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RESPONSE OF PILOT U SCINTILLATOR TO HEAVY IONS[*]

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ABSTRACT

The light output response of Pilot U Scintillator for stopped charged particles has been measured for ^{4}He, ^{6}Li, ^{12}C, ^{16}O, ^{20}Ne and ^{40}Ar ions incident at various energies up to 20 MeV/nucleon. From these we derived a systematic description of the variation of the scintillation parameters with the charge and energy of the projectile. The suitability of such a detector for the focal plane of a heavy ion magnetic spectrometer is discussed.

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I. INTRODUCTION

The light output response of organic scintillators to ionizing particles is known to depend on the nature of the particle.[1] The exact variation of this response is of considerable interest because of the possible application to particle identification systems, particularly for the identification of heavy-ion reaction products in magnetic spectrometers, in which plastic scintillators are used conveniently to span the whole focal plane. It was shown in Ref. 2 that the measurement of the time of flight (TOF) and of the specific energy loss $(\frac{dE}{dx})$ of particles detected and localized in the focal plane of a magnetic spectrometer, permits an identification of Z and A for fully ionized particles (Z and A are the atomic number and the mass number of the ion). Unfortunately, this method leaves an ambiguity in the identification arising from different charge states q of particles of given Z, because both TOF and $\frac{dE}{dx}$ depend on $\frac{A}{q}$. The range of a heavy ion in a gas counter has been measured in some detectors for this purpose[3], but this becomes unwieldy at high energies. The total energy has also been used[4], and we chose that method. The response of a scintillator stopping the detected particles in the focal plane of a magnetic spectrometer depends on the energy E, the charge Z and the mass A of the ion through a function L(E,Z,A). Since $E \propto \frac{q^2}{A}$, the parameter $L(\frac{q^2}{A}, Z, A)$ can remove the $\frac{A}{q}$ ambiguity if the dependence of L on E and Z are sufficiently distinct. In practice, the resolution of the scintillator becomes important as it sets the main limitation on the performance of the system. The energy resolution of large plastic scintillators is rather poor, from 5 to 15% depending on the ion and its energy for the measurements reported in this work. The charge state and mass selectivities $\frac{\Delta q}{q}$ and $\frac{\Delta A}{A}$ will be limited by the resolution $\frac{\Delta L}{L(E)}$. We shall discuss this point quantitatively in the last section.

Systematic measurements of the response for various particles over a wide range of energies below 300 MeV, are available so far only for light particles (protons to alphas),[5,6] or for low energy heavy ions.[7] In addition to providing information for particle identification, data for heavier particles are important for developing the theory of the scintillation process.[1,8] In the theory formulated by Birks[1], the specific scintillation response is:

$$\frac{dL}{dx} = \frac{S\,\frac{dE}{dx}}{1+kB\,\frac{dE}{dx}} \quad \text{or} \quad \frac{dL}{dE} = \frac{S}{1+kB\frac{dE}{dx}} \tag{1}$$

Where $\frac{dE}{dx}$ = specific energy loss of the ionizing particle

S = scintillation efficiency

kB = scintillation quenching factor which accounts for non-radiative deexcitation of a proportion of excited scintillating centers along the path of the ionizing particle.

From this formula we can predict some interesting features of the scintillation response:

a. for sufficiently small values of $\frac{dE}{dx}$ (corresponding to high energies), so that $kB\frac{dE}{dx} << 1$, relationship (1) reduces to:

$$\frac{dL}{dx} \approx S\,\frac{dE}{dx} \tag{2}$$

which leads to $L(E)=L_o + SE$.

In this limit, the light output depends linearly on E. The knowledge of the experimental values L(E) in this high energy region is then expected to provide a measurement of the scintillation efficiency S.

b. for large values of $\frac{dE}{dx}$ (corresponding to low energies), so that $kB \frac{dE}{dx} >> 1$ the equation (1) can be approximated by

$$\frac{dL}{dx} \approx \frac{S}{kB} \quad \text{or} \quad \frac{dL}{dE} \approx \frac{S}{kB} \left(\frac{dE}{dx}\right)^{-1} \tag{3}$$

which leads to $L(E) \approx \frac{S}{kB} R$

where $R = \int dE \left(\frac{dE}{dx}\right)^{-1}$ is the range of the ionizing particle. Thus the low energy data should yield values of $\frac{S}{kB}$.

