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Technical Note 10

CALCULATED BEHAVIOR OF A FAST NEUTRON SPECTROMETER BASED ON THE TOTAL ABSORPTION PRINCIPLE

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10

APRIL 14, 1959

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James E. Leiss

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Atomic Energy Commission

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Calculated Behavior of a Fast Neutron Spectrometer Based on the Total Absorption Principle

James E. Leiss

ABSTRACT

Performance calculations for a total absorption fast neutron spectrometer are presented. The spectrometer detecting element is a boron-10-loaded liquid scintillator. By making the scintillator a thin disk, only those neutrons whose first collision is a large-energy-loss hydrogen collision have appreciable chance of remaining in the spectrometer long enough to be captured. The expected energy resolution and efficiency of this type of spectrometer are determined, and are comparable to other types of fast neutron spectrometers.

1. Introduction

The success of total absorption spectrometers for the determination of gamma ray energies[1/] led to a study of the use of such devices for the detection of fast neutrons. Total absorption spectrometers are based on the hypothesis that essentially all of the energy of the incident particle is lost in the spectrometer. If, then, one has a detector whose response is proportional to the amount of energy lost in the spectrometer, the response of this device will be a measure of the energy of the incident particle. For gamma rays the energy loss takes place through collisions of various kinds, the secondary products of which are electrons (or positrons). Since scintillation detectors are approximately linear in response to the energy lost by electrons within them, one has only to make a sufficiently large spectrometer to insure a reasonably accurate determination of the energy of the incident gamma ray.

For a neutron spectrometer the situation is not nearly so simple. The energy loss of neutrons occurs by various elastic and inelastic collisions. If we restrict ourselves to elastic collisions, then the secondary products are recoil nuclei for which the response of scintillation detectors is <u>not</u> linear but depends greatly upon the energy and mass of the recoil particle. Thus, even though a neutron may be totally absorbed, the response of the scintillator will <u>not</u> be a measure of the energy of the neutron since the scintillator response will be a function of the detailed manner in which the collisions occurred.

To avoid the above difficulties Cleland[2/] proposed the use, and calculated the performance of a spectrometer of such small dimensions that very few neutrons would be totally absorbed, the large majority of the neutrons escaping from the spectrometer after only a very few collisions. The dimensions were so selected that those few neutrons that were totally absorbed would therefore have to lose their energy in a few large-energy-loss collisions, in which case the response of a scintillation detector should approach a known functional relation to the energy of the incident neutron.

To identify those neutrons that have been totally absorbed one may load the spectrometer with a substance such as boron-10, which has a high capture cross section for low-energy neutrons. Thus only those neutrons that had lost most of their energy in the spectrometer would be captured. (The identification of the neutron capture event can be made by scintillation detection of the characteristic products of the capture process.)

2. Description of the Calculation

2.1. General Remarks

The calculations described in this report differ from those of Cleland[2/] in only a few respects, the major advantage of the work presented here being in the considerably greater amount of information made available through the use of the S.E.A.C. digital computer.

The calculations of Cleland were made using "biased" sampling procedures. The validity of such procedures, especially for very small statistical samples, is questionable and could lead to erroneous conclusions. The calculations reported here did not use "biased" sampling but were Monte-Carlo calculations of the most straightforward sort; that is, the random sampling was performed using the same probability distributions as would hold for neutrons in the spectrometer. While this procedure limits the statistical samples that can be obtained, even with the use of a digital computer, it was felt that the added reliability of the results justified this procedure.

2.2. The Spectrometer

The calculations that were performed were for a right circular cylinder of phenylcyclohexane ($C_{12}H_{16}$) loaded, half and half, with 94 per cent boron-10 enriched methyl borate $B(OCH_3)_3$. Since the total-scattering cross section of oxygen, carbon, and boron are roughly the same for fast neutrons[3/], it was assumed that the slowing down history of fast neutrons was essentially the same in phenylcyclohexane and methyl borate. To allow for the low-energy boron capture process, a half-and-half mixture of phenylcyclohexane and enriched methyl borate was treated as pure phenylcyclohexane with 1.0 atom of boron-10 per 14 atoms of carbon.

The influence of added scintillating substances such as terphenyl should have practically no effect on the slowing down history and was neglected in the calculations.

2.3. The Incident Neutrons

It was assumed that monoenergetic incident neutrons were distributed uniformly on the front face of the spectrometer in a direction parallel to the axis of the spectrometer (normal incidence). The point of incidence on the surface of the spectrometer was chosen at random according to the above assumption.

2.4. The Slowing-down Process

Five different types of events may occur in a collision. These are:

(a) Elastic scattering with hydrogen atoms

(b) Elastic scattering with carbon atoms

(c) Inelastic scattering with carbon atoms

(d) Capture of the neutron by boron-10 atoms

(e) Capture of the neutron by hydrogen or carbon atoms

Events of types (c) and (e) were neglected in these calculations. The justification for neglecting these types of events is based on one or more of the following arguments:

(1) Insufficient experimental information available

(2) Impractical to include in the calculation because of increased computing time

(3) Expected effect on the results is negligibly small.

Events of type (e) will not effect the resolution of the spectrometer since such events can be distinguished easily from the boron capture events. They will have only a slight effect on the efficiency of the spectrometer.

