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Calibration of the Response Function of a CsI(Tl) Detector to Intermediate-Energy Heavy Ions

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Abstract

The response function of 2-cm-thick CsI(Tl) scintillators with photodiode readouts were studied by directly exposing the detectors to beams of heavy ions ($2 \leq Z \leq 36$) with energy up to 25 MeV/u. The dependence of the light output on the energy (E) as well as on the atomic number and the mass of the ion is analyzed and discussed, and a parameterization of the light output as function of Z and E is proposed.

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1. Introduction

Intermediate-energy heavy-ion reactions, and multifragment emission processes in particular, are currently under intense investigation since they are expected to provide valuable information on the formation and decay of highly excited nuclear systems [1,2]. The experimental characterization of these processes requires the simultaneous detection of many fragments, emitted over a large solid angle and with a broad range in mass and energy. Silicon detectors can be used successfully for this purpose when the number of fragments is not too large and their energy is not too high [3]. However, with increasing bombarding energy, larger numbers of more energetic fragments are produced. Since silicon detectors are not available in thicknesses greater than a few millimeters, they become unsuitable as stopping detectors. Furthermore, arrays with a large number of detectors are necessary to detect and identify the numerous fragments with good granularity and with sufficient coverage of the emission solid angle. In these cases, because of their high costs and susceptibility to radiation damage, silicon detectors are not a practical choice.

An alternative to silicon detectors in the study of intermediate-energy heavy-ion reactions is represented by scintillator detectors. In particular, CsI(Tl) scintillators with photodiode readouts are becoming increasingly popular because of their compactness, reliability, high stopping power, and relatively low cost. Furthermore, CsI(Tl) crystals have the desirable properties of being only slightly hygroscopic, mechanically rugged and easily machinable. Several detector arrays have recently been built which utilize CsI(Tl) as stopping detectors for energetic light and heavy ions [4-7]. Unfortunately, as for all scintillators, the light output from CsI(Tl) exhibits a strong dependence on the atomic number, energy and, to a somewhat lesser extent, on the mass of the detected ion. This constitutes a major drawback for studies which require accurate information on the energy of the fragments, as well as on their size. Although several studies have been made in the last few years [8-11], the response of CsI(Tl) detectors to intermediate-energy heavy-ions is still far from being quantitatively described or understood.

In this paper we report on an accurate calibration of the response function of 2-cm-thick CsI(Tl) scintillators with photodiode readouts to ions with $Z \leq 36$ and energies up to 25 MeV/u. The experimental method is described in detail in section 2. The response function is presented and analyzed in section 3. A brief discussion on the scintillation efficiency is contained in section 4. The conclusions are presented in section 5.

2. Experimental setup

The measurements were performed at the 88-Inch Cyclotron at Lawrence Berkeley Laboratory. To study the response of CsI(Tl) scintillators to ions of different atomic number and energy, the detectors were directly exposed to low intensity beams (typical intensities were of the order of 100 particles/sec). The technique used to obtain data for a wide variety of ions over a large energy range in a reasonably short amount of time is described in detail in refs. [12,13]. In brief, it relies upon the capability of: i) an Electron Cyclotron Resonance (ECR) source to simultaneously produce many different ion species with the same charge/mass (q/A) ratio and, ii) a cyclotron, to accelerate all ions having the same q/A ratio. In general, only the heaviest species were introduced into the ECR source, as the lighter ones were almost always present as trace impurities. Once produced, ions with the same q/A were selected and then injected into the cyclotron. Due to slight differences in their q/A ratios, caused by the variation of the nuclear binding energy with increasing A, different ions are accelerated with slightly different resonance frequencies. Therefore, the cyclotron was used as a mass spectrometer, with the radio-frequency adjusted a few KHz to select different co-resonant beams.

In this experiment three "cocktail" beams with charge-to-mass ratios q/A of 1/2, 1/3 and 1/4 were accelerated and extracted. The corresponding energies were 25.5, 15.5 and 8.8 MeV/u. For the two lowest energies, ions with $Z \leq 36$ were produced, while at

25.5 MeV/u, beams accelerated included ions up to Z = 18. To extend the measurement of the response function to lower energies, and to fill in between the primary energies, the beams were degraded with aluminum foils that could be positioned in front of the detectors. The degraders used had thicknesses of 15, 30, 45, 80, 150, 200, 300 and 400 μm. The energy of the degraded beams was accurately determined by means of a 2-mm-thick, surface-barrier Si detector. All of the detectors were mounted on a movable arm inside the scattering chamber and directly exposed to the same calibration beams.