II. EXPERIMENTAL SET UP AND PROCEDURE

The experiments were performed with beams from the 88-Inch Cyclotron of the Lawrence Berkeley Laboratory. The detection system is shown in Fig. 1. The scintillator was placed at the focal plane of the magnetic spectrometer and a 5 mm wide slit was placed in front of it. The measurements were made with particles elastically scattered from a thin gold target. For each incident beam, a set of different particle energies was obtained by degrading the energy of the scattered particles with aluminum absorbers placed in the scattering chamber before the entrance aperture of the spectrometer. For each particle energy in the focal plane, the spectrometer was tuned so as to center the elastic peak on the slit in front of the scintillator, ensuring a constant positioning of the particles in the focal plane. The energies were determined from the field setting of the magnetic spectrometer. The light output was collected with an XP1040 photomultiplier through a lucite light pipe (Fig. 1). The signal proportional to light output was taken from the ninth dynode of the photomultiplier, and fed to an ORTEC type 113 scintillator preamplifier.

III. EXPERIMENTAL RESULTS AND ANALYSIS

The data were analyzed in such a way as to provide experimentalists with a means of deducing with reasonable accuracy the Z of a particle from the knowledge of the scintillation response and energy. To that end, we used a convenient parametrization to reproduce the data. Values of S and kB have been tentatively deduced from a rough analysis using the approximations outlined in Section 1.

The set of data points obtained from the measurements are shown on Fig. 2. The experimental curves are in qualitative agreement with the predictions of Section 1, i.e., the variation of the light output L is linear with energy at the high energy limit. Figure 3a also shows that the dependence of L(E) on the range of the particle is approximately linear at the low energy limit. For simplicity, the data were fitted with a simple analytical parametrization suggested from the shape of the experimental curve. Good results were obtained with the trial function (see Fig. 2):

$$L(E) = \gamma E + \beta(e^{-\alpha E} - 1) \qquad (4)$$

where γ is the slope of the light output in the region linear with energy. The values of γ for the different particles are plotted as a function of Z^{-1} in Fig. 4c; they are well reproduced by the first order equation:

$$\gamma = 0.58 + 3.87\ Z^{-1} \qquad (5)$$

The value of γ for Z = 1 was extracted from the proton data of Becchetti *et al.*[7] The values of L(E) for the two experiments were normalized with the data for α particles. Although the measurements of Becchetti[7] are for NE102 scintillator, the properties of NE102 and Pilot U scintillators are close enough[9] to justify the assumption of similar responses.

The values of the parameter β were deduced from extrapolation of the asymptote ($\gamma E-\beta$) to the E axis, and the values of α from the data points in the curved region of the response. The Z dependence of the β and α parameters is shown in Figs. 4a and 4b. Their empirical values are:

$$\beta = 32. + 2.6\ Z \tag{6}$$

$$\alpha = 0.01 + 0.13\ Z^{-1} \tag{7}$$

Note that L(E) in eq. 4 is always positive for $\gamma > \alpha\beta$. In practice γ was obtained slightly smaller than $\alpha\beta$ for the cases studied here, and thus relation 4 is not valid for E lower than the solution E_o of eq. 4. The value of E_o is lower than 10 MeV from ^{4}He to ^{16}O; it is about 20 MeV for ^{20}Ne and about 60 MeV for ^{40}Ar. As shown by Fig. 2 this description is not expected to be accurate for energies below those of our experiments, especially for ^{40}Ar ions lower than 100 MeV. For this latter projectile, a more complicated parametrization is probably called for (to be discussed later).

Collecting all the previous results, one can predict the response of a Pilot U scintillator to an ion (between ^{4}He and ^{40}Ar) of given Z by using the relation:

$$NL(E) = (0.58+\frac{3.87}{Z})\,E + (32. + 2.6Z)[e^{-(0.01+\frac{0.13}{Z})E} - 1] \tag{8}$$

where N is a normalization coefficient, accounting for the effects of the photomultiplier, of the light pipe attenuation and of the experimental geometry.