Events of type (c) can be expected to produce a tail on the pulse-height distribution. As will be shown later, such a tail is rather strongly discriminated against for small spectrometers and should, therefore, not be too serious.

Since the collisions with hydrogen and carbon are considered elastic, it is necessary to make only four independent choices to completely determine a given collision; first, the distance travelled before collision; second, the type of collision (i.e. hydrogen, carbon, or boron capture); third, the angle of scattering; fourth, the azimuthal plane containing the initial and final paths. The energy lost in the collision is determined uniquely by the type of collision and the scattering angle. Isotropy of the scattering in the center of mass system was assumed.

In order to determine if the neutrons remained in the spectrometer, it was also necessary to follow the path of the neutron relative to the boundaries of the spectrometer.

The path of a typical neutron may thus be summarized as follows:

(a) Locate the point of incidence on the spectrometer according to a uniform distribution on the front surface.

(b) Locate the penetration of the neutron before its first collision.

(c) If the collision was within the spectrometer, determine the type of collision (hydrogen or carbon scattering or boron capture).

(d) If the event was not boron capture, determine the scattering angle, azimuthal angle, and energy loss.

(e) Follow along the new direction of the neutron to the next collision.

(f) Return to step (c) and repeat the loop (c) to (f) until the neutron either passes outside the boundaries of the spectrometer or is captured.

(g) If the neutron passed outside the boundaries of the spectrometer, start a new neutron with step (a).

(h) If the neutron underwent a boron capture, then specific information about that neutron was printed out of the computer before the next neutron was started with step (a). If the neutron energy dropped below 1.0 ev while in the spectrometer, it was also assumed to be captured.

The response curve of the spectrometer to recoil protons was assumed to be that due to Birks.[4/] For recoil carbon nuclei the response is quite small and was neglected. For each neutron captured in the spectrometer, the relative pulse height was determined by summing the pulse heights produced by all recoil protons produced by that neutron.

3. Results

Fig. 1a shows the spectrum of pulse heights for 14-Mev neutrons incident on a spectrometer of 50-cm radius and 50-cm depth. The efficiency of this spectrometer for 14-Mev neutrons is approximately 50 percent. The spread in pulse height produced is quite large. In Fig. 1b these same results are plotted in a different manner, which indicates the reasons for this large spread in pulse height. Here the pulse height for each captured neutron plotted against the neutron energy loss that went into collisions with hydrogen atoms is indicated by a dot. The solid curve indicates the pulse height that would be produced by protons of this same energy being stopped in the spectrometer material. From this plot it is clear that for such a large spectrometer the largest spread in the pulse-height distribution is a result of energy losses by collisions with carbon atoms; the spread due to the manner in which the hydrogen collisions occur is of secondary importance.

Fig. 2a shows the same plot for 14-Mev neutrons incident on a spectrometer of 8-cm radius and 8-cm depth. The efficiency of this spectrometer for 14-Mev neutrons is approximately 1.4 percent. The spread in the pulse-height distribution is much less.

Fig. 2b shows these same data plotted as in Fig. 1b. The number of neutron histories is approximately the same as in Fig. 1b. The percentage of captured neutrons that have lost most of their energy in hydrogen collisions has increased considerably, thereby, reducing the tail on the pulse height distribution. For a given energy loss in hydrogen collisions the spread in pulse heights has also been considerably reduced, thus narrowing the peak of the pulse height distribution. These conclusions confirm the expectation that for a small enough spectrometer only those neutrons for which the first collisions are large-energy-loss hydrogen collisions have an appreciably large chance of being captured. For thinner spectrometers, for which most of these calculations have been performed, these results become even more pronounced. It is thus felt that the neglect of inelastic collisions with carbon nuclei should not have large effects on the performance of the spectrometers proposed here.

In Fig. 3a, 3b, and 3c, are shown the calculated response of 7-Mev neutrons in spectrometers of 8-cm radius and thicknesses of 4, 3, and 2 cm respectively. The 8-cm radius is about the largest size for a practical spectrometer that might be used with existing 5-inch photomultiplier tubes. The use of a large diameter spectrometer is advantageous since it not only provides the possibility of increased counting rates, but also minimizes the leakage of neutrons out of the sides of the spectrometer before they are captured.

In these figures the spread due to statistical uncertainty in the number of photo-electrons produced in the photomultiplier detector has not been included. The pulse height distributions with this effect included are shown in Fig. 4a, 4b, and 4c. This effect has been introduced analytically by assuming that the uncorrected pulse height was constant over bins whose width was 5 percent of the maximum pulse height. The spread for a given pulse height was assumed to be gaussian whose full width at half maximum varied inversely as the square root of the pulse height, having a value of 10 percent for 7-Mev protons. This is a reasonable estimate of the resolution that can be achieved with existing liquid scintillators if sufficient care is taken in their preparation.

Fig. 4a, 4b, and 4c are summarized in Fig. 5 where is shown the full width at half maximum of the pulse height distribution and the detection efficiency of the spectrometer plotted against the thickness of the spectrometer for 7-Mev incident neutrons. From Fig. 6 there is clearly no advantage in making the spectrometer thinner than 2 cm, since the resolution is primarily determined by the statistics in the photomultiplier.

