**ASTIA AD 211761** 

# NATIONAL BUREAU OF STANDARDS REPORT

6313

PROPERTY OF
SOUTHWEST RESEARCH INSTITUTE LIBRARY
SAN ANTONIO, TEXAS

ATTENÚATION COEFFICIENTS OF HIGH ENERGY X-RAYS FINAL REPORT

1 May 1959

: by

H. W. Koch and J. M. Wyckoff
High Energy Radiation Section
Atomic and Radiation Physics Division

to

Nuclear Physics Division
Air Force Office of Scientific Research, ARDC

Washington 25, D, C. CONTRACT NO. CSO-680-57-2

FILE NO. 3-1-10



U. S. DEPARTMENT OF COMMERCE NATIONAL BUREAU OF STANDARDS

#### THE NATIONAL BUREAU OF STANDARDS

#### Functions and Activities

The functions of the National Bureau of Standards are set forth in the Act of Congress, March 3, 1901, as amended by Congress in Public Law 619, 1950. These include the development and maintenance of the national standards of measurement and the provision of means and methods for making measurements consistent with these standards; the determination of physical constants and properties of materials; the development of methods and instruments for testing materials, devices, and structures; advisory services to Government Agencies on scientific and technical problems; invention and development of devices to serve special needs of the Government; and the development of standard practices, codes, and specifications. The work includes basic and applied research, development, engineering, instrumentation, testing, evaluation, calibration services, and various consultation and information services. A major portion of the Bureau's work is performed for other Government Agencies, particularly the Department of Defense and the Atomic Energy Commission. The scope of activities is suggested by the listing of divisions and sections on the inside of the back cover.

### Reports and Publications

The results of the Bureau's work take the form of either actual equipment and devices or published papers and reports. Reports are issued to the sponsoring agency of a particular project or program. Published papers appear either in the Bureau's own series of publications or in the journals of professional and scientific societies. The Bureau itself publishes three monthly periodicals, available from the Government Printing Office: The Journal of Research, which presents complete papers reporting teclinical investigations; the Technical News Bulletin, which presents summary and preliminary reports on work in progress; and Basic Radio Propagation Predictions, which provides data for determining the best frequencies to use for radio communications throughout the world. There are also five series of nonperiodical publications: The Applied Mathematics Series, Circulars, Handbooks, Building Materials and Structures Reports, and Miscellaneous Publications.

Information on the Bureau's publications can be found in NBS Circular 460, Publications of the National Bureau of Standards (\$1.25) and its Supplement (\$0.75), available from the Superintendent of Documents, Government Printing Office, Washington 25, D. C.

Inquiries regarding the Burean's reports should be addressed to the Office of Technical Information, National Bureau of Standards, Washington 25, D. C.

# NATIONAL BUREAU OF STANDARDS REPORT

NBS PROJECT

NBS REPORT

0411-11-3150

1 May 1959

6313

## ATTENUATION COEFFICIENTS OF HIGH ENERGY X-RAYS

by

H. W. Koch and J. M. Wyckoff High Energy Radiation Section Atomic and Radiation Physics Division

to

Nuclear Physics Division Air Force Office of Scientific Research, ARDC Washington 25, D. C.

> CONTRACT NO. CSO-680-57-2 FILE NO. 3-1-10

> > IMPORTANT NOTICE

intended for use within the to additional evaluation and listing of this Report, either the Office of the Director, N however, by the Government to reproduce additional copi

NATIONAL BUREAU OF ST Approved for public release by the Director of the National Institute of Standards and Technology (NIST) on October 9, 2015.

progress accounting documents rmally published it is subjected reproduction, or open-literature sion is obtained in writing from Such permission is not needed, prepared if that agency wishes



U. S. DEPARTMENT OF COMMERCE NATIONAL BUREAU OF STANDARDS

#### ATTENUATION COEFFICIENTS OF HIGH ENERGY X-RAYS

by

## H. W. Koch and J. M. Wyckoff

## Introduction

This report is a final report issued at the termination of an Air

Force Office of Scientific Research Project entitled "Attenuation

Coefficients of High Energy X-rays". The project is continuing under the direct support of the National Bureau of Standards as project number 0466.

The objective of the program initiated with Air Force support was the direct measurement of the total attenuation coefficients for X-rays in the energy range from 5 to 180 Mev. The research to date has resulted in detailed attenuation coefficients in hydrogen, carbon, water and aluminum, which demonstrate specific areas requiring further theoretical and experimental investigations. For example, the NBS experiments have shown that the attenuation coefficients listed in the standard reference, NBS Circular 583 entitled "X-ray Attenuation Coefficients from 10 kev to 100 Mev", \frac{1}{a}\right| are incorrect by about 4% at 60 Mev for low atomic number materials. The source of the discrepancy is not understood, although the pair production cross section is suspect. A complete understanding will result from further experimental and theoretical estimates of phenomena such as the radiative corrections to the Compton and pair cross sections, and the limited accuracy of pair production predictions.