From this L(E) dependence, we can estimate the mass and charge selectivity. Variations of L(E) can be related to the variation of q and A:

$$\Delta L = \frac{\partial L}{\partial q}\,\Delta q + \frac{\partial L}{\partial A}\,\Delta A$$

Using eq. 4 to calculate the partial derivatives and using the relation $E \propto \frac{q^2}{A}$, we get:

$$\frac{\Delta L}{L(E)} = \left[2\,\frac{\Delta q}{q} - \frac{\Delta A}{A}\right]\frac{1}{\chi(E)} \tag{9}$$

With

$$\chi(E) = \frac{\gamma E - \beta(1 - e^{-\alpha E})}{\gamma E - \alpha\beta\, E\, e^{-\alpha E}}$$

We note that $\chi(E) \leqslant 1$, $\chi(0) = 1$, and $\chi(E) \geqslant 1 - \frac{\beta}{\gamma E}$ at the high energy limit where E >>1; between these limits $\chi(E)$ reaches a minimum. When $\gamma < \alpha\beta$ this is valid only for $E > E_o$ (E_o is the solution of eq. 4 for $L(E) = 0$).

Thus in the least favorable situation ($\chi(E) = 1$) the $\frac{A}{q}$ ambiguity (for which $\frac{\Delta A}{A} = \frac{\Delta q}{q}$) can be removed provided that

$$\frac{\Delta A}{A} = \frac{\Delta q}{q} \geqslant \frac{\Delta L}{L(E)} \tag{10}$$

A resolution of 10% in the experiment would therefore remove the $\frac{A}{q}$ ambiguity for $q \leqslant 10$. For example it would be possible to separate ^{16}O(8+) from ^{14}O(7+) or ^{18}Ne(9+) from ^{20}Ne(10+). Working out the actual values of $\chi(E)$ for ^{40}Ar we find out that for 150 MeV ^{40}Ar ions, $\chi(E) = 0.46$. This leads, for $\frac{\Delta L}{L(E)} = 11\%$ at this energy, to a maximum selectivity of 5%. This should permit the separation, for example, of ^{40}Ar(17+) from ^{42}Ar(18+). Figure 5 shows the variation of $\chi(E)$ for ^{4}He, ^{16}O, ^{40}Ar. A measurement of L(E) is particularly important for the identification of exotic neutron excess nuclei, such as ^{24}O, where multiple $\frac{A}{q}$ ambiguities exist, e.g., $^{21}O(7+)$, $^{18}O(6+)$, $^{15}O(5+)$.

Figure 3a displays the data points plotted as a function of the range of the particles. As shown in Section 1, the response near the origin is expected to vary linearly with the range, following the approximate relation $L(E)\approx\frac{S}{kB}R$. The data from Ref. 6 actually exhibit a roughly linear variation around the origin for projectiles from ^{1}H to ^{12}C. The data were fitted with second order polynomials with the constraint $L(0) = 0$. No significant changes occurred when higher order polynomials were used. The data points for ^{40}Ar were fitted with a straight line. The coefficients of the linear term then provided an approximate value of the ratio S/kB. Using the values of S obtained from the high energy data and the relation $S=\gamma$ (approximation a) in Section 1), we obtain tentative values for the quenching factor, kB. However, consistent results were not obtained when these values were used to calculate the term $kB\frac{dE}{dx}$. Although approximation b) $(kB\frac{dE}{dx})_{max}$) is justified ($kB\frac{dE}{dx}$ varies from 3 to 9.5 depending on the particle), approximation a ($kB\frac{dE}{dx} << 1$) is not justified; in fact $kB(\frac{dE}{dx})_{min}$ varies from approximately 0.5 to 1.1. The values of S were therefore corrected using relation (1):

$$S = \gamma(1 + kB\frac{dE}{dx})$$

These estimates for S and kB are given in Table 1 and were used to integrate equation (1). Values of $\frac{dE}{dx}$ were taken from the tables of Ref. 10 for $(CH_2)_n$, which are expected to be close to the values for Pilot U scintillator. The results are compared to the experimental values in Fig. 3b. The quality of the fits is reasonable for the light ions but deteriorates with increasing mass of the projectile and becomes quite poor for ^{40}Ar. For this latter case we could not find any value of the parameters that would improve the fit. This suggests that a second order term, $C(\frac{dE}{dx})^2$, in the denominator of Eq. 1, as proposed in Ref. 11, might be necessary to reproduce the data. Calculated curves are not very sensitive to the value of kB; however the order of magnitude of kB is expected to be correct and the dependence of kB on Z (see Table 1) seems to be genuine. The values obtained for light ions compare reasonably with the results from other works.[6]

IV. CONCLUSION

The measurements reported allowed an analytical description of the Z and energy dependence of the scintillation response of Pilot U scintillator. Unfortunately the data did not permit the dependence on A to be deduced in the same way. This variation with A is expected to be weak, but some data[3,6] provide unambiguous evidence for such a dependence.