Two CsI(Tl) detectors were used in this experiment. The detectors, manufactured by Solon [14], have a front face of 5.1x5.1 cm^2 and are 4.1 cm thick. To couple efficiently to the photodiodes, they are shaped for the last 2 cm as truncated pyramids with rear faces of 2.5x2.5 cm^2. This last section also acts as a light guide. To optimize the light collection, the crystals were highly polished and wrapped in Teflon on the sides and covered with 1.5-μm-thick aluminized Mylar on the front face. A Hamamatsu photodiode [15] was optically coupled to the scintillators. The photodiode has an active area of 1.8x1.8 cm^2 and, when operated at 100 V presents a capacitance of 80 pF. The two CsI(Tl) detectors were chosen from a set of 50 detectors that constitute the telescopes of the MULTICS array [7]. The preamplifiers, whose features are reported in ref. [16], were mounted inside the scattering chamber.

The shaping time used on the amplifiers for the two scintillators and for the Si detector was 3 μsec. The gains were set approximately to the desired values using the 5.4 MeV α particles from an ^{241}Am source. A precision pulser was used to check the linearity of the amplifiers and the ADC. The data were recorded on magnetic tape for off line analysis.

3. Scintillation response

Fig. 1 shows the composite energy spectrum of one of the CsI(Tl) detectors directly exposed to a "cocktail" of undegraded beams characterized by q/A = 1/3 (E/A =

15.5 MeV). The spectrum was generated by combining runs at different frequency settings and different beam attenuation factors. For this "cocktail" beam, oxygen was used as the ECR support gas and trace amounts of krypton were fed into the source.

The energy resolution of both detectors was found to be between 1 and 2 % at FWHM, relatively independent of the ion mass and energy. To accurately determine the energy of the degraded beams, the Si detector was first calibrated with undegraded beams. This was done using only the lightest ions (C, O and Ne) at all three energies. For these light ions the Pulse Height Defect (PHD) is expected to be negligible [17] and therefore no correction was applied in the calibration. For the heavy ions ($Z>15$) the PHD was extracted and parametrized as a function of Z and E for the undegraded beams. This parametrization was then used to correct the measured energy when degraders were used. A correction for the energy loss in the Si dead layer (40 $\mu g/cm^2$ Al) was performed using range-energy tables [18]. Finally, the energy of all beams was corrected for the energy loss in the Mylar foil in front of the CsI(Tl). We estimate that the uncertainty in the energy due to the above described procedure is of the order of 1%.

Fig. 2 shows the measured light output, in arbitrary units, as a function of the energy for a set of representative ions, from ^{4}He up to ^{84}Kr. The symbols represent the experimental data, while the curves are the results of least square fits with the function [9]:

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

Only one isotope for each element was included in the fit, to eliminate any possible mass dependence effect. Before choosing the function (1), several others were tried, such as the power law proposed in ref. [11], and a linear function. None of these gave satisfactory results over the entire energy range studied. As can be seen from the figure, however, a linear function could reproduce quite closely the data for the highest energies.

Contrary to the observation of ref. [9] and in agreement with the results of Buenerd et al. for a Pilot U scintillator [19], the parameters of the fit present a regular behavior as a function of the ion atomic number. In fig. 3, the values of α, β and γ as a function of Z are plotted, together with the results of least square fits. Reasonably good fits of the three parameters were obtained with a constant-plus-exponential form. The results of the fits are the following:

$$\begin{aligned} \gamma &= 1.136 + 2.184\, e^{-0.189\, Z} \\ \beta &= 30.36 + 63.53\, e^{0.0667\, Z} \\ \alpha &= 0.001 + 0.022\, e^{-0.0974\, Z}\ . \end{aligned} \qquad (2)$$

The light response of the second CsI(Tl) detector was also analyzed. For sake of comparison, the light output of this detector was normalized to the first device, so to give the same value for the 8.8 MeV/u ^{12}C. The fits performed on the response of this second detector gave values of γ and β systematically lower with respect to the first detector, by about 6 and 10 %, respectively. The values of α, instead, were found to be, within the experimental errors, the same as for the first CsI(Tl). As will be discussed later, the different values of γ and β indicate different scintillation properties of the two detectors. However the parameter α seems to be independent of the particular detector used.