To investigate the performance as a function of neutron energy, a specific spectrometer, 2-cm thick and 8-cm radius was chosen. Fig. 6a to 6d show the expected pulse height distributions for this spectrometer to four different neutron energies. Figs. 7 and 8 summarize these results. Curve A of Fig. 7 shows the percentage full width at half maximum plotted against incident neutron energy. Curve B shows this same width for monoenergetic protons of the same energy.

In Fig. 8 is plotted the efficiency of boron capture as a function of neutron energy. This efficiency drops somewhat faster than the mean free path in the spectrometer material.

In most experimental situations the beam of incident neutrons would have a uniform distribution on the front surface of the spectrometer, as was assumed for these calculations, although in some cases the neutrons may be in a collimated beam. For a uniform distribution on the front surface the incident neutrons would have a radial distribution:

$$P(r)dr = \frac{2}{r_{max}^2} r\, dr$$

where r_{max} is the radius of the spectrometer and $P(r)dr$ is the probability of a neutron having incident radius between r and $r + dr$. In Fig. 9 the number of captured neutrons divided by $P(r)$ is plotted on a relative scale against the incident radius of the captured neutron. All energies of incident neutrons were included in this plot, since this radial dependence proved to be insensitive to the incident neutron energy. This plot is a relative measure of the efficiency of capture as a function of the incident radius and gives a direct indication of the effects of the escape of neutrons out of the sides of the spectrometer. This plot can be used to estimate the efficiency of spectrometers having different radii or different distributions of the incident neutrons. From this plot one would thus estimate for a beam of incident neutrons collimated along the central axis of the spectrometer that the efficiency of the spectrometer would be about 1.6-times greater than that shown in Figs. 5 and 8. For smaller spectrometers the efficiency would drop very rapidly as the spectrometer radius was made less than about 3 cm.

4. Identification of the Boron Capture Event

The boron capture reaction, $B^{10}(n,\alpha)Li^7$ proceeds in two ways. At thermal neutron energies 5.8 percent of the disintegrations produce Li^7 in the ground state, the energy of the alpha being 1.77 Mev. In the other 94.2 percent the lithium-7 nucleus decays to its ground state by the emission of a 478-kilovolt gamma ray. The present discussion will concern itself

only with the latter, more probable disintegration scheme.

There are three possible means by which the boron-capture event may be distinguished. Following the initial large pulse in the spectrometer due to the slowing down of the neutron, one may look for: (a) a delayed small pulse in the spectrometer due to the 1.46-Mev alpha particle, (b) a delayed pulse due to the 478-kilovolt gamma ray either in the spectrometer or in a closely adjacent NaI(Tl) scintillator, (c) a delayed fast coincidence between the alpha pulse in the spectrometer and the 478-kilovolt gamma rays in an adjacent NaI(Tl) scintillator.

In the spectrometer material, the delayed alpha particle pulse is expected to be quite small, amounting to an average of about 15 photoelectrons released from the photocathode of the photomultiplier. Because of the very large number of "small" pulses that are inevitably present in experimental situations and because of the possible confusion with photomultiplier "after pulsing", it is felt that detection of the alpha pulse by method (a) would be quite difficult to achieve in practice, although it would provide almost 100 percent detection of the capture process.

Detection of the 478-kilovolt gamma-rays in an adjacent NaI(Tl) scintillator seems a quite attractive alternative. For this gamma-ray energy the pulse-height resolution that can be achieved in a NaI(Tl) scintillator is quite respectable (~10%) and can thus be used to good advantage in distinguishing the boron-10 capture event more uniquely, using either methods (b) or (c) above. This has the additional advantage of insuring against the absorption of the 478-kilovolt gamma ray in the neutron spectrometer itself, where it could cause an appreciable spread in the neutron pulse-height distribution if care were not taken in the electronic circuitry involved. The requirement of absorbing the 478-kilovolt gamma ray in an adjacent scintillator will reduce the expected efficiency of the spectrometer by an appreciable amount depending upon the experimental arrangement used. It should be possible, however, to collect 30 or 40 percent of these capture gamma rays.

The distribution in time between the pulse from the slowing down of the neutron and its subsequent capture is almost independent of the size

of the spectrometer or the initial energy of the neutron. This is because the large part of this slowing down time occurs at low neutron energies where the neutron has essentially forgotten its previous history. Fig. 10a shows the distribution in capture time (time between the incidence of neutrons on the spectrometer and the neutron capture by boron-10). Here the number of neutrons captured in .05-microsecond intervals is plotted on a relative scale against the capture time. Data from all neutron energies for a spectrometer 2-cm thick by 8-cm radius are included. Fig. 10b shows this same data plotted in a different manner. Here the fraction of neutrons captured prior to a given time, t, is plotted against t. From this it is seen that by opening a 0.5-microsecond gate immediately after the slowing down pulse one could detect 90 percent of the capture events.

The distribution given in Fig. 10 strongly favors detection of the neutron-capture event by method (b) above. Because the pulses of interest occur in separate scintillators it would be relatively easy to open the delayed gate almost instantaneously after the initiating neutron pulse. This could be achieved with conventional circuitry by suitable time delays on the pulses from the two scintillators. Detection by methods (a) or (c) would require rather elegant circuitry in getting the gate opened quickly enough to keep the counting losses small, and in distinguishing the small alpha pulse from the tail of the neutron slowing down pulse.