During the course of the present experiments  $\frac{2}{3}$  it was necessary to investigate such related areas as high-energy X-ray spectra  $\frac{4}{5}$ ,  $\frac{6}{7}$ , development and operation of large scintillation spectrometers  $\frac{8}{9}$ ,  $\frac{10}{11}$ ,  $\frac{11}{12}$ ,

The references identified by superscripts in the introduction and background sections are listed at the end of the background section.

pulse height analyzers 13/(four separate analyzers were investigated for this project), and the principles of absorption and scattering experiments. 14/15/Most of these investigations were made possible because of the AFOSR support of this project. In order to illustrate these investigations, this final report includes additional background material (attachment A), a copy of a paper in the Review of Scientific Instruments (attachment B) that provided the basis of the present work, and two papers (attachments C and D) that have been prepared for publication. The papers are:

- B) R. S. Foote and H. W. Koch, Scintillation Spectrometers for Measuring the Total Energy of X-ray Photons, Rev. Sci. Instr., 25, 746 (1954)8/.
- C) J. M. Wyckoff and H. W. Koch, X-ray Attenuation Coefficients from

  15 to 80 Mev for Hydrogen, Carbon, Water, and Aluminum, Phys. Rev.,

  (To be submitted for publication) 3/
- D) H. W. Koch and J. W. Motz, Bremsstrahlung Formulas and Experimental Data, Rev. Mod. Phys., (To be submitted for publication) 7/.

## Additional Background Material

The experiment described in Attachment C used the bremsstrahlung spectrum of X-rays from a 180 Mev synchrotron. The X-rays were transmitted through long attenuators to measure the attenuation coefficients versus X-ray energy. The X-ray detector was a large scintillation spectrometer consisting of a sodium-iodide crystal arrangement whose dimensions were 5" diameter by 9" long 10 mg 10 mg

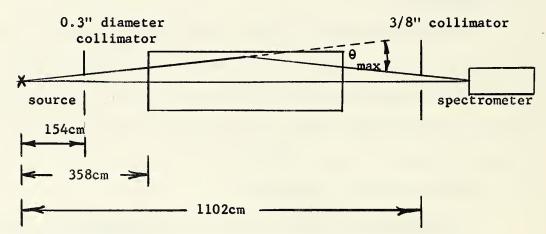
Although the detailed results of the project are given in attachment C, it was not possible in that description to emphasize the various experimental and theoretical conditions that were important to the attenuation experiment. The following is an enumeration and an amplification of those conditions.

The important requirements were:

1. A high energy X-ray source that was continuously distributed in energy with X-rays in the energy range from 10 to 90 Mev. This energy range permitted an accurate evaluation of the total attenuation coefficient from 30 to 80 Mev where the electronic processes predominate. The range also permitted a determination of the coefficients from 15 to 30 Mev where the nuclear absorptions are also important for low atomic number materials. The shape of the distribution of X-ray intensity (photon number times photon energy) was derived by Hisdal 16/ for the case of a small-solid-angle detector

located on the axis of the X-ray beam. The geometrical conditions assumed by Hisdal were very well satisfied in the present experiment. Hisdal's shape has further been changed to account for the coulomb corrections of Davies, Bethe, and  $\frac{7}{17}$ .

2. A good attenuation geometry that was necessary to insure a measurement of the primary interaction probability without appreciable secondary inscattering corrections. The corrections can be understood from the schematic arrangement of the geometries:



 $\theta_{\rm max}$  is the maximum scattering angle of photons that can get into the spectrometer and is  $4.2 \times 10^{-3}$  radians. The ratio of the scattered intensity, S, to the direct intensity, D, is given by:

$$\frac{S}{D} = N \pi r_o^2 \frac{Z}{A} t_o \theta_{\text{max}}^2 \left[ 1 - \frac{\theta^2}{12} (9 \times + 4) \right]$$
 (1)

where  $N \pi r_0^2 \frac{Z}{A} = 0.150 \frac{Z}{A} \text{ cm}^2/\text{g}$ 

 $t_{\rm omax} = 700 {\rm g/cm}^2$  for carbon, 428  ${\rm g/cm}^2$  for aluminum, and 461  ${\rm g/cm}^2$  for water.

Thus  $\frac{S}{D} = 0.075 \text{cm}^2/\text{g} \times 700 \text{ g/cm}^2 \text{x} (4.2 \text{x} 10^{-3})^2 \text{ for carbon} \frac{3}{2} / .$ = 0.9x10<sup>-3</sup> or 0.1%, which is negligible.

- 3. A high intensity X-ray source. The intensity of the synchrotron operating at 90 Mev was 30 mw/cm<sup>2</sup> at 1 meter from the target which is large compared to most other high energy X-ray sources. This energy flux density permitted the use of the long attenuators with the scintillation spectrometer.
- 4. An X-ray spectrometer whose detection efficiency was almost 100% and whose energy resolution was about 12%.