Given the previous results, it is possible to calibrate a CsI(Tl) scintillator detector with a function:

$$L(E) = c_1\, \gamma E + c_2\, \beta\, (e^{-\alpha E} - 1)$$

where α, β and γ are given by the eq. (2) and c_1, c_2 are normalization constants that depend on both the amplification gain and the scintillation efficiency of the detector.

We have also investigated, for some elements, the response of the CsI(Tl) scintillators to different isotopes. In fig. 4, the light output for the ^{18}O and ^{30}Si isotopes at energies between 10 and 15 MeV/u, (solid symbols), is compared to the result of the fits (solid lines) performed on the 8.8 and 25.5 MeV/u ^{16}O and ^{28}Si data. As can be seen in the figure, at a given energy the light output produced by the heavier isotopes is systematically lower than that produced by the lighter ones. The difference amounts to about 4% for the ^{16,18}O and to 3 % for the ^{28,30}Si isotopes. A 3 % difference was also observed between the light output for the ^{78}Kr and ^{84}Kr isotopes.

The observed mass dependence of the light output of CsI(Tl) scintillators is consistent with the results of a recent work by Horn et al. [20] in which, for example, the light output of the ^{7}Be and ^{9}Be isotopes at energies around 10 MeV/u were found to differ by about 10 %. It is interesting to try and understand whether the observed differences are connected to a dependence of the scintillation efficiency dL/dE on the mass of the ion, or whether they are simply the result of the different ranges of the isotopes in the detector. We have performed a comparison between the scintillation efficiencies for the various isotopes. For the ^{18}O and ^{30}Si, dL/dE was extracted from the slope of the linear fits of the data (dashed lines). For the ^{16}O and ^{28}Si isotopes some points were first extracted from the solid line and then fitted with a linear form. To perform the comparison at the same dE/dX, the points were chosen so to have the same E/A of the heavier isotopes data. The values of dL/dE obtained in this way were, within the experimental uncertainty, the same for the different isotopes, as expected from theoretical considerations (to be discussed later).

4. Scintillation efficiency

The differential scintillation efficiency, defined as dL/dE, can provide information on the scintillation mechanism. In particular, the behavior of dL/dE as a function of the specific energy loss (dE/dX) can be directly compared with predictions of different theoretical models for the scintillation process. In fig. 5 a plot of dL/dE versus dE/dX is presented for ions from ^{4}He up to ^{84}Kr in the first CsI(Tl) detector. The scintillation efficiency was extracted by differentiation of eq. (1). Range-energy tables were used to calculate dE/dX. The solid lines correspond to the region of the data presented here, while dashed lines are extrapolations to higher energy losses. The scintillation efficiency of the second detector is also plotted in the figure for C, Ar and Cu ions (dotted lines).

The curves for different ions show a similar evolution, increasing with decreasing energy loss. However, for a given value of dE/dX, the scintillation efficiency is an increasing function of the ion atomic number. This behavior can be understood in the framework of the model first proposed by Meyer and Murray [21]. According to this model, the total light emitted per unit energy is considered as the sum of two contributions: one from the primary ionization column or "core", and the other from a "halo" of energetic secondary electrons (δ-rays) which escape the primary column and produce light with high efficiency. The first component is due to saturated light emission dominated by the quenching probability in the scintillator and depends on the type of material and energy loss per unit length. This is the dominant component for electrons and light ions, and has been discussed extensively by Birks [22]. The second component depends on the number of energetic electrons (E>1.5 keV) which escape the "core" and enter "virgin" regions of the crystal, where they can produce light with high efficiency. Since, at a given dE/dX, heavier ions have higher E/A, they produce a more energetic δ-ray spectrum. Consequently, a bigger fraction of the energy deposited will be more efficiently converted into light. For this reason, for a fixed dE/dX, the scintillation efficiency increases with increasing ion atomic number.

A general expression has been proposed for the scintillation efficiency, which is similar to Birk's formalism but includes the contribution from the halo of secondary electrons [23]:

$$\frac{dL}{dE} = C\left\{\frac{(1-F_S)}{1+B_S(1-F_S)dE/dX} + F_S\right\} .$$

In this expression C includes the absolute scintillation efficiency and gain factors, B_S is the quenching probability in the primary column, and F_S is the fraction of the total energy loss that has been deposited outside the primary column of ionization in form of δ-rays. The factor B_S depends on the material, and in particular on the concentration of quenching impurities present in the scintillator. For example, the second detector used in this experiment seems to be made of a purer crystal than the first one, as can be seen from the slope of the corresponding efficiency curves. The factor F_S, on the other hand, does not depend on the material nor on the atomic number or mass of the ion, but only on its energy/nucleon (for this reason, for example, different isotopes with the same E/A are expected to have the same scintillation efficiency). An expression for F_S can be found in ref. [24]. A detailed analysis of this parameter could help refine the existing models; however, such an analysis is beyond the scope of the present work.

