Title
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Publication Date
1987-10-01

LBL-24147

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Accelerator & Fusion Research Division

Presented at the IEEE 1987 Nuclear Science
Symposium, San Francisco, CA,
October 21–23, 1987

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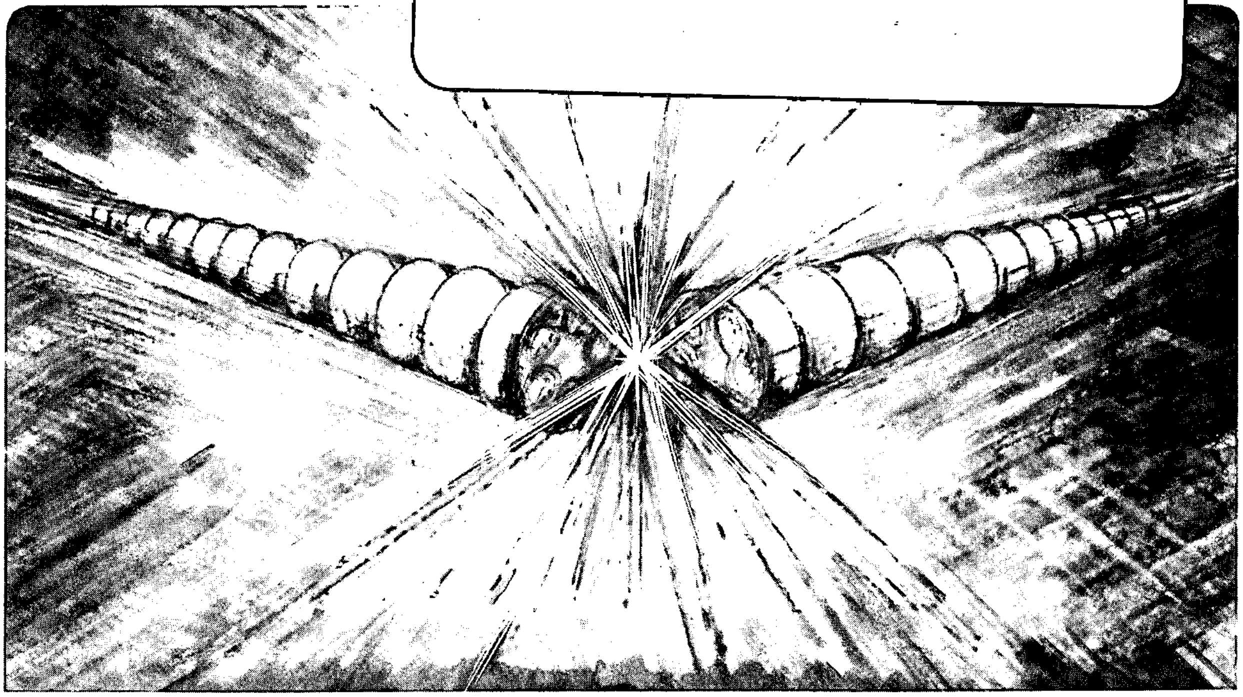

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

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 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 parametrizations 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 normalization that allows use of the whole set of curves. The response functions are compared to previous parametrizations at lower energies and discussed in terms of the theory of δ-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/u ^{4}He or 70 MeV/u ^{20}Ne. This energy ^{4}He will stop in 17 mm. of plastic or 5 mm. of CsI[1], 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 4π detector systems, but 12π. With silicon a 12 or even 4π detector system becomes very expensive and with gas detectors, very cumbersome. Because of all these factors, investigators are rediscovering[2] 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" ΔE-E telescope, or with some of the inorganic scintillators, pulse shape discrimination can give Z and A discrimination for particles of $Z \leq 2$ 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 ($Z \geq 1$) 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 $Z \leq 7$ and $E < 100$ MeV in early experiments[3-7]. 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 $Z \leq 36$ and $E \leq 1200$ 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.

