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THE RESPONSE OF SCINTILLATORS TO HEAVY IONS - I. PLASTICS

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THE RESPONSE OF SCINTILLATORS TO HEAVY IONS--

I. PLASTICS

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THE RESPONSE OF SCINTILLATORS TO HEAVY IONS -
I. PLASTICS

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Abstract

The response of various scintillator detectors to ions of A = 1-84 and energies E/A = 5-30 MeV/n have been measured, and are found to be linear above an energy of 100 MeV. Results are presented for a typical organic plastic scintillator including parametrisations of the data as a function of Z, A, and energy. These results can be used by anyone using scintillators as heavy ion detectors, with one calibration point giving a normalisation that allows use of the whole set of curves. The response functions are compared to previous parametrisations at lower energies and discussed in terms of the theory of Ï€-ray formation in the scintillator.

Introduction

After having been supplanted by silicon detectors in the early 1970's, scintillators have recently enjoyed a renaissance in nuclear physics. This is primarily due to the increased energy available from newer accelerators. The maximum thickness of silicon detector which is presently feasible is about 5 mm., which will stop up to ~30 MeV/n 4He or 70 MeV/n 20Ne. This energy 4He will stop in 17 mm. of plastic or 5 mm. of CsI, either of which are readily available. A further consideration is that accelerators are becoming increasingly more expensive to run and experiments increasingly more complex. Given this, the natural trend is to build large arrays of detectors. This has progressed to the point where recent talks address not 41t detector systems, but 121t. With silicon a 12 or even 41t detector system becomes very expensive and with gas detectors, very cumbersome. Because of all these factors, investigators are rediscovering both the advantages and disadvantages of scintillators.

The advantages of scintillators are many. The variety of scintillating material available (ranging from inert gases to organic plastic detectors to inorganics to glass) means one can tailor the detectors to fit the application, choosing between high or low density materials, short or long time constants, etc. The scintillators can be made thin enough to act as a low threshold trigger counter or thick enough to stop almost any desired particle. Two scintillators with different time constants can be sandwiched to make a "phoswich" ÂEÂE telescope, or with some of the inorganic scintillators, pulse shape discrimination can give Z and A discrimination for particles of Z ≤ 2 or 3. Most scintillating material is easily machined to any geometry, allowing for close packing in arrays, and is relatively inexpensive compared to silicon. In addition, the electronics is often simpler and more inexpensive/channel than silicon.

The major drawback of scintillators as detectors for light and intermediate mass fragments (Z ≥ 1) is the fact that the light output depends not only on the energy but also the charge of the incoming ion. This makes it difficult to use scintillators for heavy ions without undertaking a long and involved calibration procedure. In addition, some scintillating material has poor timing characteristics.

The response functions of some solid scintillators to heavy ions were first investigated for Z ≤ 7 and E < 100 MeV in early experiments5-7. Later studies extended these measurements to heavier ions in the same energy range for certain organic scintillators.8 In tests performed with the ECR source and 88 Cyclotron at Lawrence Berkeley Laboratory, we have greatly extended these early studies, up to Z ≤ 36 and E ≤ 1200 MeV for several different scintillating material, primarily plastic (Bicron B-400) and CsI(Tl), with some results for BGO and scintillating glass. For the limited scope of this paper, we will restrict ourselves to a discussion of the plastic data only. We will discuss the qualitative features of the energy and Z response in this energy range, fit the data to a set of parameters which can be used as an aid in calibrating detectors, and compare the results to model calculations.

Figure 1.
Composite spectra of some of the undegraded beams observed at a) q/A = 1/2, b) q/A = 1/3, and c) q/A = 1/4.
the ions is adjusted by means of a set of attenuators at the entrance to the cyclotron and/or by bunching or debunching the beam before injection. These ions are run directly into a scintillator, or degraded first to measure the energy dependence of the light output.

The plastic employed in these studies was a 3" diameter by 3" long cylinder of Bicron B-400 attached directly to a 3" PMT tube. The unit, provided by Bicron, was coated on the sides with white reflective paint and on the front was evaporated an approximately 100 µg/cm² layer of Aluminum. The response was found to be independent of the position in which the ion hit the plastic. This plastic is equivalent to another commonly used plastic NE102.11. Composite spectra are shown in Figure 1 at three q/A ratios. This figure is a good illustration of the power of the technique. At q/A = 1/3, fully stripped ions, a cocktail gas of He, Ar, and Ne was run in the ECR source. All other ions seen were due to impurities in the source. In addition to those ions shown, in other runs we occasionally observed 3Li, 32S, and 40Ca. The q/A = 1/3 (15.5 MeV/µ) and q/A=1/4 (8.75 MeV/µ) series show most masses up to krypton. A few of these are not identified. Some impurities are invariably present, for instance O and N from air leaks, C from the pump oil, and Cu from the tubing. The presence of other impurities depends on what has been recently run in the source. (Some species, particularly solids, contaminate the source for weeks.) By combining results from these three q/A ratios, we can study a wide range of energies, charges, and isotopes of heavy ions. At q/A = 1/4, the response of a scintillator to over twenty different ions was measured in a two hour period.