5. Conclusions

In this work we have investigated the response function of CsI(Tl) scintillator detectors to heavy ions in the intermediate energy region. The study was performed by directly exposing the detectors to low intensity beams of ions with $2 \leq Z \leq 36$ and energies up to 25.5 MeV/u. Satisfactory fits to the response functions over the whole energy range were obtained with a linear-plus-exponential function. General expressions are given for the parameters of the fit as a function of the atomic number. A mass dependence of the total light output for different isotopes was observed. However, a simple analysis suggests that the scintillation efficiency does not depend on the mass of the isotope, as expected from existing models.

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Figure Captions

Fig. 1 : Composite spectrum of a "cocktail" of undegraded beams measured in a CsI(Tl) scintillator detector. All ion species have $q/A = 1/3$ and $E/A = 15.5$ MeV/u.

Fig. 2 : Light output of the CsI(Tl) as a function of energy for some representative ions (filled diamonds). The solid lines are the results of fits with eq. (1) (see text).

Fig. 3 : The values of the parameters α, β and γ in eq. (1) are plotted as a function of Z. The curves, obtained by least square fits, are expressed by the eqs. (2). The values of α and β for ^{4}He were not included in the fits since they could not be determined with sufficient accuracy.

Fig. 4 : Light output of the CsI(Tl) for O and Si isotopes. The solid lines are the fits for the lighter isotopes, while the symbols represent the data for the heavier ones. Linear fits performed on these isotopes are represented by the dashed lines.

Fig. 5 : Scintillation efficiency dL/dE as a function of the energy loss per unit length dE/dX. The curves were obtained by differentiating eq. (1). The solid lines correspond to the region of the data presented in this work, while the dashed lines are an extrapolation to higher energy loss. The extracted scintillation efficiencies of a second CsI(Tl) scintillator for C, Ar and Cu ions are plotted as dotted curves.

