galindo-Uribarri, Prog. Part. Nucl. Phys., 28, 463, (1992).

[13] I. Iori et al., Nucl. Instr. and Meth. A325, 458 (1993).

[14] K. Kwiatkowski, D.S. Bracken, K.B. Morley, J. Brzychczyk, E. Renshaw Foxford, K. Komisarcik, V.E. Viola, N.R. Yoder, J. Dorsett, J. Poehlman, N. Madden, and J. Ottarson, Nucl. Instr. and Meth. A360, 571 (1995).

[15] J. Pouthas et al., Nucl. Instr. and Meth. A357, 418 (1995).

[16] J.C. Steckmeyer, D. Cussol, J. Duchon, J.M. Gautier, J.L. Laville, P. Le Botlan, A. Leconte, J. Lelandais, V. Métivier, P. Mosrin, E. Rosato, J. Tillier, and A. Wieloch, LPCC 94-13, submitted to Nucl. Instr. and Meth.

[17] J.B. Birks, The Theory and Practice of Scintillation Counting, (Pergamon, 1964).

[18] A. Meyer and R.B. Murray, Phys. Rev. 128, 98 (1962).

[19] R. Voltz, J. Lopes da Silva, G. Laustriat, and A. Coche, J. Chem. Phys. 45, 3306 (1966).

[20] G. Tarlé, S.P. Ahlen, and B.G. Cartwright, Ap. J. 230, 607 (1979).

[21] K. Michaelian and A. Menchaca-Rocha, Phys. Rev. B49, 15550 (1994).

[22] K. Michaelian, A. Menchaca-Rocha, and E. Belmont-Moreno, Nucl. Instr. and Meth. A356, 297 (1995).
[23] G.D. Badhwar, C.L. Deney, B.R. Dennis, and M.F. Kaplon, Nucl. Instr. and Meth. 57, 116 (1967).

[24] M.A. McMahan, IEEE Trans. on Nucl. Sci. 35, 42 (1988).

[25] E. Newman, A.M. Smith, and F.E. Steigert, Phys. Rev. 122, 1520 (1961).

[26] M. Buenerd, D.L. Hendrie, U. Jahnke, J. Mahoney, A. Menchaca-Rocha, C. Olmer, and D.K. Scott, Nucl. Instr. and Meth. 136, 173 (1976).

[27] F.D. Becchetti, C.E. Thorn, and M.J. Levine, Nucl. Instr. and Meth. 138, 93 (1976).

[28] C.J.W. Twenhöfel, P.F. Box, P. Schotanus, T.M.V. Bootsma, G.J. van Nieuwenhuizen, P. Decowski, and R. Kamermans, Nucl. Instr. and Meth. B51, 58 (1990).

[29] N. Colonna, G.J. Wozniak, A. Veeck, W. Skulski, G.W. Goth, L. Manduci, P.M. Milazzo, and P.F. Mastinu, Nucl. Instr. and Meth. A321, 529 (1992).

[30] Y. Larochelle, L. Beaulieu, B. Djerroud, D. Doré, P. Gendron, E. Jalbert, R. Laforest, J. Pouliot, R. Roy, M. Samri, C. St-Pierre, Nucl. Instr. and Meth. A348, 167 (1994).

[31] D. Horn, G.C. Ball, A. Galindo-Uribarri, E. Hagberg, R.B. Walker, R. Laforest, and J. Pouliot, Nucl. Instr. and Meth. A320, 273 (1992).

[32] S.P. Ahlen, Rev. Mod. Phys. 52, 121 (1980).

[33] Code STOPX by T. Awes, based on the stopping power parametrization of U. Littmark, and J.F. Ziegler, Handbook of Range Distributions for Energetic Ions in all Elements, ed. J.F. Ziegler (Pergamon, 1980) vol. 6, p. 4.
FIGURES

FIG. 1. $\Delta E$ (fast signal)–$E$ (slow signal) plot for $^{70}\text{Ge}+^{\text{nat}}\text{Ti}$ at $E/A = 35 \text{ MeV}$ at $\theta_{\text{lab}} = 13.4^\circ$. The inset shows an enlargement of the lower left corner.

FIG. 2. $\Delta E$ (fast signal)–$E$ (slow signal) plots for secondary beams for (a) $B\rho = 1.50Tm$ and (b) $B\rho = 2.17Tm$. Selected isotopes are indicated.

FIG. 3. Final results of fits of Eq. (8) to the light ion data for detector #34. The data are shown as points, the results of the fits are indicated by lines.

FIG. 4. Selected fits of Eq. (8) to the heavy ion data for detector #34. The data are shown as points, the fit results are shown as lines.