It is possible to affect considerably the time distribution shown in Fig. 10 by changing the concentration of boron-10 in the spectrometer material. As has been shown by Cleland, the mean time of capture changes from 0.25 microseconds to 2.1 microseconds as one changes from 94 percent enriched boron-10 to normal 18.8 percent boron-10. However, the shape of the distribution in time remains essentially the same (i.e. peaked at small capture times).

5. Comparison with Other Neutron Spectrometers

It is very difficult to compare the usefulness of various neutron spectrometers since the most desirable spectrometer to use is strongly dependent on the particular experiment of interest. The choice of spectrometer to use in a given experiment depends upon the energy resolution required, the efficiency of the spectrometer for detection, the solid angle

that the spectrometer subtends, and the background radiations present. As can be seen from Fig. 5, it is possible to select a sufficiently thin spectrometer of the type proposed here that the energy resolution is almost entirely due to the statistical uncertainties in the number of photo-electrons produced in the photomultiplier. This has been shown to be true also for lower neutron energies. Thus, it may be concluded that the energy resolution of this type of spectrometer may be made as great as that of any other spectrometer of the organic scintillator type, since this same statistical uncertainty is present in all such spectrometers.

In comparing various spectrometers, it is not sufficient to compare just the efficiency of the spectrometer, which is the fraction of the incident neutrons that are detected. It is necessary also to consider the number of neutrons incident on the detector, which depends upon the effective area of the spectrometer. The calculations presented in Fig. 8, for a 2-cm thick by 8-cm diameter spectrometer, indicate an efficiency almost an order of magnitude greater than that achieved by other types of scintillation spectrometers of comparable energy resolution. If one assumes that the boron-10-capture event is detected with only 30-percent efficiency, the proposed spectrometer should still have an efficiency comparable to or greater than these other spectrometers.

To preserve the energy resolution of neutron spectrometers of the recoil type it is necessary to restrict the effective area of the spectrometer so as to define the proton or neutron recoil angle sufficiently well. This limits the effective area of such spectrometers to a maximum of about 4 cm^2 for energy resolutions comparable to those given in Fig. 7. The spectrometer used in calculating Fig. 7 had an effective area of about 200 cm^2 or a factor of fifty greater. It should be possible to receive a considerably greater flux of incident neutrons with this spectrometer, and, thus, achieve reasonably greater counting rates.

Background difficulties in the proposed spectrometer are likely to be severe. The size of the spectrometer is quite large and the sensitivity to low-energy-neutron backgrounds will be very great due to the heavy boron-10 loading. This is accentuated by the necessity of opening a gate that is

at least 0.5-microseconds long for the delayed capture pulse. Thus, "pile up" of pulses and accidental-counting-rate problems may limit the usefulness of this type of spectrometer.

A very comprehensive survey of various types of neutron spectrometers has been given by C. D. Swartz.[5] The comparisons discussed above were made with reference to this survey.

6. Conclusions and Summary

An attempt has been made using the S.E.A.C. digital computer and Monte-Carlo calculations to investigate in some detail, the usefulness and expected performance of a fast-neutron spectrometer proposed by Cleland and based upon the total absorption principle. Sufficient information has been presented to allow a reasonable estimate of the predicted performance for different sizes of the spectrometer, and to serve as a guide for the experimental investigation of this type of neutron spectrometer.

These calculations indicate that there is considerable flexibility in the design of the spectrometer, allowing the emphasis to be placed upon either good energy resolution or upon high efficiency.

The energy resolution and efficiency predicted by these calculations indicate that the proposed spectrometer should prove a useful tool in the study of neutron energy spectra. Because of the very large effective area of the spectrometer, a considerable increase in counting rates might be achieved relative to counting rates obtainable with existing neutron spectrometers of comparable energy resolution.

Although the calculations presented here were for a boron-10-loaded spectrometer, there are other arrangements which migh be used. One could load the detector with other substances having a high capture cross section for low-energy neutrons. One could also place a low-energy neutron detector very close to a liquid or plastic scintillator of the sizes discussed here and detect low-energy neutrons leaving the spectrometer following the slowing-down process. In this latter case some deterioration of the efficiency and pulse-height resolution would be expected. A

spectrometer of this latter type operating on the principles described in this report has been reported.[6/]

7. Acknowledgments

It is a pleasure to acknowledge many helpful conversations with H. W. Koch and J. McElhinney. The coding of this problem for the S.E.A.C. was done in collaboration with Mrs. Ida Rhodes of the NBS Computations Section.

Figure Captions

Fig. 1 (a) Pulse-height distribution. 14 Mev neutrons on a spectrometer of 50 cm radius by 50 cm depth. No correction made for photomultiplier statistics.

(b) Pulse height vs. energy lost in hydrogen collisions for spectrometer of Fig. 1a for each captured neutron.

Fig. 2 (a) Pulse-height distribution. 14 Mev neutrons on a spectrometer of 8 cm radius by 8 cm depth. No correction made for photomultiplier statistics.

(b) Pulse height vs. energy lost in hydrogen collisions for spectrometer of Fig. 2a for each captured neutron.

Fig. 3 (a) Pulse-height distribution, 7 Mev neutrons on a spectrometer of 4 cm thick by 8 cm radius. Uncorrected for photomultiplier statistics.