The analysis also provided rough values for the scintillation efficiency S and quenching factor kB. More precise determination of these variables requires more complete analysis such as performed in ref. 12 on more detailed experimental measurements.

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Table 1. Values of the scintillation efficiency S and the quenching factor kB obtained from this analysis. S is in arbitrary units and kB in mg/cm^2.

Particle	S	kB
^{4}He	3.92	3.8
^{6}Li	3.50	2.2
^{12}C	2.07	.44
^{16}O	1.79	.24
^{20}Ne	1.80	.18
^{40}Ar	1.	.1

FIGURE CAPTIONS

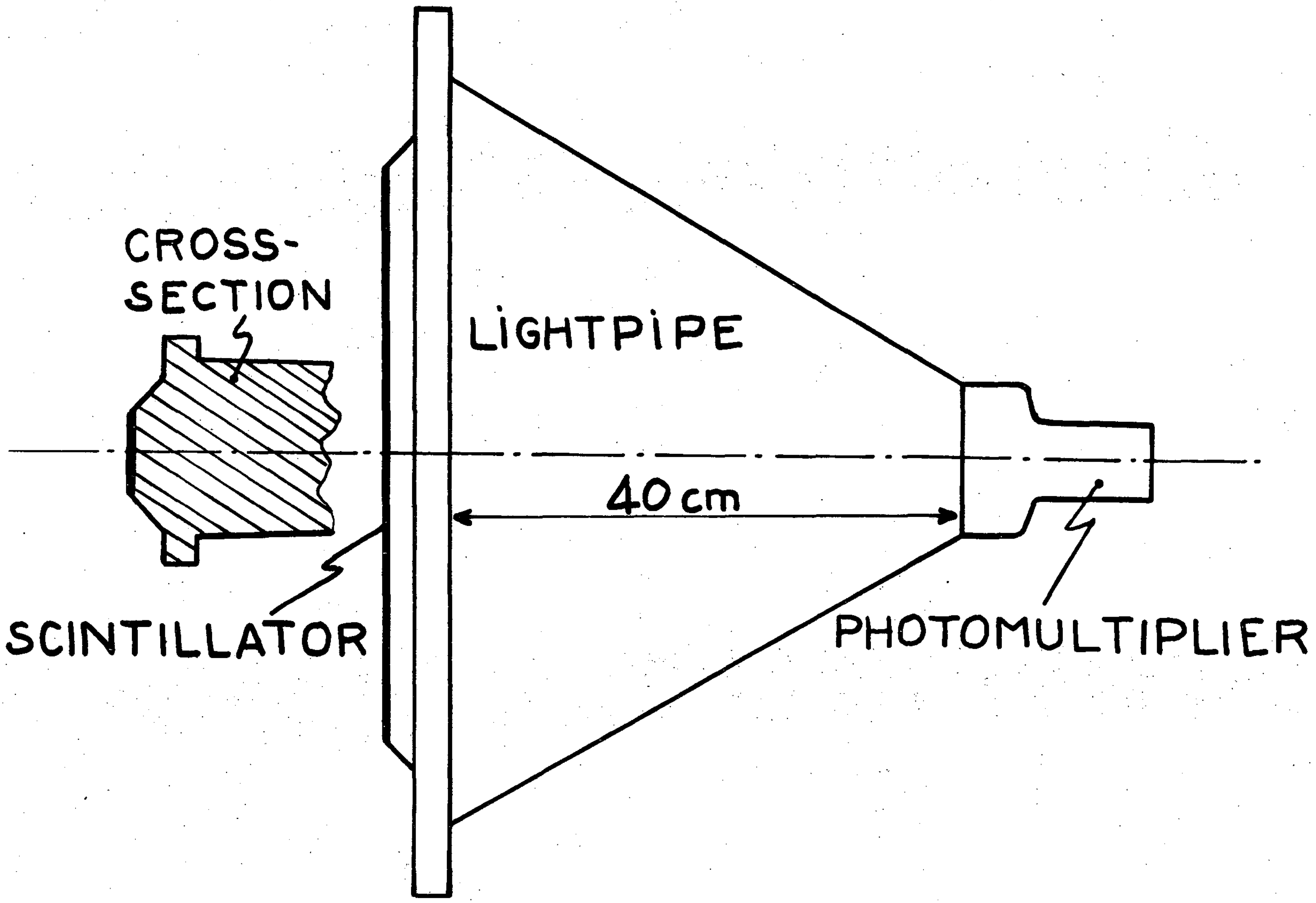
Fig. 1. Schematic view of the detection system.