Technique

The combination of ECR (Electron Cyclotron Resonance) source and cyclotron is ideal for these kind of studies. The technique has been described in a recent paper.[9] In short, a whole series of ions of a given charge to mass ratio (q/A), many due to impurities in the source, can be accelerated in the cyclotron, and individual ions extracted by varying the frequency of the cyclotron. The intensity of

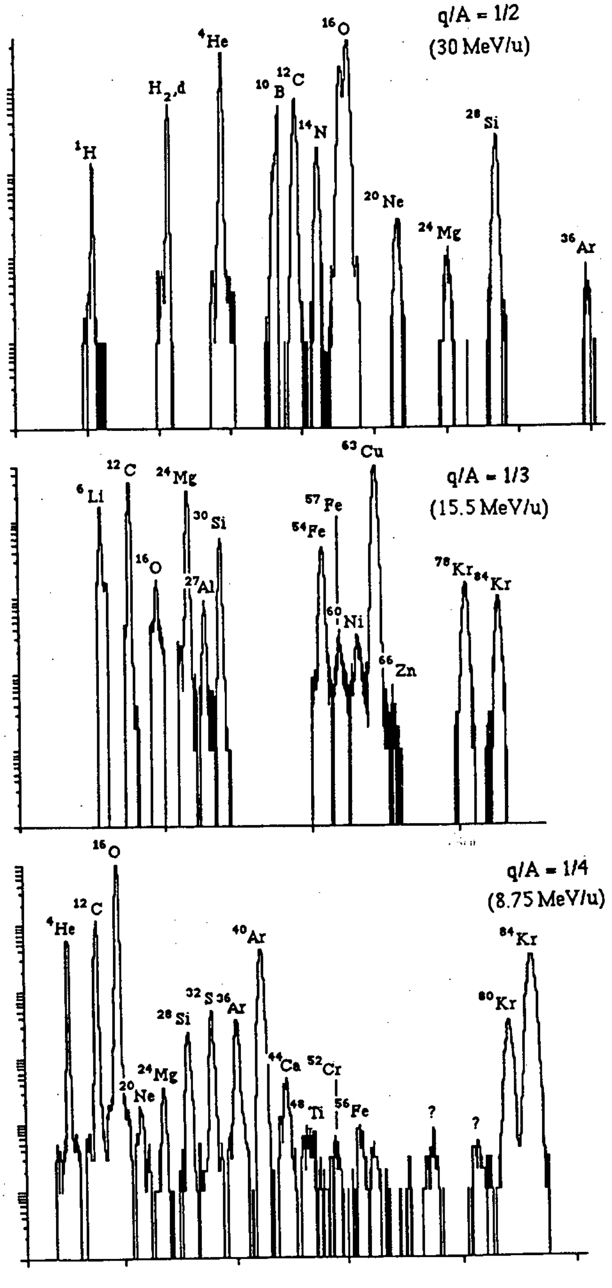

Figure 1.
Composite spectra of some of the undegraded beams observed at a) q/A = 1/2, b) q/A = 1/3, and c) q/A=1/4.

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[10], was coated on the sides with white reflective paint and on the front was evaporated an approximately 100 $\mu g/cm^2$ 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 = 1/2, 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 ^{6}Li, ^{32}S, and ^{40}Ca. The q/A = 1/3 (15.5 MeV/u) and q/A=1/4 (8.75 MeV/u) 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 ^{4}He 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, I_{100}, follow the same trend. The values for both parameters seem to fit very well with a two-exponent fit, dL/dE or $I_{100} = a_1 Z^{a_2}$, with a_1 and a_2 chosen separately for $Z \leq 8$ and $Z \geq 8$. 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 χ^2, and give the dashed