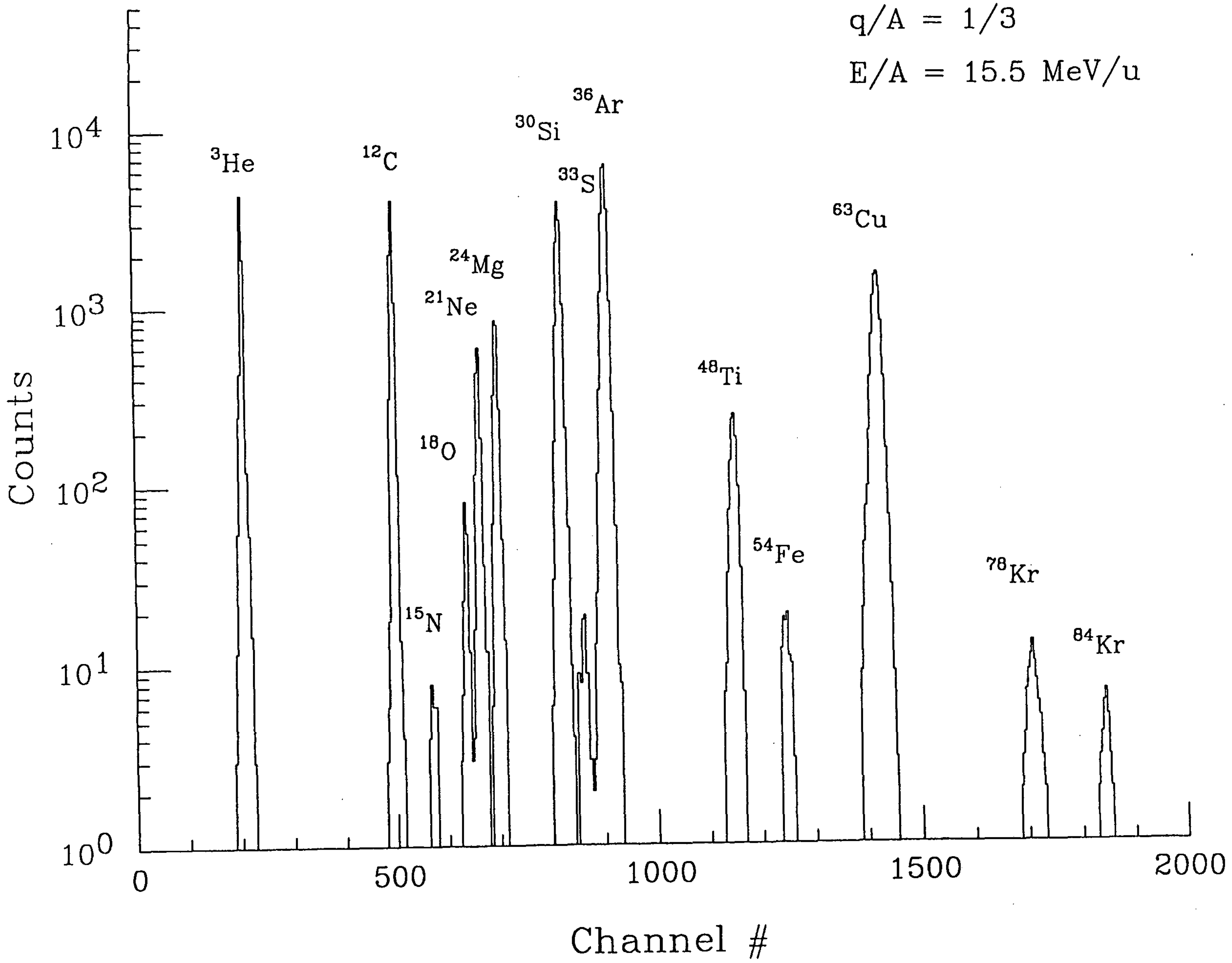

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Figure 1

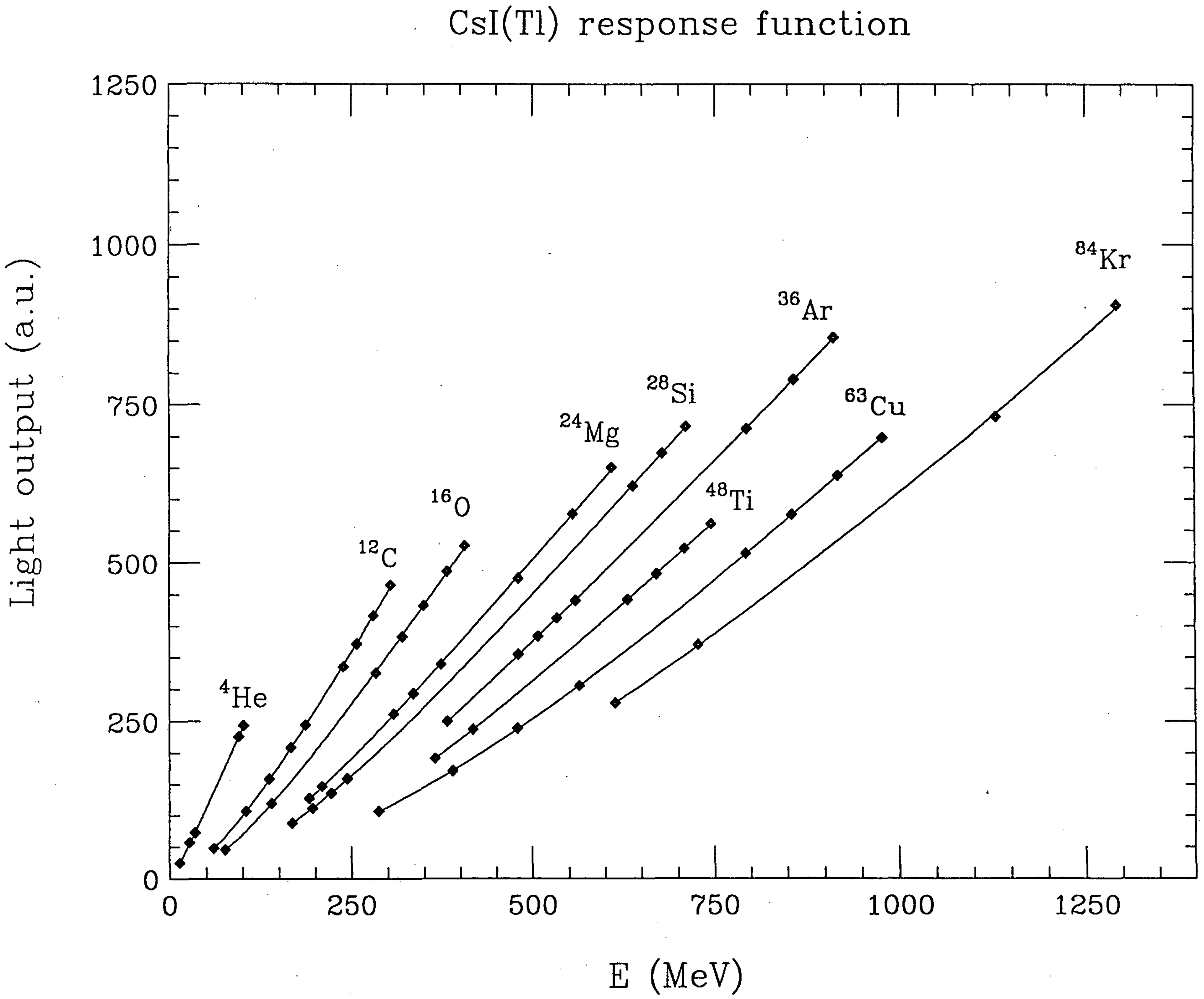