Response Functions

The measured light output L, in arbitrary units, as a function of E for various ions is shown in Figure 2, where the experimental data is given by the symbols, and the lines are linear fits for each species. Also included on this curve are measurements of 4He taken at the LBL Bevalac at higher energies. The measurements span a range of total energy from H and He at 30 MeV to Kr at >1 GeV. It can be seen that above a total energy of approximately 100 MeV, the response for each ion is quite linear.

The data was fitted with a linear least-squares analysis, yielding slopes and intercepts (at E = 100 MeV) shown in Figures 3a and 3b. The slope parameter, dL/dE, is quite large for light ions and levels off for the heavier ions. The intercepts, L(100), follow the same trend. The values for both parameters seem to fit very well with a two-exponent fit, dL/dE or L(100) ≈ a1Za2, with a1 and a2 chosen separately for Z ≤ 8 and Z ≥ 8. The two exponent fit yields, for this energy region, the parametrizations for L(Z,E) given in Table 1, Rows A and B, along with the associated χ², and give the dashed

![Figure 2](image)

**Figure 2.** The light output in arbitrary units as a function of energy and Z of the incident ion, for ions with total energy E above 100 MeV. Symbols are the experimental data, and the solid lines are linear fits for each Z. The dashed lines are calculated using the parametrization given in Table 1 and Figure 4. The symbols for the data are as follows: c(H, 12C, 20Ne), g(He, 14N, 30Ar), o(He, 160, 40Ar), a (6Li, 14O, 40Ca), w (10B, 24Mg, 84Kr)
lines in Figure 2. One can see that such a "universal" parametrization in this energy region qualitatively fits the data over the wide range of Z and energy studied; however, because of the power law form of the fitting function, small errors in \( a_2 \) lead to discernable differences in the slope and intercepts for individual ions. The deviations are worse for Kr (which had poor statistics) and He at high energies. For these two ions, the error is as high as 20-30%. For the medium mass ions in the range carbon to argon, however, the error does not exceed 5%. There is no obvious trend to the deviations with Z or E. Because of the exponential nature of the light output, this level of agreement appears to be the best one can do with such "universal" parametrizations of the light output.

For the region \( E < 100 \text{ MeV} \), the experimental points are shown on an expanded scale in Figure 4. Also included are earlier results reported in literature by Becchetti et al.\(^8\) for NE102. These results were normalized to C at 100 MeV, and the other ions and energies agree very nicely with the present measurements. The data for each ion were fit with a simple quadratic function in energy, shown by the solid lines. The long dashed lines are fits from one of the parametrizations derived by Becchetti et al., \( L(E,Z,A) = 4.0E^{1.62(ZA)} - 0.63 \) (shown in Row D of Table 1). It can be seen that this parametrization predicts the light output reasonably well for the heavier ions measured in this low-energy range, but deviates significantly for the lightest ions. Refitting the combined data with the same functional form (but weighted equally for each data point rather than each ion, as was done in Ref. 8) gives the results of Row E in Table 1. Using this parametrization to predict the light outputs gives the short dashed lines in Figure 3, which show improvement for the lighter ions, but not for the heavy ones.

It is very important to take great care in applying these parametrizations to a particular experiment. The limitations are as follows:

i) As far as comparing data taken with different experimental setups, PMT tubes, type of plastic, etc., the agreement between the Becchetti results and the present data is evidence that the measured response functions are independent to within 10% of the details of packaging, electronics, or the exact plastic used. This result was verified directly by Becchetti et al.\(^8\) and gives encouragement to the hope that fits to these functions can be utilized by persons calibrating detector systems without having to obtain a large number of heavy ions. Otherwise, one should use the coefficients of the polynomial fits for the individual ions, which have been tabulated in Table 1.

Table 2. In either case, one should insure that there exists a good overlap point in both energy and ion for a normalization value.