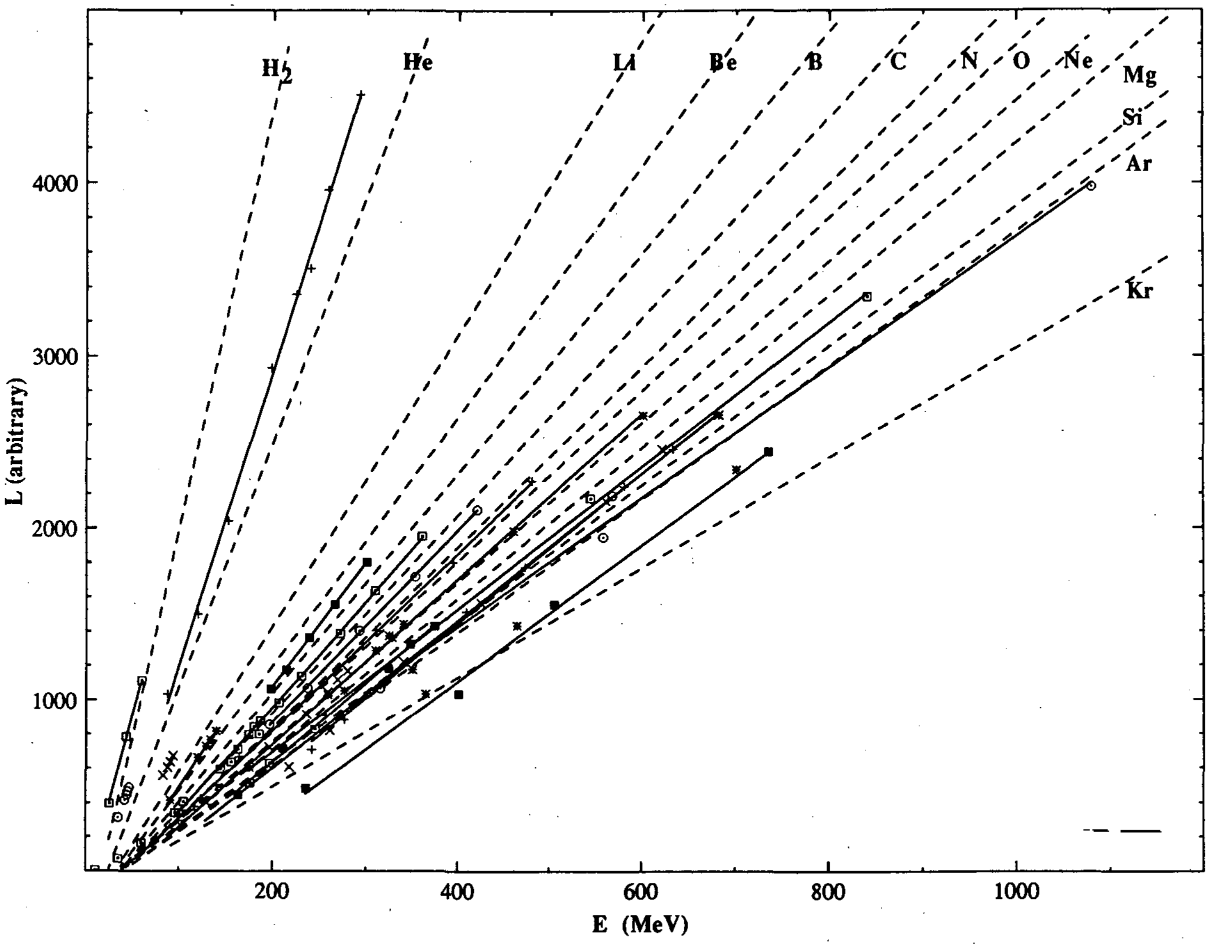

Figure 2.
The light output in arbitrary units as a function of energy and Z of the incident ion, for ions with total energy E above 100 MeV. Symbols are the experimental data, and the solid lines are linear fits for each Z. The dashed lines are calculated using the parametrization given in Table 1 and Figure 4. The symbols for the data are as follows: □(^{2}H, ^{12}C, ^{28}Si), ⊙(^{3}He, ^{14}N, ^{36}Ar), +(^{4}He, ^{16}O, ^{40}Ar), ▲ (^{6}Li, ^{18}O, ^{40}Ca), ✱ (^{9}Be, ^{20}Ne, ^{80}Kr), ■(^{10}B, ^{24}Mg, ^{84}Kr)

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 MeV, the experimental points are shown on an expanded scale in Figure 4. Also included are earlier results reported in literature from 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 deviaties 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 give 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 calibration points for each individual detector.

ii) It should be strongly emphasized that the parametrizations are quite different for the two energy regions. This will be discussed in the following section in regards to models of the scintillation process in organic scintillators. One knows from cosmic ray studies[12] and some studies with relativistic heavy ions[13-14], that at even higher energies, the response is different yet again. Thus one <u>should not</u> extrapolate to energies that have not been measured.