Fig. 2. Experimental results obtained in this work. The error bars are less than the size of the data points. The curves are obtained from a parametrization of the light output L as a function of energy using eq. 4 in the text.

Fig. 3. a). Experimental values of the light output L as a function of the range of the particles. The range values have been taken from ref. 8 for $(CH_2)_n$. b) The data points are compared to the values L(E) obtained by integrating eq. 1 as described in the text.

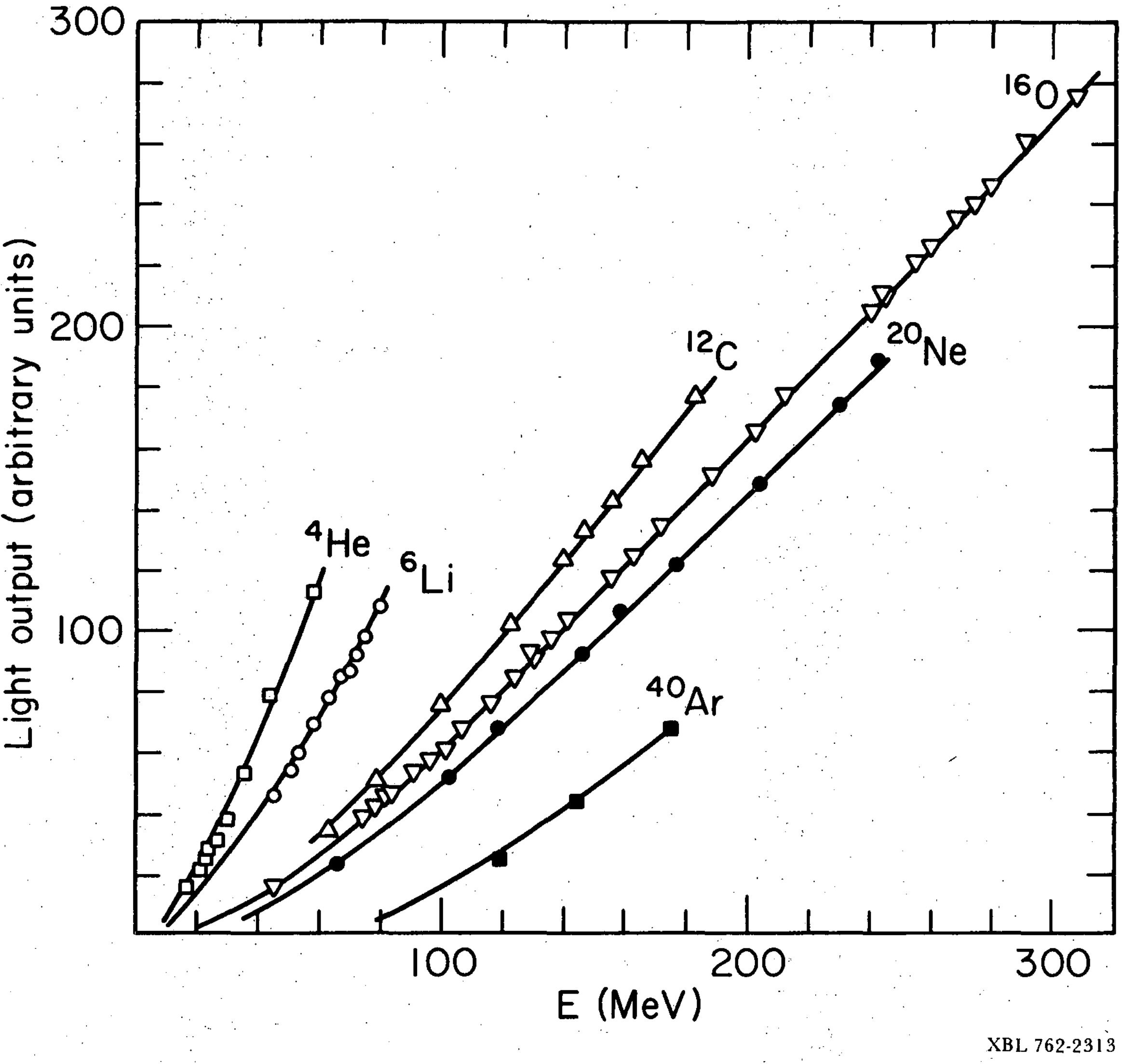
Fig. 4. The values of the parameters γ^ β^ α from eq. 4, For each particle, β is plotted as a function of Z, and α and γ as a function of Z^{-1}. The equations of the straight lines are given in the text (eq. 5, 6, 7).