FIG. 5. Sensitivity of the detector gains to changes in the slow gate width and delay. The data are from one detector for runs with $B\rho=1.5 \text{Tm}$. Multiple isotopes are included for some fragment charges. (a) Percentage shift in the detector gains for slow gate widths of 150 and 215 ns relative to the normal slow gate width of 183 ns. (b) Percentage shift in the detector gains for slow gate delays of 150, 178, and 240 ns relative to the normal slow gate delay of 210 ns.
TABLES

TABLE I. Beamline rigidity, $B\rho$, $^{12}$C production target thickness, charge range of measured fragments, and degraded $^{18}$O energy. For $B\rho=2.17$ Tm the energy for fragments with $Z/A=0.5$ is given.

| $B\rho$ (Tm) | Production Target (mg/cm$^2$) | $Z$ range | $^{18}$O Energy (MeV/nucleon) |
|--------------|-------------------------------|-----------|-------------------------------|
| 1.25         | 307                           | 1-9       | 14.8                          |
| 1.33         | 307                           | 8         | 16.6                          |
| 1.50         | 80                            | 1-10      | 21.2                          |
| 1.75         | 80                            | 2-8       | 28.8                          |
| 1.86         | 80                            | 8         | 32.3                          |
| 2.17         | 80                            | 1-5       | 25.0 ($Z/A=0.5$)              |
TABLE II. Light ion (1 ≤ Z ≤ 3) fit parameters $T_0$ and $kB$, and average percentage difference between the fit and the slow-plastic data for each detector. The average percentage difference includes only data points with 10 or more counts which are at least 40 channels beyond the backbone. The electron cut-off energy $T_0$ was fixed after the first pass, and the quenching coefficient $kB$ was fixed after the second pass.

| Detector | Pass 1 | Pass 2 | Pass 3 |
|----------|--------|--------|--------|
|          | $T_0$  | $kB$  | Difference | $T_0$  | $kB$  | Difference | $T_0$  | $kB$  | Difference |
|          | (keV)  | (%)   |           | (keV)  | (%)   |           | (keV)  | (%)   |           |
| 33       | 2.84   | 8.13  | 3.9       | 2.85   | 8.11  | 3.9       | 2.85   | 8.25  | 3.9       |
| 34       | 3.24   | 7.36  | 3.0       | 2.85   | 7.89  | 2.8       | 2.85   | 8.25  | 2.9       |
| 35       | 2.71   | 8.27  | 3.2       | 2.85   | 8.04  | 3.3       | 2.85   | 8.25  | 3.3       |
| 48       | 2.60   | 9.46  | 2.2       | 2.85   | 8.94  | 2.4       | 2.85   | 8.25  | 2.4       |
| Average  | 2.85   | 8.31  |           |        |       |           | 8.25   |       |           |
TABLE III. Heavy ion (4 ≤ Z ≤ 10) fit parameters, $T_0$ and $kB$, and average percentage difference between the fit and the slow-plastic data for each detector. The average percentage difference includes only data points with 10 or more counts which are at least 40 channels beyond the backbone. The electron cut-off energy $T_0$ was fixed after the first pass, and the quenching coefficient $kB$ was fixed after the second pass.

| Detector | Pass 1 | Pass 2 | Pass 3 |
|----------|--------|--------|--------|
|          | $T_0$  | $kB$  | Difference | $T_0$  | $kB$  | Difference | $T_0$  | $kB$  | Difference |
|          | (keV)  | (%)   |           | (keV)  | (%)   |           | (keV)  | (%)   |           |
| 33       | 1.02   | 7.18 | 1.7       | 1.13   | 7.54 | 1.8       | 1.13   | 7.18 | 1.8       |
| 34       | 1.31   | 8.14 | 1.5       | 1.13   | 7.51 | 1.6       | 1.13   | 7.18 | 1.6       |
| 35       | 1.06   | 6.98 | 1.6       | 1.13   | 7.22 | 1.7       | 1.13   | 7.18 | 1.7       |
| 48       | 1.13   | 6.44 | 1.6       | 1.13   | 6.43 | 1.6       | 1.13   | 7.18 | 1.7       |
| Average  | 1.13   | 7.18 |           |        |      |           |        |      |           |

TABLE IV. Gain factors from light-ion, $S_{LI}$, and heavy-ion, $S_{HI}$, fits to Eq. (8), and the ratio $S_{LI}/S_{HI}$.

| Detector | $S_{LI}$ | $S_{HI}$ | $S_{LI}/S_{HI}$ |
|----------|----------|----------|-----------------|
| 33       | 4.54     | 3.52     | 1.29            |
| 34       | 4.26     | 3.33     | 1.28            |
| 35       | 5.11     | 3.94     | 1.30            |
| 48       | 4.69     | 3.58     | 1.31            |
| Average  |          |          | 1.30            |
(a) Slow Gate Width
- 150 ns
- 215 ns

(b) Slow Gate Delay
- 150 ns
- 178 ns
- 240 ns

Percent Shift

Z

0 5 10 15 20 25 30

-15 -10 -5 0 5 10 15 20 25 30

0 5 10 15

-10 -5 0 5 10 15