(b) Same as 3a, but 3 cm thick spectrometer

(c) Same as 3a, but 2 cm thick spectrometer

Fig. 4 (a) Same as 3a but corrected for photomultiplier statistics.

(b) Same as 3b but corrected for photomultiplier statistics.

(c) Same as 3c but corrected for photomultiplier statistics.

Fig. 5 Dependence of resolution and efficiency on spectrometer thickness for 7 Mev neutrons.

Fig. 6 Pulse-height distribution for a 2 cm thick, 8 cm radius spectrometer at different neutron energies.

(a) 2 Mev.

(b) 4 Mev.

(c) 7 Mev.

(d) 10 Mev.

Fig. 7 Resolution dependence on energy. Spectrometer 2 cm thick by 8 cm radius.

Fig. 8 Efficiency dependence on energy. Spectrometer 2 cm thick by 8 in radius.

Fig. 9 Relative efficiency for capturing neutrons as a function of radius of incidence of neutrons.

Fig. 10 (a) Distribution of neutron capture times. Spectrometer 2 cm thick, 8 cm radius.

(b) Fraction of neutrons captured prior to a given time. Spectrometer 2 cm thick, 8 cm radius.

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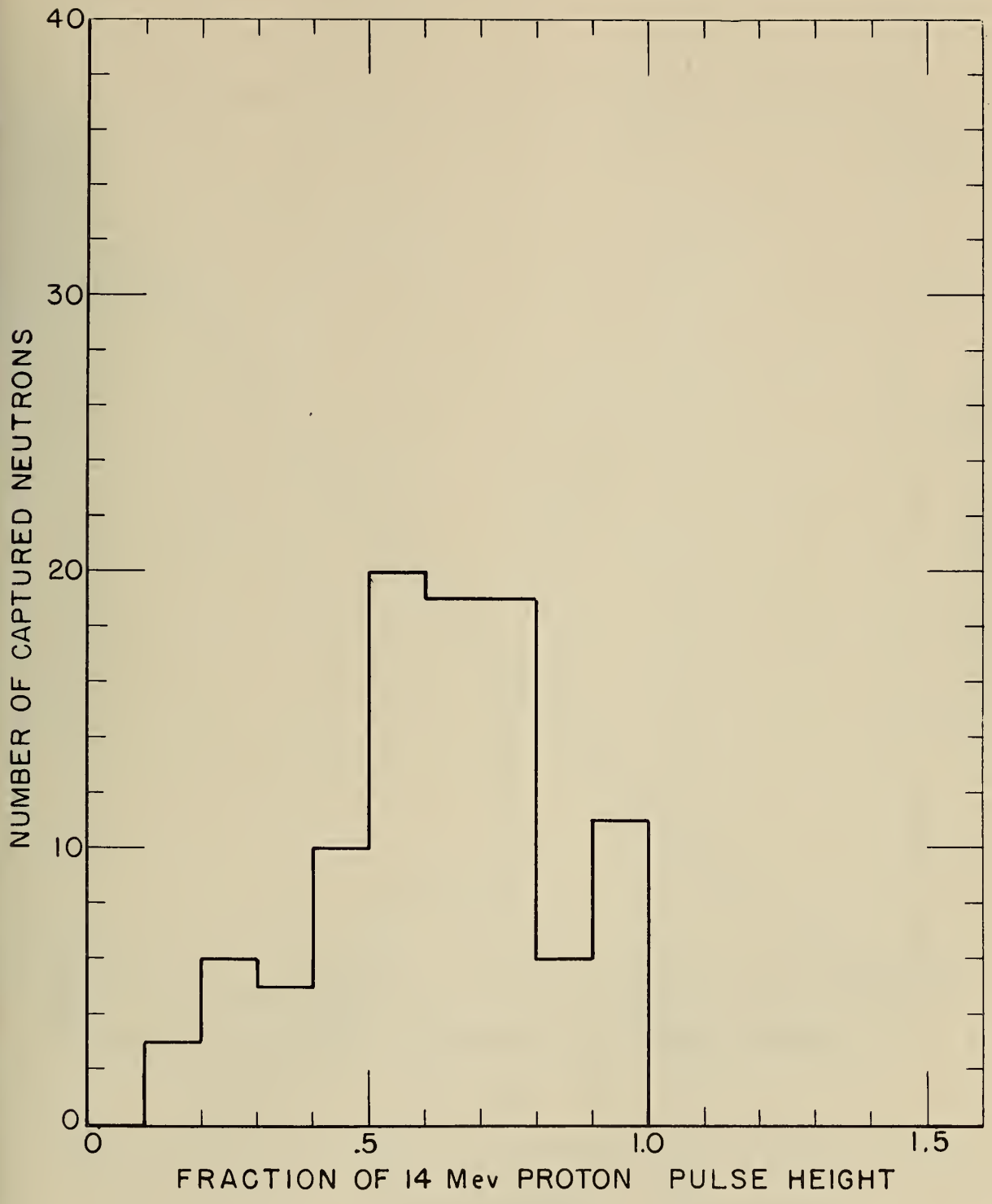
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30
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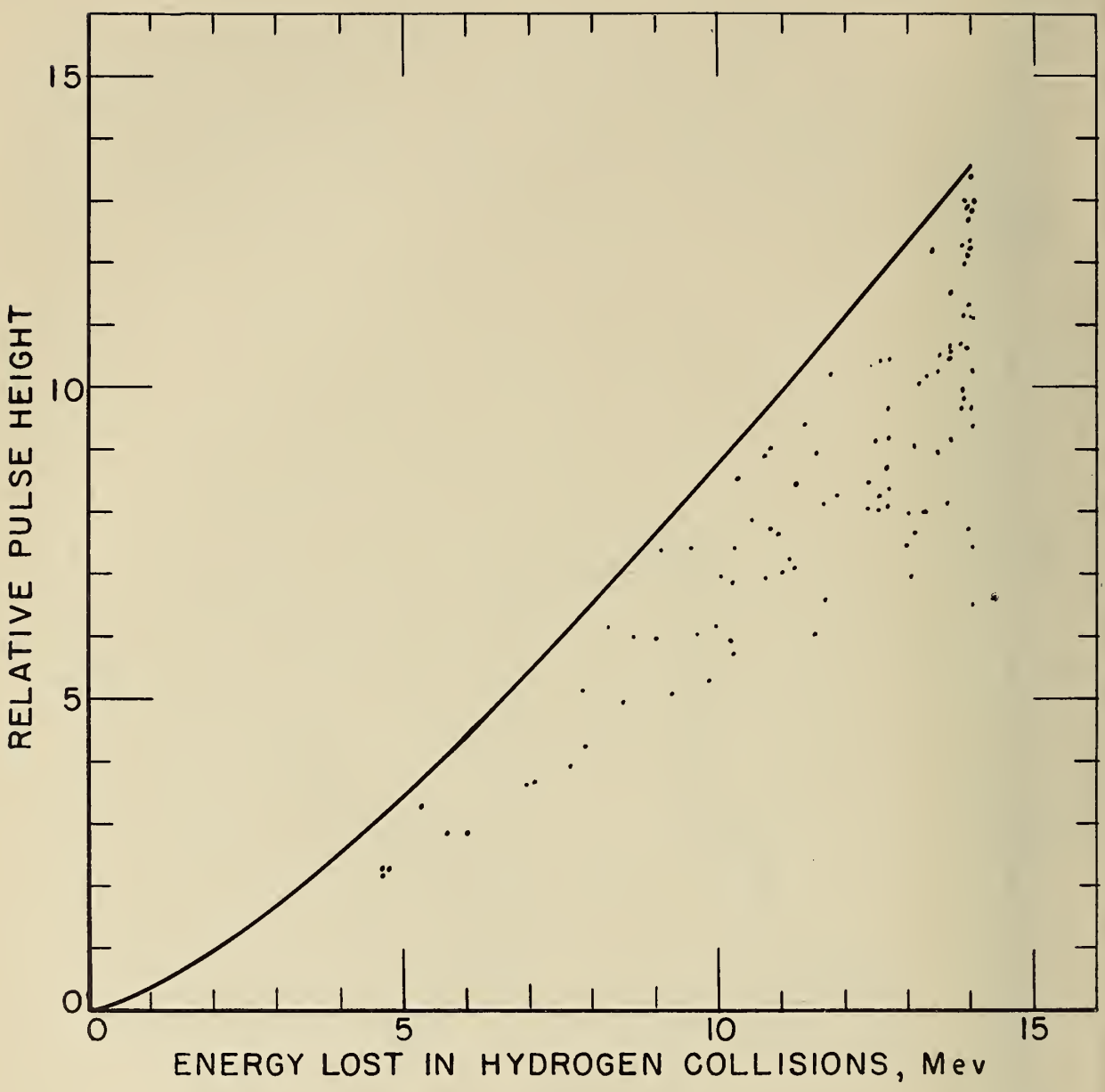
1.5
FRACTION OF 14 Mev PROTON PULSE HEIGHT