With these points in mind, one is free to choose a parametrization from Table 1, if one only needs the response function good to 5-10% (in the medium mass region) or 20-30% for very heavy ions. Otherwise, one should use the coefficients of the polynomial fits for the individual ions, which have been tabulated in Table 2. In either case, one should insure that there exists a good overlap point in both energy and ion for a normalization value.

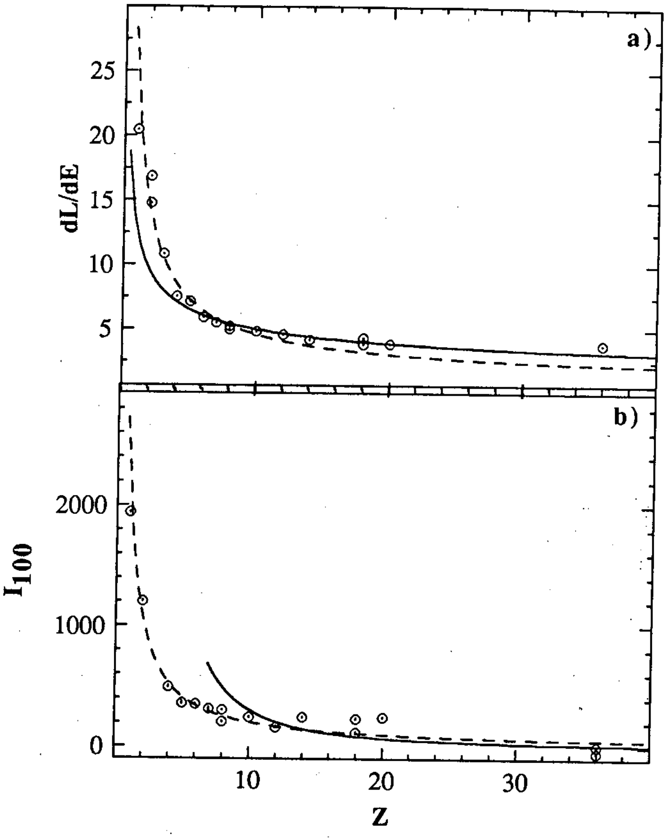

Figure 3

Slope (a) and intercept (b) parameters for the linear portions (E> 100 MeV) of the response curves. The intercept parameter is taken at E = 100 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 ≤ 8, and the solid line are Parametrization II for Z ≥ 8.

Table 1. Parametrizations of Plastic Response Functions

Parametrization #	Z-range	E-range	Functional Form	Constants	χ^2	Ref
A	1-8	100 - 1000 MeV	$L = a_1(E\text{-}100) + a_2$	$a_1 = 1.+ 22.06Z^{-.8006}$ $a_2 = 1. + 2207.3Z^{-1.042}$	0.931 2.073	
B	8-36	100 - 1000 MeV	$L = a_1(E\text{-}100) + a_2$	$a_1 = 1. + 8.525Z^{-.3532}$ $a_2 = 1. + 44127.Z^{-2.1648}$	0.554 28.01	
C	1-36	100 - 1000 MeV	$L = a_1(E\text{-}100) + a_2$	$a_1 = 1. + 18.96Z^{-.6657}$ $a_2 = 1. + 2939.Z^{-1.3009}$	1.664 24.05	
D	1-36	.5 - 5 MeV/nucleon	$L = a_1E^{a_2}$	$a_1 = 4.0(ZA)^{-0.63}$ $a_2 = 1.62$	12.0	8
E	1-16	10 - 100 MeV	$L = a_1E^{a_2}$	$a_1 = 1.47(ZA)^{-0.70}$ $a_2 = 1.83$	45.49	