![Figure 3](image)

Table 2. Slope (a) and intercept (b) parameters for the linear portions (\( E > 100 \text{ MeV} \)) of the response curves. The intercept parameter is taken at \( E = 100 \text{ MeV} \). The points give the slopes and intercepts from linear least-square fits to the data for each Z. The error bars are calculated from the fit assuming 5% error in the initial data points. The dashed lines are using Parametrization I of Table 2, fitting \( Z \leq 8 \), and the solid line are Parametrization II for \( Z \geq 8 \).

<table>
<thead>
<tr>
<th>Parametrization #</th>
<th>Z-range</th>
<th>E-range</th>
<th>Functional Form</th>
<th>Constants</th>
<th>( \chi^2 )</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1-8</td>
<td>100-1000 MeV</td>
<td>( L = a_1(E=100) + a_2 )</td>
<td>( a_1 = 1. + 22.067Z - 806 )</td>
<td>0.931</td>
<td>8</td>
</tr>
<tr>
<td>B</td>
<td>8-36</td>
<td>100-1000 MeV</td>
<td>( L = a_1(E=100) + a_2 )</td>
<td>( a_1 = 1. + 2207.3Z - 1.042 )</td>
<td>2.073</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>1-36</td>
<td>100-1000 MeV</td>
<td>( L = a_1(E=100) + a_2 )</td>
<td>( a_1 = 1. + 8.525Z - 3532 )</td>
<td>0.554</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>1-36</td>
<td>0.5-5 MeV/nucleon</td>
<td>( L = a_1E^{a_2} )</td>
<td>( a_1 = 4.0(ZA)^{-0.63} )</td>
<td>12.0</td>
<td>8</td>
</tr>
<tr>
<td>E</td>
<td>1-16</td>
<td>10-100 MeV</td>
<td>( L = a_1E^{a_2} )</td>
<td>( a_1 = 1.47(ZA)^{-0.70} )</td>
<td>45.49</td>
<td></td>
</tr>
</tbody>
</table>
Comparisons to models

Several observations can be made when perusing the data of Figures 2 and 4, as well as the parametrizations obtained in Figure 3 and Table 1. Some of these are as follows:

i) For $E > 100$ MeV, the light output is linear with $E$ but dependent on $Z$, with a slope that decreases with increasing $Z$.

ii) For $E < 100$ MeV, the light output is approximately quadratic in $E$ and still dependent on $Z$.

iii) For heavy ions and/or low energy, there is an additional $A$ dependence in the response function. This does not seem to exist for heavier ions or higher energies.

These qualitative results can be understood in terms of the model of Voltz, et al. for organic scintillators. This model is very similar in formulation to an earlier model of Meyer and Murray for inorganic scintillators. In both models, the measured light output per unit distance traveled by an ion through the scintillator is a sum of a "core" emission component of primary scintillation and a "halo" emission component of secondary electrons ($\delta$-rays). The core term is saturated emission dominated by the quenching probability in the scintillator and depends on the type of material and the energy deposition ($dE/dx$) in the material. It is the dominant component of the scintillation for electrons and light ions and was discussed extensively by Birks. The halo emission from $\delta$-rays becomes dominant when $dE/dx$ is large, i.e. for heavy ions at intermediate energies. The light output is then proportional to energy/nucleon of the ion as well as $dE/dx$ ($Z$), but does not depend on either the scintillator material or the mass of the ion.

Table 2. Polynomial fits to response data for individual ions. 
$L = a_1 + a_2 E + ... + a_n E^{n-1}$
with units of $E$ in MeV and $L$ in arbitrary units.

<table>
<thead>
<tr>
<th>$E &gt; 100$ MeV</th>
<th>$E \leq 100$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n = 2$</td>
<td>$n = 3$</td>
</tr>
<tr>
<td>$a_1$</td>
<td>$a_1$</td>
</tr>
<tr>
<td>$a_2$</td>
<td>$a_2$</td>
</tr>
<tr>
<td>$a_3$</td>
<td>$a_3$</td>
</tr>
<tr>
<td>$2\text{He}$</td>
<td>$-169.34$</td>
</tr>
<tr>
<td>$3\text{He}$</td>
<td>$-3.0197$</td>
</tr>
<tr>
<td>$4\text{He}$</td>
<td>$-513.8$</td>
</tr>
<tr>
<td>$\text{Li}$</td>
<td>$-24.633$</td>
</tr>
<tr>
<td>$\text{Be}$</td>
<td>$-20.156$</td>
</tr>
<tr>
<td>$\text{B}$</td>
<td>$-17.508$</td>
</tr>
<tr>
<td>$\text{C}$</td>
<td>$-12.414$</td>
</tr>
<tr>
<td>$\text{O}$</td>
<td>$-330.95$</td>
</tr>
<tr>
<td>$\text{Ne}$</td>
<td>$-41.49$</td>
</tr>
<tr>
<td>$\text{Ar}$</td>
<td>$-84.348$</td>
</tr>
<tr>
<td>$\text{Kr}$</td>
<td>$-295.35$</td>
</tr>
<tr>
<td>$\text{S}$</td>
<td>$-255.48$</td>
</tr>
<tr>
<td>$\text{Cl}$</td>
<td>$-364.57$</td>
</tr>
<tr>
<td>$\text{Br}$</td>
<td>$-483.43$</td>
</tr>
<tr>
<td>$\text{Kr}$</td>
<td>$1000$</td>
</tr>
<tr>
<td>$\text{O}$</td>
<td>$200$</td>
</tr>
<tr>
<td>$\text{Ne}$</td>
<td>$50$</td>
</tr>
<tr>
<td>$\text{Ar}$</td>
<td>$20$</td>
</tr>
<tr>
<td>$\text{Kr}$</td>
<td>$10$</td>
</tr>
</tbody>
</table>