Fig. 1(a)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0
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5
10
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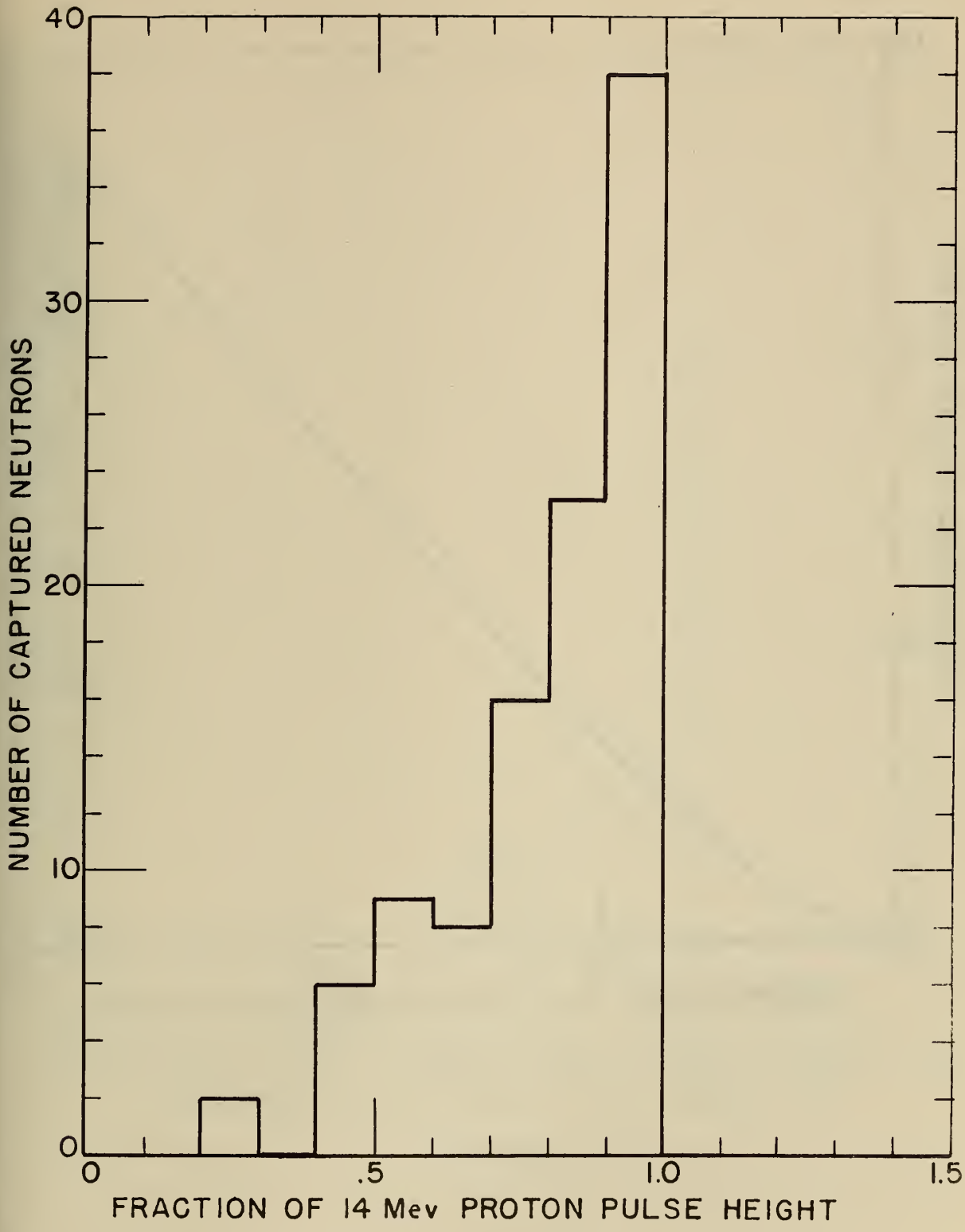
ENERGY LOST IN HYDROGEN COLLISIONS, Mev