Fig. 5. Energy dependence of the resolution factor $\chi(E)$ (equation 9) for ^{4}He, ^{16}O and ^{40}Ar projectiles.



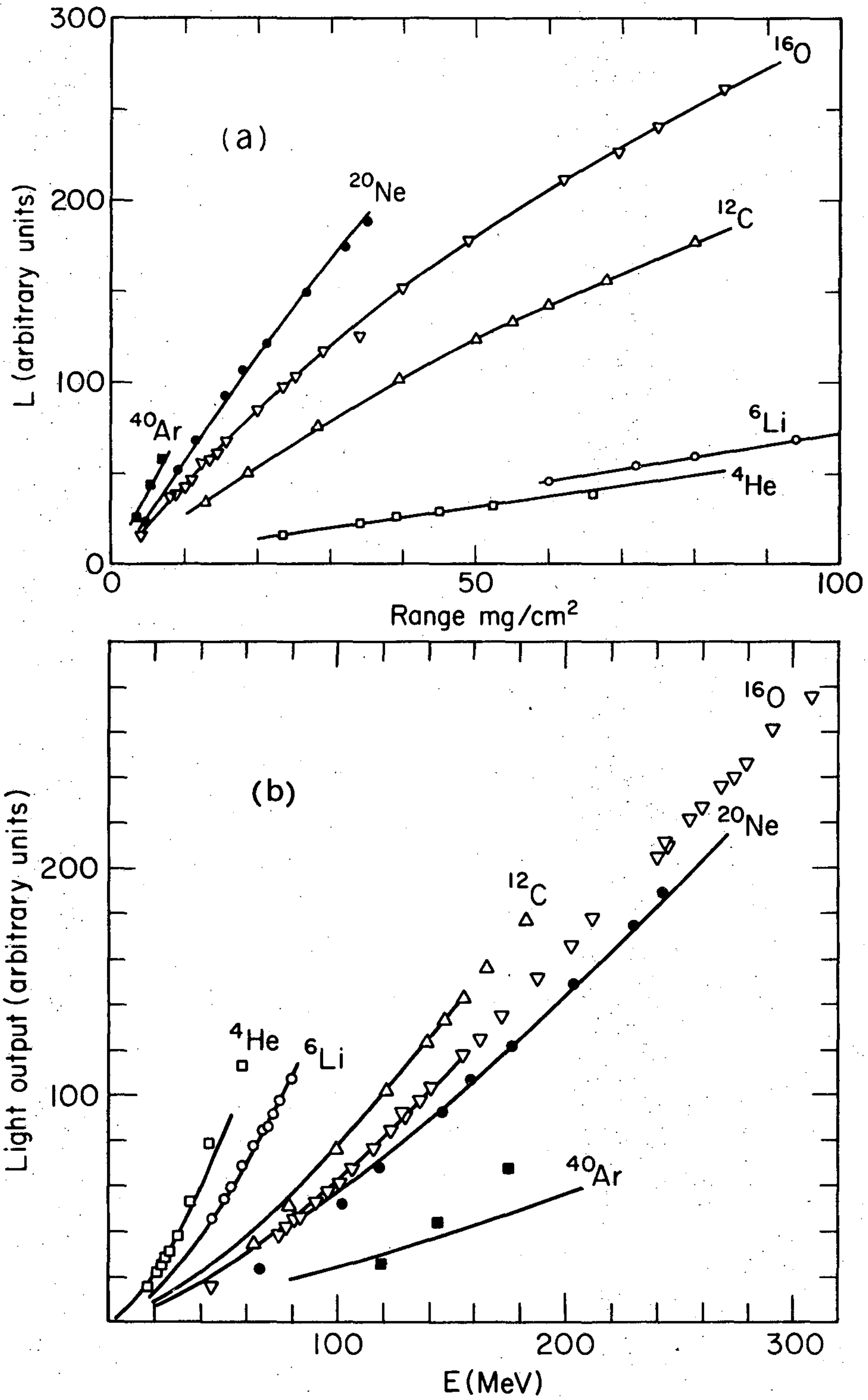