Figure 2

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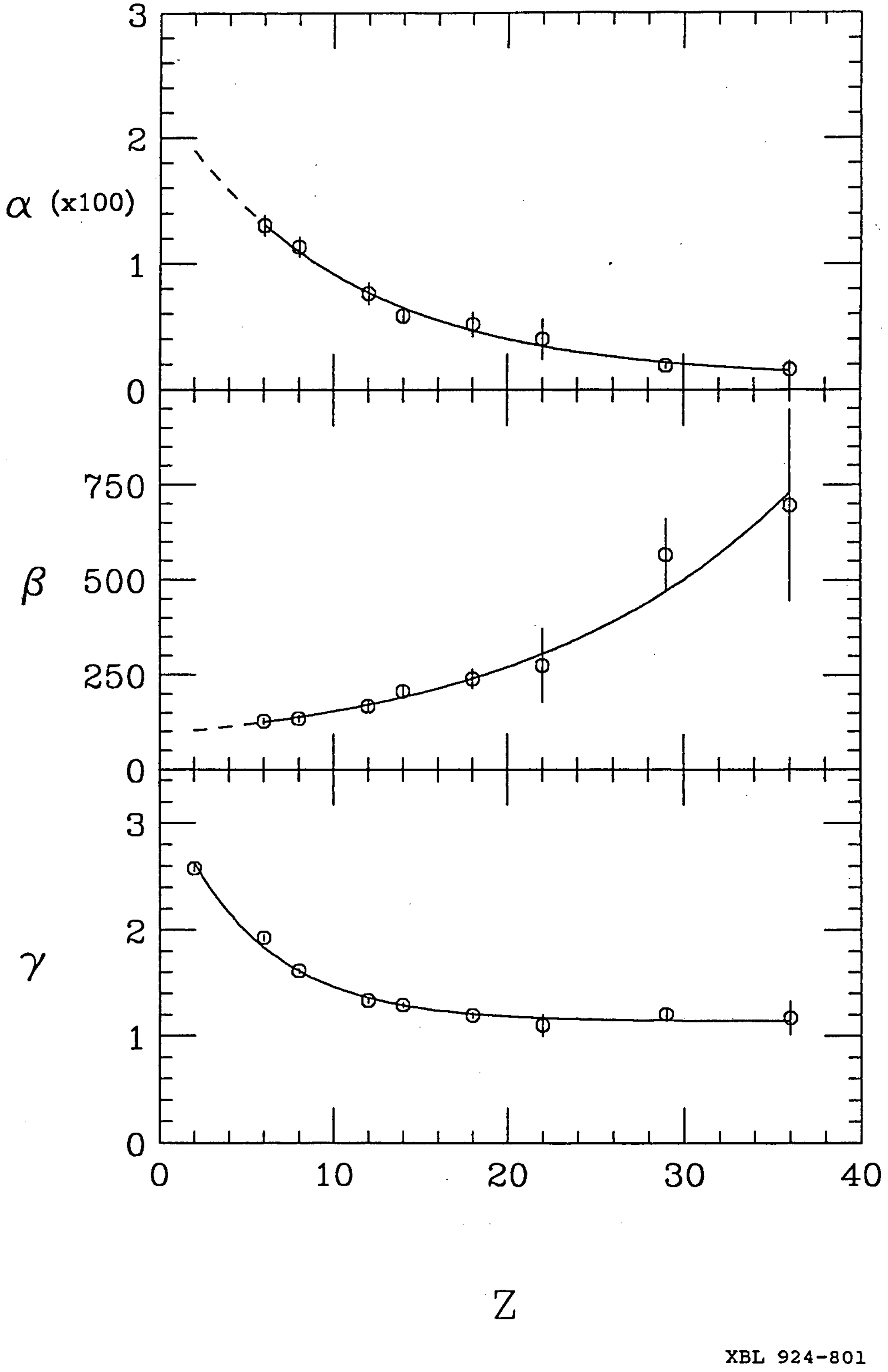