The model of Voltz derives an expression for the slope $dL/dE$ (or scintillation efficiency) of the light output as a function of $dE/dx$ given by

$$dL/dE = A \left[ \frac{(1-F_s)exp[-B_s(1-F_s)dE/dx]}{1 + B_s(1-F_s)dE/dx} + F_s \right]$$

where $F_s$ is the fraction of the energy loss going into $\delta$-ray production, $A$ is an arbitrary gain factor, and $B_s$ is the quenching probability in the core region.

Adapting the Birk's formalism for lighter ions with the Voltz model for the $\delta$-ray region gives an alternate expression for the scintillation efficiency $\gamma$

$$dL/dE = A \left\{ \left( \frac{1-F_s}{1 + B_s(1-F_s)dE/dx} + F_s \right) \right\}$$

Here the arguments are the same as in Eqn. 1. An expression for $F_s$ has been derived by Ahlen

$$F_s = \frac{1}{2} \frac{ln(2mc^2g/\gamma^2 - 1) - B_s}{ln(2mc^2g/\gamma^2 - 1) - B_s}$$

where $\gamma$ is the ion velocity in units of $c$, $\gamma = (1 - \beta^2)^{-1/2}$, $m$ is the electron mass, $\gamma$ is the mean logarithmic ionization potential of the scintillator, and $T_0$ is the threshold energy for $\delta$-ray formation, and determines the core-halo boundary. One can fit either Eqn. 1 or 2 to the data $dL/dE$ vs. $dE/dx$ by varying the parameters $A$, $B_s$, and $T_0$. The velocity and ion $Z$ dependence are contained in the conversion from $T_0$ to $F_s$. This has been done in Figure 5 for $\text{Ne}$. Values of $dE/dx$ were taken from Hubert et al. below 25 MeV/u and from Ahlen above 25 MeV/u. $F_s$ was taken to be constant rather than $T_0$, an assumption that is good in the nonrelativistic velocity region. The values of the parameters derived for this fit using the Voltz model are $A = 18.149$ MeV$^{-1}$, $B_s = 4.565$ mg/(MeV-cm$^2$), and $F_s = 0.129$, that is the Voltz model predicts more $\delta$-ray production and less core quenching than the BTV model. The Voltz model seems to fit better for this case, but a more extensive fitting procedure needs to be followed to determine one set of parameters that best fits all the ions studied. Such an analysis is beyond the scope of the present paper.

It is interesting to note that as $dE/dx$ is further increased (the energy decreased), then $dL/dE$ will become nonconstant again. This behavior cannot be explained by either model, both of which predict constant $dL/dE \rightarrow A'F_s$ as $dE/dx$ becomes large. If one assumes that...
the nonlinearities at low energies are due to some other mechanism, than the slopes of the response functions in the linear region (i.e. Figure 3a) are directly proportional to the fraction of the energy loss which goes into $\gamma$-rays.

14. The points include the present data as well as a fifth order polynomial fit to the data for relativistic Ne measured by Saloman and Ahlen. The solid line is from the model of Voltz and the dashed line from the BTM model.

Conclusion

In conclusion, we have greatly extended the data available on the response of a typical organic plastic scintillator, B-400, to heavy ions for the energy range 8-30 MeV/nucleon. These results are quite important for anyone wishing to use scintillators as heavy ion detectors in this energy range. Universal parametrizations are given for two energy ranges that allow one to extend the results to ions that were not measured. In addition, this data can be used in conjunction with theoretical models to elucidate the competition between primary scintillation and the production of secondary electrons during the passage of an ion through the scintillator material.

References

10. Bicron Corporation, Newbury, Ohio, USA

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