XBL 762-597

Fig. 1



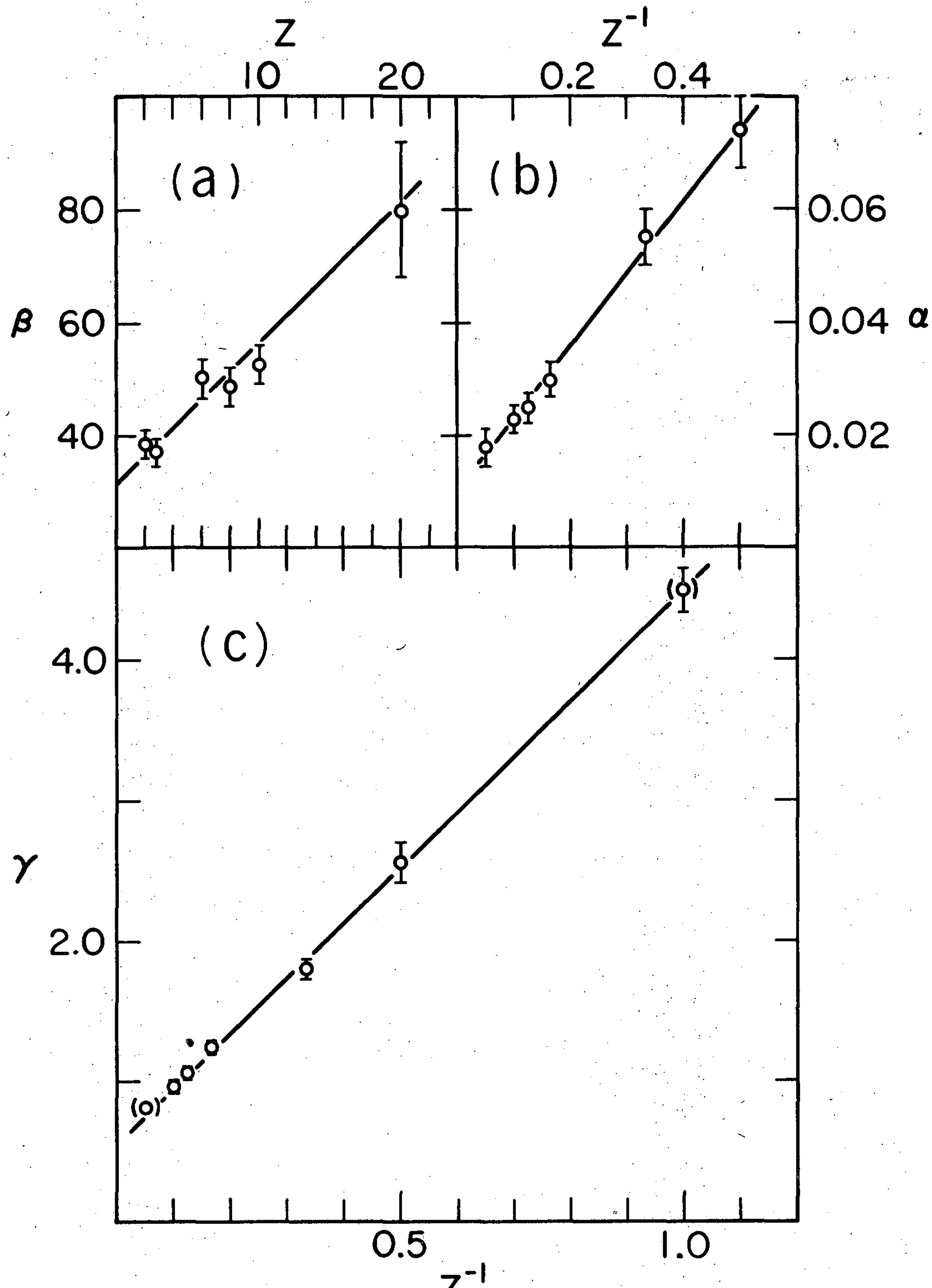
XBL 762-2313

Fig. 2



XBL 762-2312A

Fig. 3



XBL 762-2311

Fig. 14