Figure 3

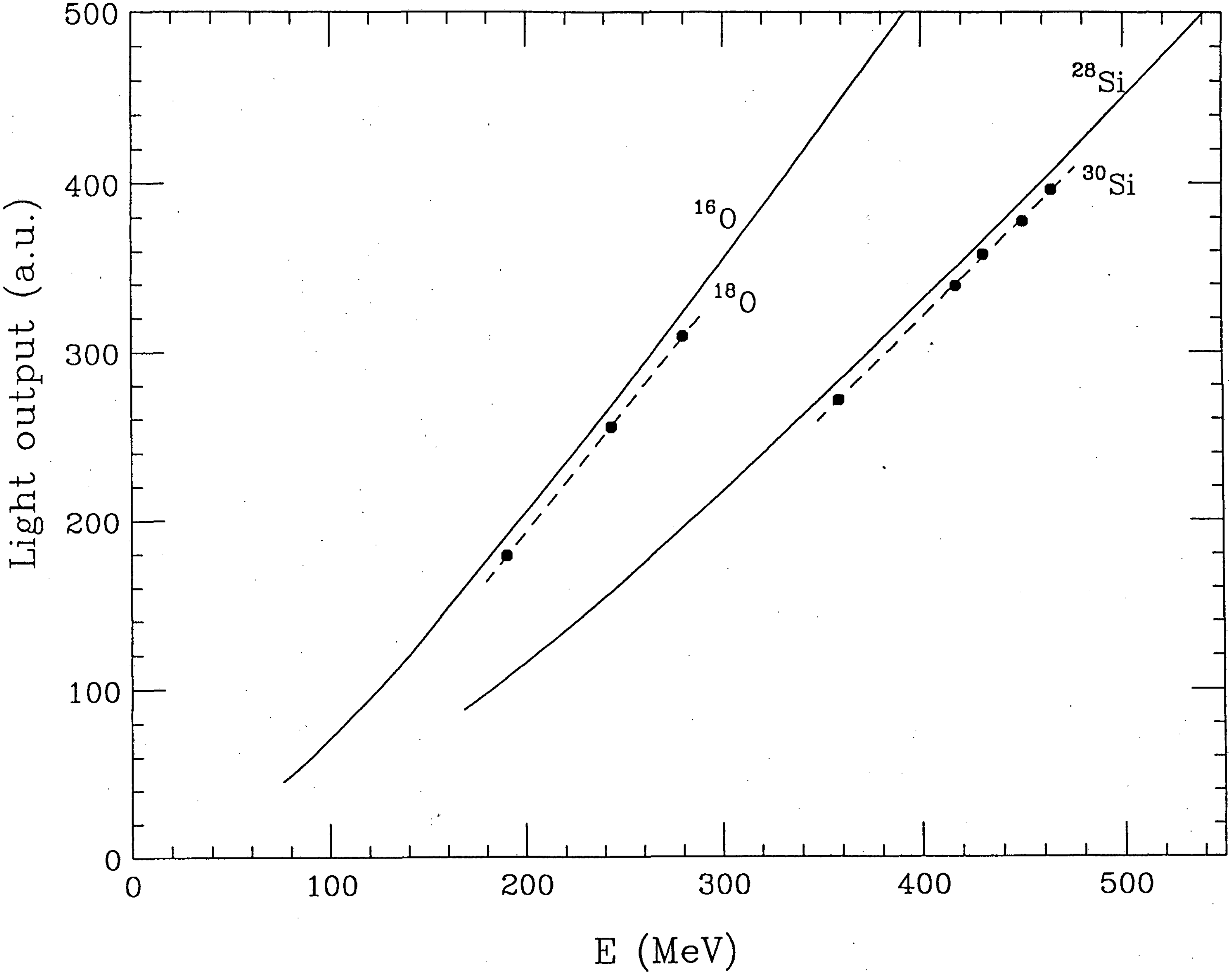

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Figure 4