  This resolution was tolerable for the attenuation coefficients versus energy measured in the present experiment. The determination of the response functions for the spectrometer was the subject of a separate investigation 12/.
- 5. Recording of all photon energies simultaneously. The spectrometer characteristic of continous recording of all photon energies in conjunction with a 256 channel pulse height analyzer made possible the good precision of one photon energy relative to another that was possible in the attenuation coefficient measurements in this experiment.
- 6. The ability to use long attenuators. Long attenuators are desirable in order to amplify the sensitivity of an X-ray intensity change to an attenuation coefficient change. The amplification can be understood from the differential attenuation relation:

$$\frac{dI}{I} = \mathcal{T} \rho \chi \left( \frac{d\mathcal{T}}{\mathcal{T}} \right) \tag{3}$$

where d $\Upsilon$  is the change in the total attenuation coefficient,  $\Upsilon$ , that produces the intensity change,  $\frac{dI}{I}$ , in transmission of X-rays through an absorber length of  $\Upsilon$  PX mean free paths. In the present experiment attenuators of 10 mean free paths ( $\Upsilon$  PX = 10) of carbon, water, and aluminum were used. Thus, since a 2% intensity change was easily measureable, a measurement of an attenuation coefficient to 0.2% was in principle possible. It is also obvious from Table 1 that the total nuclear cross sections are sufficiently large compared to the electronic cross sections that a large dip will be produced in a high-energy X-ray spectrum by an attenuator whose length is 10 mean free paths.

TABLE 1

Material	Energy	Total Nuclear	Total Nuclear Plus Electronic	Expected $\frac{dI}{I}$ for $frac{1}{1}$ $frac{1}{1}$
Carbon	22.4 Mev	0.0012cm <sup>2</sup> /g	0.0164cm <sup>2</sup> /g	73%
Water	22.5 Mev	0.00075cm <sup>2</sup> /g	0.01855cm <sup>2</sup> /g	40%
Aluminum	20.5 Mev	0.0012cm <sup>2</sup> /g	0.0228cm <sup>2</sup> /g .	53%

7. The attenuators are of such a length that the data may be interpreted

easily. It is shown below that for relatively broad nuclear levels and
short attenuators the attenuation dip in the X-ray spectrum will be a
direct function of length and integrated nuclear cross section. For either
a very sharp resonance or very long attenuators, the attenuation will be
a function of the square root of length and integrated cross section. The
results of the experiment reported in attachment C have been analyzed by
assuming that the nuclear cross section shape could be resolved by the
spectrometer and that the nuclear attenuation was exponential (linear for
short lengths). These analyses have resulted in experimental nuclear cross

sections that are fairly close to, and somewhat larger than, cross sections synthesized from data obtained by very different methods. If resonances as sharply defined as the 15.1 Mev carbon resonance (an extreme example) made up the giant resonance region, the experimental nuclear cross sections would have been much smaller (and not larger) than the synthesized cross sections. These results suggest that the nuclear cross sections for carbon, water, and aluminum have very little fine structure in the giant resonance region.

The above comments can be understood from a calculation of the quantity measured experimentally - the number of photons removed by nuclear absorption from the spectrum,  $I_0 \Gamma_{eff}$ . For the case where the doppler width may be neglected, this quantity can be evaluated from the expression:

$$\Gamma_{\text{eff}} = \int_{-\infty}^{+\infty} \left[ 1 - e^{-\sigma_{\mathbf{q}}(E) \, \text{Nx}} \right] d(E - E_0) \tag{4}$$

where 
$$\sigma_{\mathbf{q}}(\mathbf{E}) = \frac{\pi}{2} \chi^2 \left(\frac{2J+1}{2I+1}\right) \frac{\Gamma \Gamma_{\mathbf{g}}}{\left(\mathbf{E}-\mathbf{E}_{\mathbf{o}}\right)^2 + \frac{\Gamma^2}{4}}$$
 cm<sup>2</sup>

r = total width for a nuclear level in e.v.

 $\Gamma_{\times}$  = radiation width for a nuclear level in e.v.

$$\chi = \frac{1.95 \times 10^{-11}}{\text{E(Mev)}} \text{ cm}$$

N = atoms/cc

E = photon energy

E = resonance energy

and 
$$\int \sigma_{\alpha} dE = \frac{\pi}{\Gamma} \left[ \pi \chi^2 \left( \frac{2J+1}{2I+1} \right) \Gamma \Gamma_{\gamma} \right] e.v..cm^2$$

The integral (4) can be solved explicitly in Bessel functions as done by Dardel and Persson  $\frac{18}{}$  or can be solved for two special cases in series expansions  $\frac{19}{}$  in the variable, t, where

$$t = 2\pi \chi^2 \left(\frac{2J+1}{2I+1}\right) \frac{\Gamma_s}{\Gamma} \times N.$$

When t<<1, 
$$\Gamma_{\text{eff}} = \frac{\Gamma}{2} \pi \left[ t - \frac{1}{2} \frac{t^2}{2} + \frac{3t^3}{8 \cdot 3} + \cdots \right]$$

or, to a first approximation, 
$$\Gamma_{\text{eff}} = (\Gamma \pi t/2)$$
 (5)