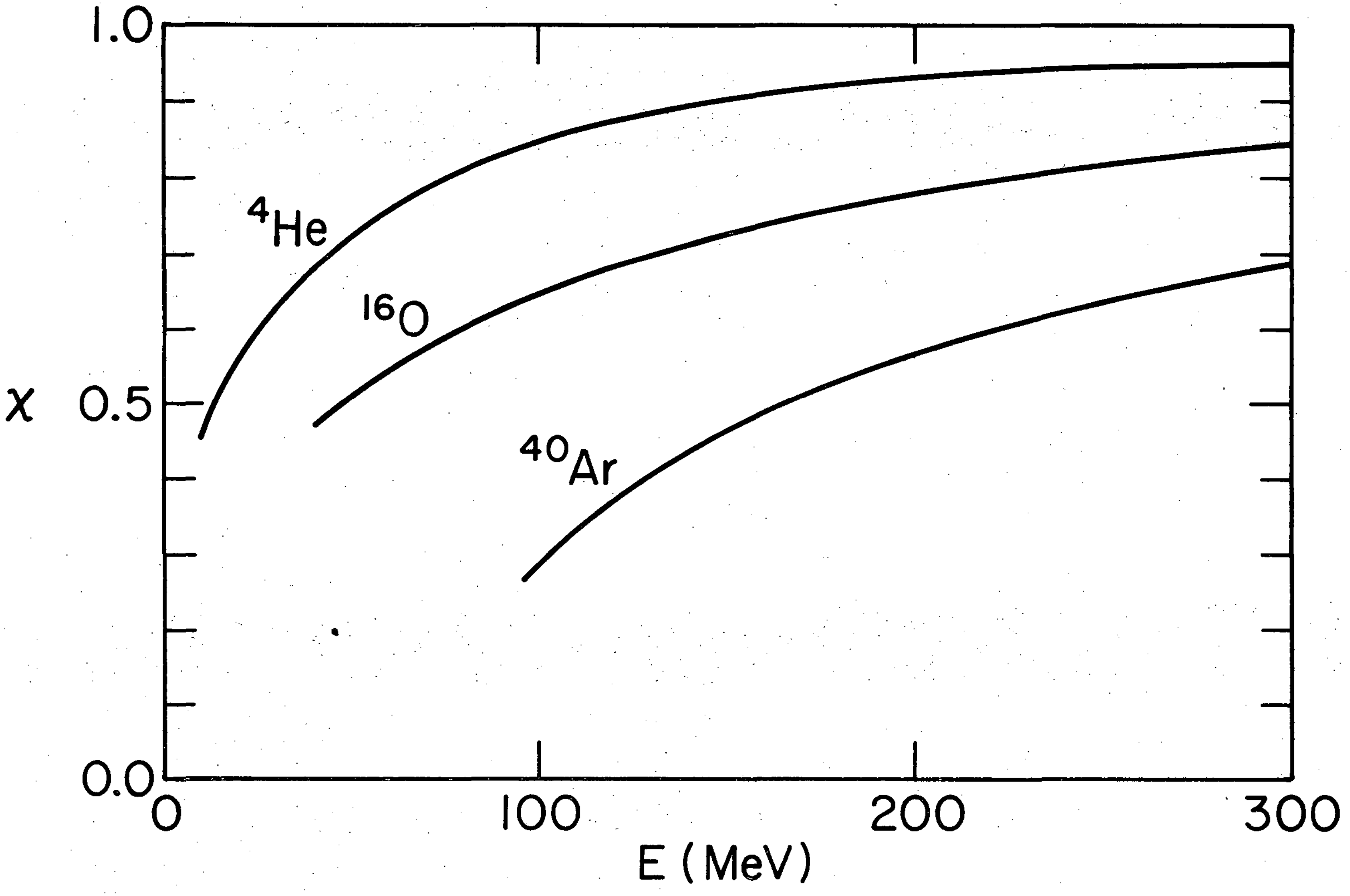


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Fig. 15

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