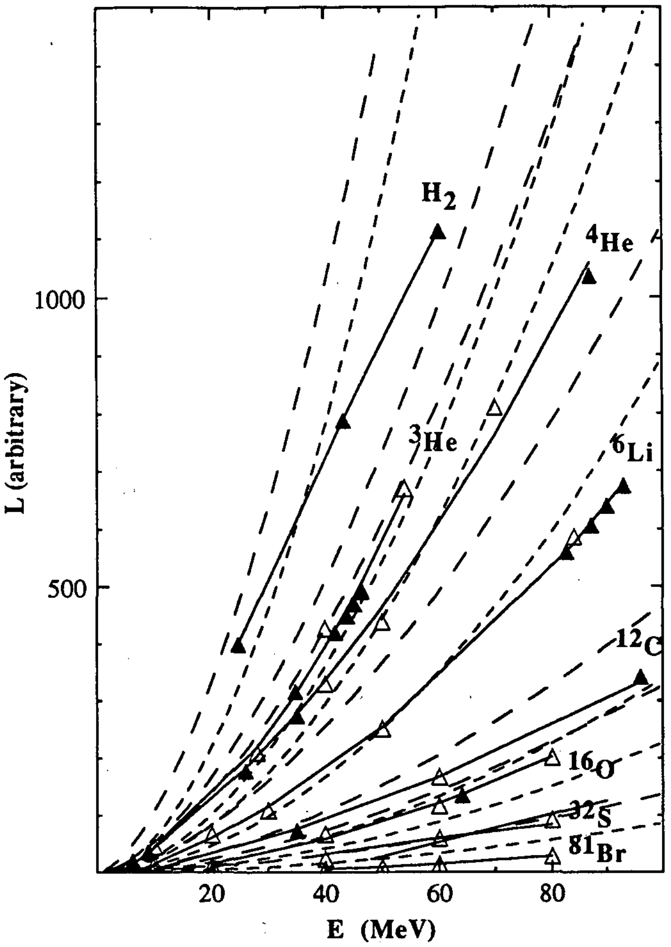

Figure 4.
Light output as a function of Z, A, and energy for the energy region E < 100 MeV. Solid symbols are present data, open symbols from Becchetti, et al. Solid lines are quadratic fits for each ion, dashed lines are the parametrization of Becchetti et al., and dotted lines are fits to the present data plus that of Becchetti with the functional form given by Becchetti, $L(Z,A,E) = a_1(ZA)^{a_2}E^{a_3}$.

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 light 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.[15] for organic scintillators. This model is very similar in formulation to an earlier model of Meyer and Murray[16] 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 (δ-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.[3] The halo emission from δ-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 the 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.
$L = a_1 + a_2E + \dots a_nE^{n-1}$
with units of E in MeV and L in arbitrary units.

	E > 100 MeV n = 2		E ≤ 100 MeV n = 3		
	a_1	a_2	a_1	a_2	a_3
^{2}H			-169.34	24.115	-0.04524
^{3}He			-3.0197	3.2108	0.16780
^{4}He	-513.8	17.175	-24.633	6.0370	0.07385
^{6}Li			-20.156	3.0882	0.04751
^{9}Be	-305.89	8.0418			
^{10}B	-353.72	7.1852			
^{12}C	-180.19	5.7342	-17.508	2.1318	0.01577
^{14}N	-240.54	5.5785			
^{16}O	-205.37	5.1454	-12.414	0.9150	0.02197
^{18}O	-330.95	5.3574			
^{20}Ne	-221.56	4.8176			
^{24}Mg	-275.18	4.5746			
^{28}Si	-132.59	4.1587			
^{32}S			-41.49	2.1154	-0.00699
^{36}Ar	-84.348	3.7775			
^{40}Ar	-295.35	4.3622			
^{40}Ca	-255.48	4.2974	-113.97	3.0844	-0.00478
^{80}Kr	-364.57	3.8615			
^{84}Kr	-483.43	3.9773			

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

$$dL/dE = A\{(1-F_\delta)\exp[-B_\delta(1-F_\delta)dE/dx] + F_\delta\} \tag{1}$$

where F_δ is the fraction of the energy loss going into δ-ray production, A is an arbitrary gain factor, and B_δ is the quenching probability in the core region.