When t>>1, 
$$\Gamma_{\text{eff}} = \frac{\Gamma}{2} \pi \left[ 2 \sqrt{\frac{t}{\pi}} - \frac{1}{2} \frac{1}{\sqrt{\pi t}} - \frac{3}{16\sqrt{\pi t^3}} + \dots \right]$$

or, to a first approximation, 
$$\Gamma_{\text{eff}} = (\Gamma \sqrt{\pi t})$$
 (6)

Since 
$$t = \frac{2xN}{\pi r} \int \sigma_a(E) dE$$
, (7)

equation (5) becomes

$$\Gamma_{\rm eff} = xN \int \sigma_{\rm a}(E) dE \quad \text{for } t << 1$$
 (8)

and equation (6) becomes

$$\Gamma_{\text{eff}} = \sqrt{2 \times N \Gamma \int \sigma_{a}(E) dE} \text{ for } E >> 1$$
 (9)

For purposes of illustration, let us apply these expressions to the extreme example of the 15.1 Mev level in carbon whose characteristics have been reported  $\frac{20}{}$  as

$$\frac{\Gamma_{8}}{\Gamma} = 0.77 \pm 0.08, \Gamma = 74 \pm 11 \text{ ev}$$

$$\int \sigma_{q} dE = \frac{\Gamma}{\Gamma_{8}} \int \sigma_{S} dE = \frac{2.1 \pm 0.2 \text{ MeV mb}}{.77} = 2.7 \times 10^{-21} \text{ ev} \cdot \text{cm}^{2}$$

The value of t obtained from equation (7) is 996. This value makes appropriate the use of equation (9) from which is obtained  $\Gamma_{\rm eff} = 4.2$  kev for a 500cm carbon attenuator.

If the integrated cross section of the 15 Mev level had been in a broad resonance, the  $\Gamma_{\rm eff}$  from equation (8) would have been 116 kev and the number of photons removed from the spectrum for a 500cm carbon rod would have been 27 times larger. The experimental effect, therefore, is considerably suppressed by very sharp resonances. As stated previously, the approximate agreement of the giant resonance, differential and integrated cross sections from the present experiment with other data suggests that sharp resonances do not play a large role in the giant resonance absorption for carbon, oxygen, or aluminum.

## References for the Introduction and Background Sections

- G. W. Grodstein, X-ray Attenuation Coefficients from 1C kev to 100 Mev, NBS Circular No. 583, (U. S. Government Printing Office, Washington, D. C., 1957).
- J. M. Wyckoff and H. W. Koch, Mass-absorption Coefficients for 40 to 80 Mev X-rays in Carbon, Water and Aluminum, Bull. Am. Phys. Soc. Ser. II, 3, 174 (1958).
- 3. J. M. Wyckoff and H. W. Koch, X-ray Attenuation Coefficients from
  15 to 80 Mev for Hydrogen, Carbon, Water and Aluminum., Phys. Rev.

  (To be submitted for publication)
- 4. N. Starfelt and H. W. Koch, Differential Cross Section Measurements of Thin-Target Bremsstrahlung Produced by 2.7 to 9.7 Mev Electrons, Phys. Rev., 102, 1598 (1956).
- 5. E. G. Fuller, E. Hayward, and H. W. Koch, Shape of the High-Energy End of the Electron-Bremsstrahlung Spectrum, Phys. Rev., 109, 630 (1958).
- 6. U. Fano, H. W. Koch, and J. W. Motz, Evaluation of Bremsstrahlung Cross Sections at the High-Frequency Limit, Phys. Rev., 112, 1679 (1958).
- 7. H. W. Koch and J. W. Motz, Bremsstrahlung Formulas and Experimental Data, NBS Report No. 6104 (1958); a revised version of this report is included in this final report.
- 8. R. S. Foote and H. W. Koch, Scintillation Spectrometers for Measuring the Total Energy of X-ray Photons, Rev. Sci. Instr., 25, 746 (1954).

- H. W. Koch and J. M. Wyckoff, Response of a Sodium-Iodide Scintillation Spectrometer to 10- to 20-Million-Electron-Volt Electrons and X-rays,
   J. Research Natl. Bur. Standards <u>56</u>, 319 (1956).
- 10. H. W. Koch, J. E. Leiss, and J. S. Pruitt, Crystal Spectrometer Calibration of a High Energy X-ray Intensity Monitor, Bull. Am. Phys. Soc. II, 1, 199 (1956)A; this work has been extended in a report entitled "Crystal Spectrometer Calibration of High Energy X-ray Intensity Monitors", J. E. Leiss, J. S. Pruitt, R. A. Schrack, NBS Report 6149 (1958).
- 11. J. E. Leiss and J. M. Wyckoff, Angular Distribution of the 15-Mev Gamma-Rays Scattered from C<sup>12</sup>, Bull. Am. Phys. Soc. II, 1, A(1956).
- 12. H. W. Koch and J. M. Wyckoff, Response Functions of Total-Absorption Spectrometers, IRE Trans. on Nuclear Science, NS-5, No. 3, 127 (1958).
- 13. H. W. Koch and R. W. Johnston, Editors, Multichannel Pulse Height Analyzers, NAS-NRC Publication 467, (1957).
- 14. H. W. Koch and R. S. Foote, Total-Absorption X-ray Spectrometry:

  Application to Betatron Experiments, Nucleonics 12, No. 3, 51, (1954)
- 15. H. W. Koch, Direct Observation of Nuclear Absorption and Elastic Scattering of X-rays, Proceedings of the 1954 Glasgow Conference on Nuclear and Meson Physics, Edited by E. H. Bellamy and R. G. Moorhouse (Pergamon Press, New York, 1955).
- 16. E. Hisdal, Bremsstrahlung Spectra Corrected for Multiple Scattering in the Target, Phys. Rev. <u>105</u>, 1821 (1957).

- 17. H. Davies, H. A. Bethe, L. C. Maximon, Theory of Bremsstrahlung and Pair Production, II. Integral Cross Section for Pair Production, Phys. Rev. 93, 788 (1954)
- 18. G. V. Dardel and R. Persson, Determination of Neutron Resonance Parameters from Measurements of the Absorption Integral, Nature 170, 1117 (1952)
- 19. M. Abramowitz, Private Communication.
- 20. E. Hayward and E. G. Fuller, Photon Self-Absorption and Scattering by the 15.1-Mev Level in C<sup>12</sup>, Phys. Rev. <u>106</u>, 991 (1957), and Private Communication.

## Scintillation Spectrometers for Measuring the Total Energy of X-Ray Photons

R. S. FOOTE AND H. W. KOCH Radiation Physics Laboratory, National Bureau of Standards,\* Washington, D. C. (Received October 7, 1953)

X-ray spectrometers are described that operate on the principle of totally absorbing the energy of an individual x-ray photon in a scintillator. Experiments with scintillators of xylene containing terphenyl, and of sodium iodide activated by thallium, show that detection efficiencies better than 80 percent and energy resolutions better than 10 percent are attainable in the x-ray energy range from 1/2 to 50 Mev. Monte Carlo calculations and crude scaling laws that simplify extrapolations to other size scintillators are discussed.

#### INTRODUCTION

HE determination of the energy of an individual x-ray photon is usually accomplished by the analysis of a single interaction of the photon with matter. The interaction processes that have permitted accuracies of better than 5 percent in the energy measurement are coherent scattering, photoelectric absorption, Compton scattering, and pair production.1 Although good energy resolution<sup>2</sup> is obtainable by these techniques, their main disadvantage is low detection efficiencies, which are characteristically of the order of 10<sup>-8</sup> percent,

The combination of a detection efficiency close to 100 percent and a good energy resolution is attainable by the application of scintillation spectrometers in which x-ray photons interact multiple times and are totally absorbed. The total absorption of an x-ray photon in a large volume of scintillation material will produce a light pulse amplitude that is proportional to the x-ray energy. Preliminary results have been reported on a spectrometer that employed a tank of xylene liquid and terphenyl plus photomultiplier light detectors. The following report will describe the details of the xylene spectrometer and two sodium iodide spectrometers that are intended for research with pulsed accelerators in the x-ray energy range from  $\frac{1}{2}$ to 50 Mev.

Several physicists at other laboratories have made independent suggestions, experiments, and calculations on the general principle of "total absorption" spectrometers.

R. Sternheimer<sup>5</sup> has made shower calculations in order to estimate the energy resolution obtainable with a 4 in. diameter and 10 in. long sodium iodide crystal spectrometer that was proposed for the measurement of the energy of 2-Bev x-ray photons. He also investigated a combination of lead glass and organic liquid scintillator for the same measurement.

The recent work of Kantz and Hofstadter has permitted useful predictions on the performance of sodium-iodide, total-absorption spectrometers for 100 to 160 Mev electrons and x-rays. In their experiments they measured the distribution of energy loss in copper produced by 110 and 157 Mev electron beams.

The results in references 3, 5, and 6 show that total absorption spectrometers can provide good energy detection efficiencies resolution with high x-rays. A third desirable and concomitant characteristic of this type of spectrometer is the possibility of supplying the x-ray energy information from a single voltage pulse instead of the requirement of a coincident counting of two particles as in a pair spectrometer.

The importance of high detection efficiencies and the disadvantage of two-particle coincident counting in work with pulsed accelerators were demonstrated by J. L. Lawson. He analyzed the length of experimental time required to measure a spectrum of betatron x-rays with a pair spectrometer. Low x-ray intensities were required with the betatron in order to minimize the possible confusion of the positron from one pair with the electron from another. As a result, the experimental time for many low-energy, pulsed-accelerator experiments using a pair spectrometer is of the order of weeks<sup>7</sup> or longer, and is intolerably long.