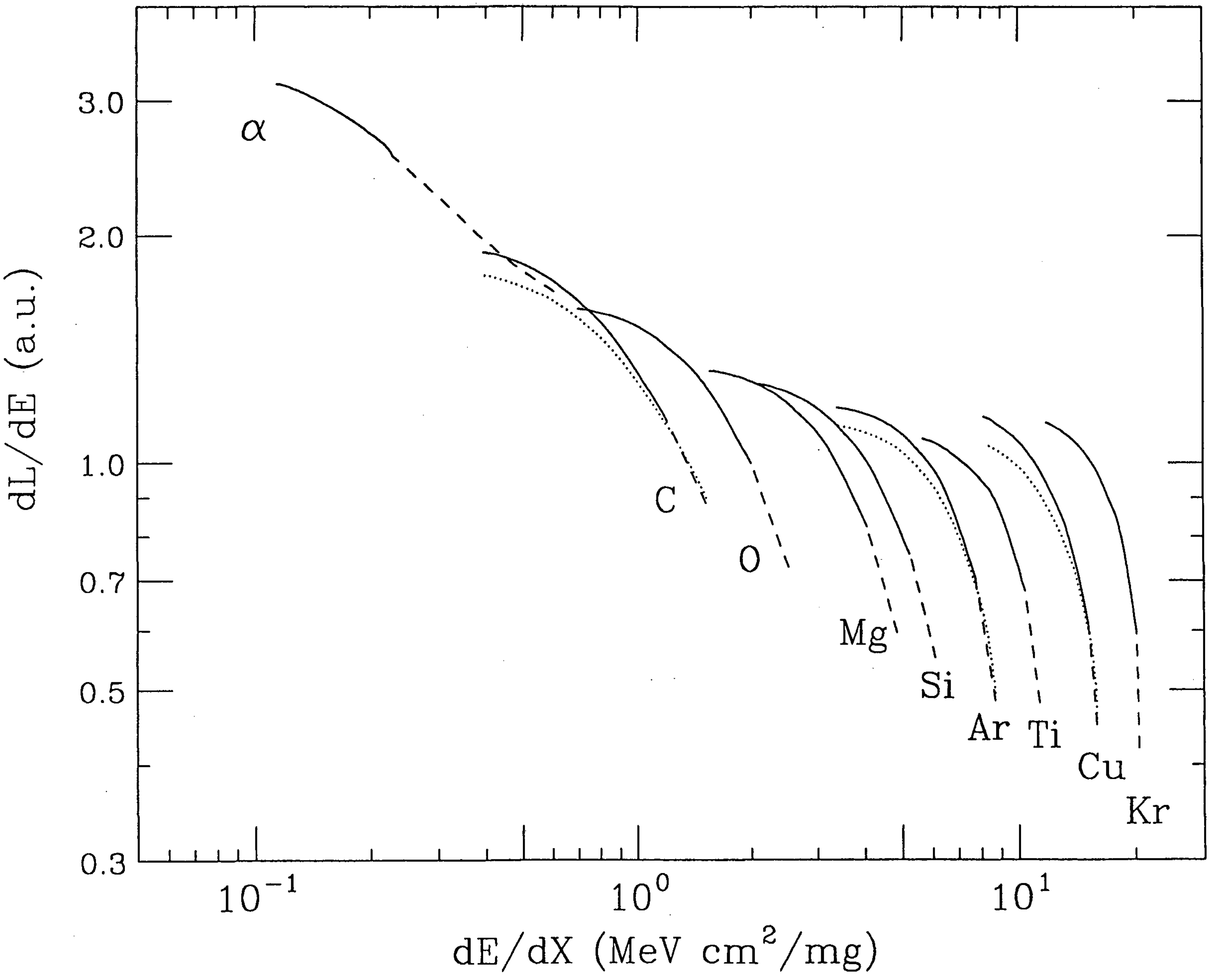

Figure 5

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