Fig. 1(b)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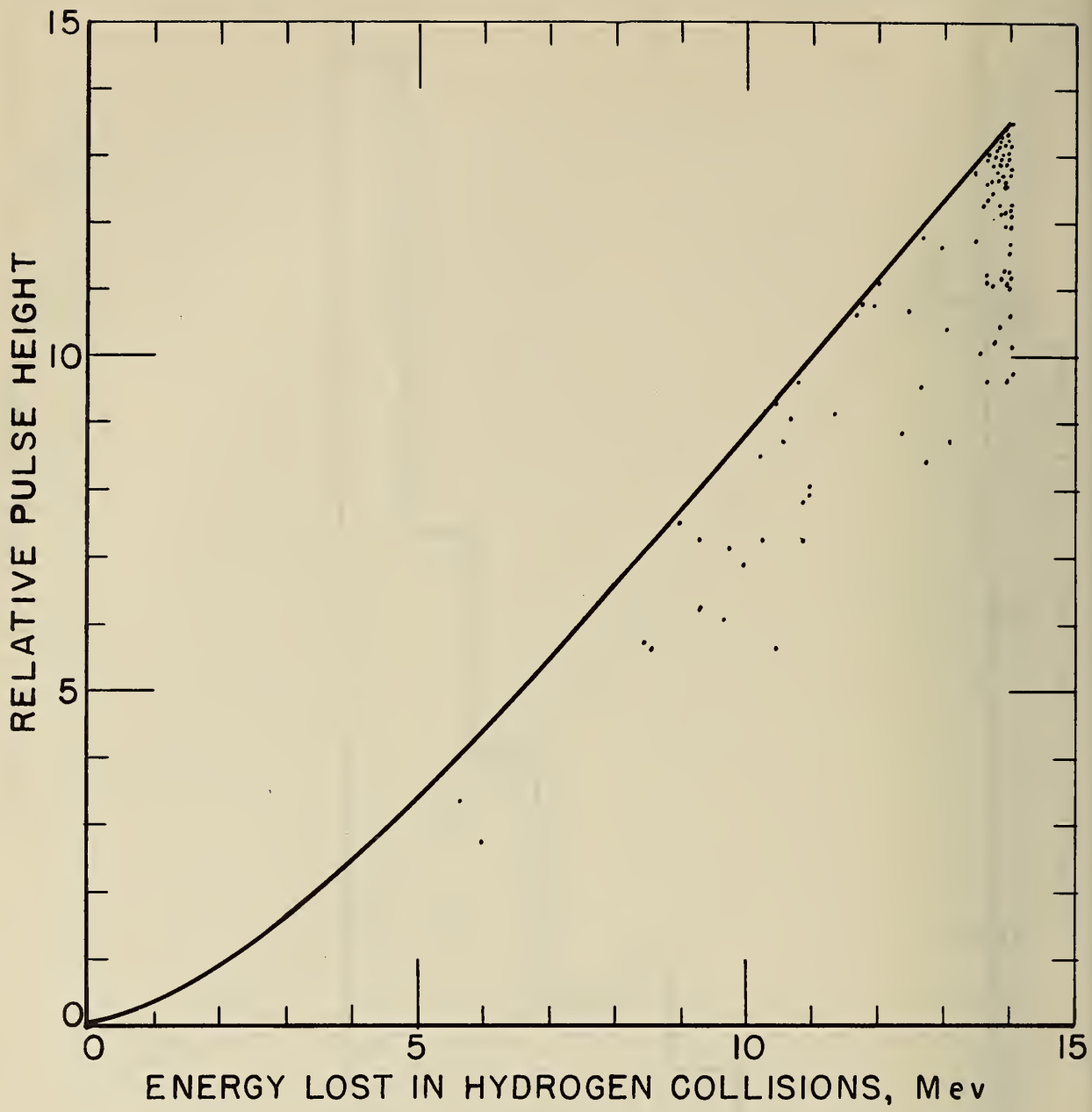
FRACTION OF 14 Mev PROTON PULSE HEIGHT