Adapting the Birk's formalism for lighter ions with the Voltz model for the δ-ray region gives an alternate expression for the scintillation efficiency[17]

$$dL/dE = A\left\{ \frac{(1-F_\delta)}{1+ B_\delta\,(1-F_\delta)\, dE/dx} + F_\delta \right\} \tag{2}$$

Here the arguments are the same as in Eqn. 1. An expression for F_δ has been derived by Ahlen[18]

$$F_\delta = \frac{1}{2}\,\frac{\ln(2mc^2\beta^2\gamma^2/T_0) - \beta^2}{\ln(2mc^2\beta^2\gamma^2/I) - \beta^2} \tag{3}$$

where β = the ion velocity in units of c, $\gamma = (1 - \beta^2)^{-1/2}$, m = the electron mass, I is the mean logarithmic ionization potential of the scintillator, and T_0 is the threshold energy for δ-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_δ, and T_0. The velocity and ion Z dependence are contained in the conversion from T_0 to F_δ. This has been done in Figure 5 for ^{20}Ne. Values of dE/dx were taken from Hubert et al.[1] below 25 MeV/u and from Ahlen[18] above 25 MeV/u. F_δ 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_δ = 4.565 mg/(MeV-cm^2), and F_δ = 0.269 and using the BTV model are A = 31.28 MeV^{-1}, B_δ = 19.74 mg/(MeV-cm^2), and F_δ = 0.129, that is the Voltz model predicts more δ-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 → AF_δ 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 δ-rays.

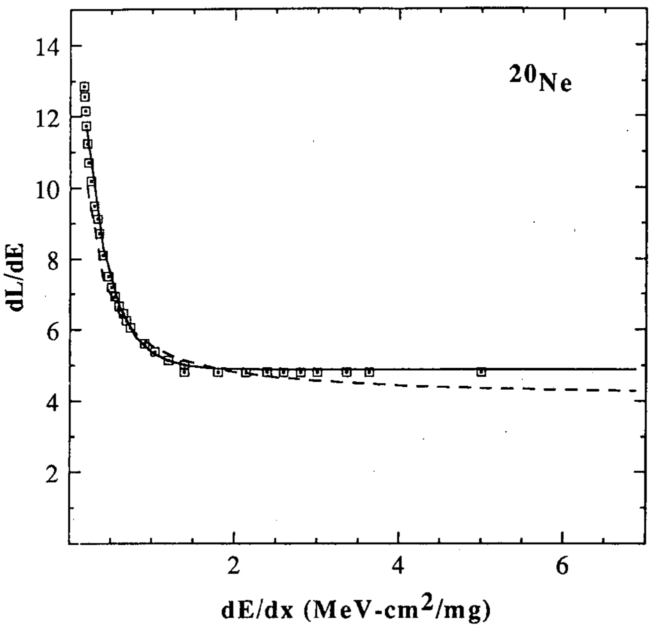

Figure 5

dL/dE vs. dE/dx for ^{20}Ne. 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.[14] *The solid line is from the model of Voltz* [15] *and the dashed line from the BTV model.*[17]

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.

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Acknowledgements

The author would like to thank the following colleagues who were instrumental in helping collect the data shown in this work: G.J. Wozniak, D.R. Bowman, R.J. Charity, H. Han of LBL, and W. L. Kehoe of Univ. of Maryland. She would also like to thank Claude Lyneis, Dave Clark, John Roberts, and the other members of the 88" Cyclotron staff who were instrumental in delivering the beams from the ECR source, and Gordon Wozniak for many helpful discussions on the data analysis and modelling.

This work was supported by the Director, Office of High Energy Research, Division of Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.