In contrast, the time for similar experiments with a total absorption spectrometer is of the order of hours.8 Therefore, many experiments with pulsed accelerators should become feasible by the proper application of these spectrometers.

<sup>\*</sup>Supported in part by the U. S. Office of Scientific Research of the Air Research and Development Command.

1 J. W. M. DuMond, Rev. Sci. Instr. 18, 626 (1947); Motz, Miller, Wyckoff, Kim, and Gibson, Rev. Sci. Instr. (in press); R. V. Miller, Wyckoff, X. M. January, N. Walespier 7, No. 3, 23 (1950).

Hofstadter and J. A. McIntyre, Nucleonics 7, No. 3, 32 (1950); R. L. Walker and B. D. McDaniel, Phys. Rev. 74, 315 (1948).

<sup>2</sup> Energy resolution of the pulse-height distribution produced by monoenergetic x-rays will be defined as the width at half of the maximum intensity divided by the pulse height at this maximum. The width defined here is the total width of the distribution and includes the width of the photoelectric peak which forms the basis of a more common and less stringent definition of resolution.

<sup>&</sup>lt;sup>8</sup> M. Cleland and H. W. Koch, Phys. Rev. 86, 588A (1952). <sup>4</sup> The word "pulsed" refers to the short burst of x-rays that is repeated at the repetition rate or operating frequency of the accelerator.

<sup>&</sup>lt;sup>6</sup> R. Sternheimer, Brookhaven National Laboratory No. RS-5 (Oct. 11, 1951).

<sup>&</sup>lt;sup>6</sup> A. Kantz and R. Hofstadter, Phys. Rev. 89, 607 (1953). <sup>7</sup> J. L. Lawson *et al.*, Quarterly Progress Report No. 6, General Electric Research Laboratory, Contract N7onr-332 (Sept. 1, 1948).

Following the arguments of reference 7, one can show that 46 minutes is the required experimental time to obtain 10 000 real counts with a single count device, such as a total absorption spectrometer,

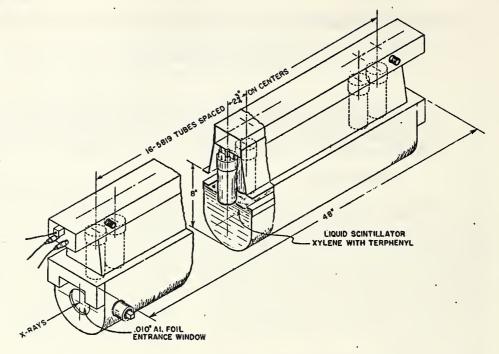


Fig. 1. A xylene (terphenyl) total absorption x-ray spectrometer. The xylene container is  $7\frac{1}{8}$  in. inside diameter by 48 in. long.

The discussion of spectrometers that follows deals with the Monte Carlo calculations, the construction details, and the experimental applications for the three models that have been built at the National Bureau of Standards. The general characteristics of these devices are:

- 1. Scintillator: Xylene liquid with 2 g/liter of terphenyl. Size:  $7\frac{1}{8}$  in. diameter by 48 in. long. Light detectors: sixteen 2-in. diameter photomultipliers.
- 2. Scintillator: Thallium activated sodium iodide crystals. (a) Size: 2 in. by 2 in. by 5 in. in three separate units. Light detectors: three 2-in. diameter photomultipliers. (b) Size: 5 in. diameter by 8 in. long in two separate units. Light detectors: eight 2-in. diameter photomultipliers.

#### XYLENE SPECTROMETER

A liquid scintillation spectrometer was the first model constructed because of its ease of fabrication and relatively small cost. The scintillator consisted of a  $7\frac{1}{8}$  in diameter by 48 in long tank of xylene liquid in which was dissolved terphenyl crystal to a concentration of 2 grams per liter. Single x-ray photons, whose energies were to be measured by the spectrometer, were directed down the central axis of the effective scintillator volume. The light resulting from the absorption of radiation energy in the liquid was detected by sixteen RCA 5819 photomultipliers. A schematic picture of the spectrometer is shown in Fig. 1.

The photomultiplier output pulses can supply the data from which the energy can be obtained with good

energy resolution, for the individual x-rays producing those pulses, if three conditions are satisfied.

First, most of the cascading interactions by which the original x-ray photon dissipates its energy must be confined to the spectrometer scintillator.

Second, the light resulting from energy loss in the scintillator must be collected uniformly.

Third, the number of light photons detected by the photomultiplier tubes for each absorbed x-ray must be large enough to minimize the effect of statistical fluctuations. This is particularly a problem for the xylene (terphenyl) scintillator because of its large size and poor geometry, and because the number of photons liberated for a given electron energy loss is small.<sup>9</sup>

Most of the time during the development of the spectrometer of Fig. 1 was spent in insuring uniform and efficient light collection to satisfy conditions 2 and 3. However, because of the recent availability of self-absorption data<sup>10</sup> for light in scintillators and of large-area photomultipliers, the present xylene-spectrometer design can be considerably improved and will not be described in detail. Therefore, only the results of calculations will be given, since they should prove to be a useful guide to satisfying condition 1 in any future design of a spectrometer employing an organic scintillator.

<sup>&</sup>lt;sup>o</sup> Experimental Nuclear Physics (John Wiley and Sons, New York, 1952), Vol. 1, p. 52; and J. I. Hopkins, Rev. Sci. Instr. 22, 29 (1951).

<sup>&</sup>lt;sup>10</sup> Princeton University results on xylene and toluene aim private communication from A. Meyer.

#### MONTE CARLO CALCULATIONS FOR XYLENE

The Monte Carlo sampling technique<sup>11</sup> was used to provide quantitative evaluation of the performance of a specific scintillator in a total absorption spectrometer. The calculations for xylene were done for the five x-ray photon energies of 1, 5, 15, 25 and 35 Mev, and for a tank that was 6.5 in. in diameter and 48 in. long. A larger diameter of  $7\frac{1}{8}$  in, was used in practice. For each Monte Carlo history an individual x-ray photon was followed in to the xylene until the x-ray energy was degraded to a value that was 0.2 percent of the initial energy. The energy that was retained in the xylene was divided by the primary x-ray energy to obtain a fractional pulse height. The calculations were performed for 78 cases of 1-Mev primary photons, 71 cases of 5 Mev, 128 cases of 15 Mev, 201 cases of 25 Mev, and 267 cases of 35 Mev.

The distributions of fractional pulse heights are plotted in Fig. 2. The ordinate scale is the frequency of events on a logarithmic scale. The pulse height distribution for 1 Mev x-rays shows an extremely poor energy resolution, since almost all pulse heights up to the maximum are equally probable. At 5 Mev, the energy resolution is about 10 percent and is improving with energy. At energies of 15, 25, and 35 Mev the energy resolution is better than 7 percent.

These energy resolutions would have been those found in practice if the energy resolution had been determined solely by the electronic energy retained in the scintillator. However, experiments with betatron x-ray

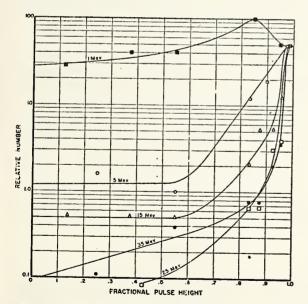


Fig. 2. Monte Carlo predictions for a xylene (terphenyl) spectrometer. The fractional pulse height distributions are predicted to result from the absorption of monoenergetic x-rays of the energies labeled above each curve.

spectra and arguments on light collection efficiencies indicated that energy resolutions poorer than those predicted were obtained.

#### SODIUM IODIDE SPECTROMETER

The attractiveness of sodium iodide as the total absorption scintillator comes from the large density, high atomic number, large light emission per Mev of electron energy loss, and good optical properties. Other advantages will become obvious from the discussion on the x-ray measurements at energies from 87 kev to 17.6 Mev. In this range, the xylene spectrometer, as it was built, would have been completely unsuitable because the energy resolution was poor and the cosmicray background was large.

Rough scaling laws were applied in order to determine the size requirements of the sodium iodide from the experiences with the xylene. On this basis the two sizes, 2 in. by 2 in. by 10 in. and 3 in. by 3 in. by 10 in., of sodium iodide were selected for the Monte Carlo calculations. The x-ray photons were directed along the long dimension, and were centered on the square cross section.

#### (a) Theory

### (1) Monte Carlo Calculations

The detail with which Monte Carlo calculations† had to be performed for sodium iodide was greater than that for xylene. This arises from the high atomic number of sodium iodide which makes necessary the additional detailed examination of the photoelectric, pair production, bremsstrahlung, and annihilation processes. The calculations were performed for 166 cases of primary photons of 4.45 Mev, 66 cases of 16 Mev and 18 cases of 40 Mev.

The most significant results of the calculations were the predictions of the pulse height distributions to be expected from a 2-in. by 2-in. by 10-in. and a 3-in. by 3-in. by 10-in. sodium iodide, total-absorption spectrometer. These results are shown in Fig. 3. Each curve has been averaged from histograms that were based admittedly on poor statistics. Therefore, not too much significance should be placed on the detailed shape of each curve. However, the trends among the three x-ray energies, and from the smaller crystal to the larger crystal, are thought to be significant. Note that the 4.5-Mev pulse height distribution shows evidence of subpeaks due to the escape of one and two annihilation quanta. Note also that the energy resolution obtainable with the 3-in. by 3-in. by 10-in. spectrometer is almost energy independent and is approximately 10 percent.

ii G. Goertzel, AECD 2808 (February 1950); Natl. Bur. Standards, Publication AMS-12 (1951); H. Kahn, Nucleonics 6, 27, 60 (1950).

<sup>†</sup> Note added in proof.—A recent paper by J. G. Campbell and A. J. F. Boyle [Australian J. Phys. 6, 171 (1953)] contains the details of a Monte Carlo calculation for sodium iodide which differs slightly from the procedure used in the present work.

# (2) Extrapolation to Other Sizes

Predictions and experiments with a small-sized crystal in a total absorption spectrometer can be used as the basis for understanding the results obtainable with larger-sized crystals. Since Monte Carlo calculations for a variety of crystal sizes are tedious, and since large crystals are expensive, the description of the crude extrapolation procedure used by the authors is given here. This method was intended only for x-ray photons with energies greater than 10 Mev.

The main features of the pulse height distribution produced by monoenergetic x-rays are the percentage energy resolution and the relative pulse height position of the most probable pulse height. If the most probable pulse height is located at the fractional pulse height of 1 and if the energy resolution is 0 percent, then all of the pulses will be located at one pulse height and the spectrometer is said to operate perfectly. As the most probable pulse height decreases from 1, the percent energy resolution increases approximately in proportion to the decrease in the most probable height. This proportion results from the nature of the cascade process by which an x-ray loses energy. Therefore, in the following it is assumed that the most probable pulse height is displaced from 1 by an amount determined by the average loss,  $\Delta E_T$ , of the initial photon energy,  $E_0$ , from the crystal. Likewise, it is assumed that the energy resolution is given by

$$\frac{2\Delta E_T}{(E_0 - \Delta E_T)}.$$

The question of extrapolating between different sized crystals resolves itself into a prediction of the average energy loss of photons from the various crystals.

To the assumptions on the pulse height distributions was added the assumption that the average energy losses produced by finite radii  $(\Delta E)_t$  and léngths  $(\Delta E)_t$  are independent. Therefore, the combined average energy loss will be

$$(\Delta E)_T^2 = [(\Delta E)_I]^2 + [(\Delta E)_\tau]^2. \tag{1}$$

(a) Effect of radius.—The Monte Carlo calculations for the 3-in. by 3-in. by 10-in. sodium iodide crystal showed that an energy resolution of 10 percent or a  $(\Delta E)_r$  of  $0.05\ E_0$  is obtainable. This imperfect resolution can be assumed to be due entirely to the small size of the crystal in the lateral dimension. The radiation that propagates sideways is composed of annihilation radiation, low energy Compton scattered secondaries, and low energy bremsstrahlung. This energy will be attenuated with an absorption coefficient of approximately 1 Mev radiation, which is  $0.544\ \text{in.}^{-1}$ . Therefore, the average energy loss produced by a finite radius, r, can be derived by setting the integral of the exponential, constant  $xe^{-0.644r}$ , from 1.8 to infinity, equal to  $0.05E_0$ . Thus it can

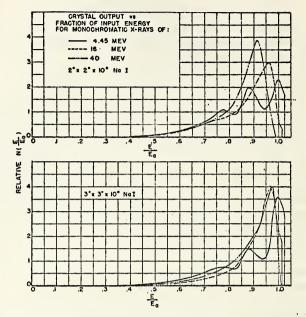


Fig. 3. Monte Carlo predictions for a 2-in. by 2-in. by 10-in, and a 3-in. by 3-in. by 10-in., NaI(Tl) spectrometer.

be shown that

$$(\Delta E)_{\tau} = 0.136 E_0 e^{-0.544 \tau}, \tag{2}$$

where r is greater than 1.8 in.

The results of this calculation are given in Table I. It will be noted from the values of (% energy resolution), that a crystal with a 5 in. diameter cross section will provide an energy resolution that is approximately a factor of 2 better than that obtainable with a 2-in. by 2-in. by 10-in. crystal.

(b) Effect of length.—The absorption coefficient of the x-ray energy that determines the shape of the energy absorption versus depth curve in the material governs the length of the spectrometer. Kantz and Hofstadter<sup>6</sup> have shown experimentally that the slope of the semilog plot of energy versus depth in copper is somewhat smaller than that obtained from the absorption coefficient,  $\mu_m$ , of the most penetrating photons.<sup>12</sup>

The minimum absorption coefficient,  $\mu_m$ , for sodium iodide is 0.32 in.<sup>-1</sup> and occurs at 5 Mev. Therefore, in a manner similar to extrapolations described for the radial direction, the average energy loss resulting from a crystal that is l in. long is

$$(\Delta E)_1 = 2.47 R E_0 e^{-0.321}, \tag{3}$$

where l is greater than 5 in., and R is the energy resolution obtained experimentally for a 5 in. long, and infinitely wide crystal. An approximation to R can be found from the measurements with a 2-in. by 2-in. by 5-in. crystal. These results as drawn in Fig. 8 show that R is approximately 15 percent. The results in

<sup>&</sup>lt;sup>12</sup> U. Fano, Nucleonics 11, (Sept. 1953) has shown theoretically that the energy *versus* depth relationship is expected to be  $\exp{-\mu mx \cdot \exp{H \cdot [(\mu mx)\frac{1}{3}] \cdot x^{-5/6}}}$  at extremely great depths. H is a constant for each material and has values around 2 to 3.