Fig. 2(a)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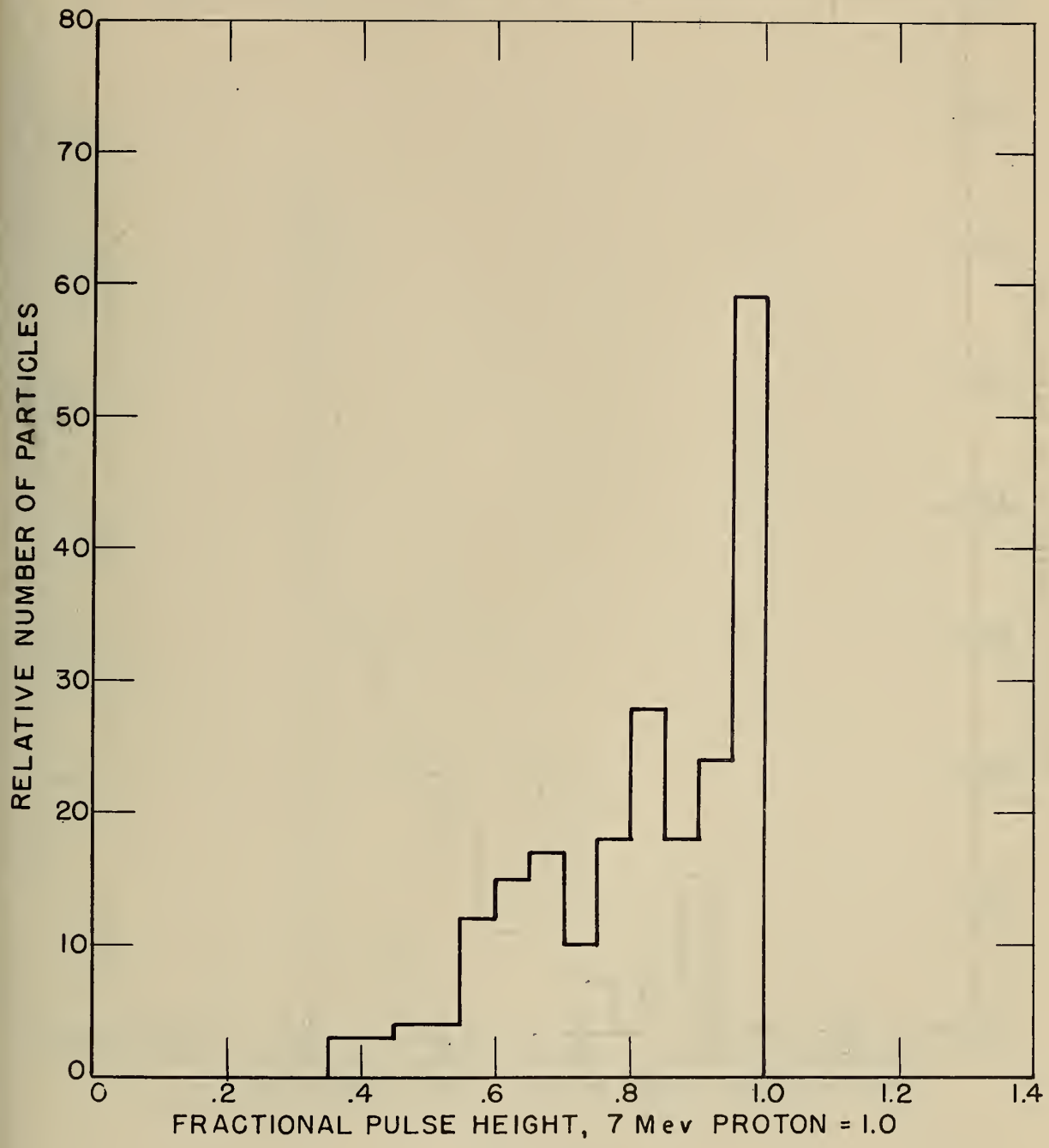
ENERGY LOST IN HYDROGEN COLLISIONS, Mev

Fig. 2(b)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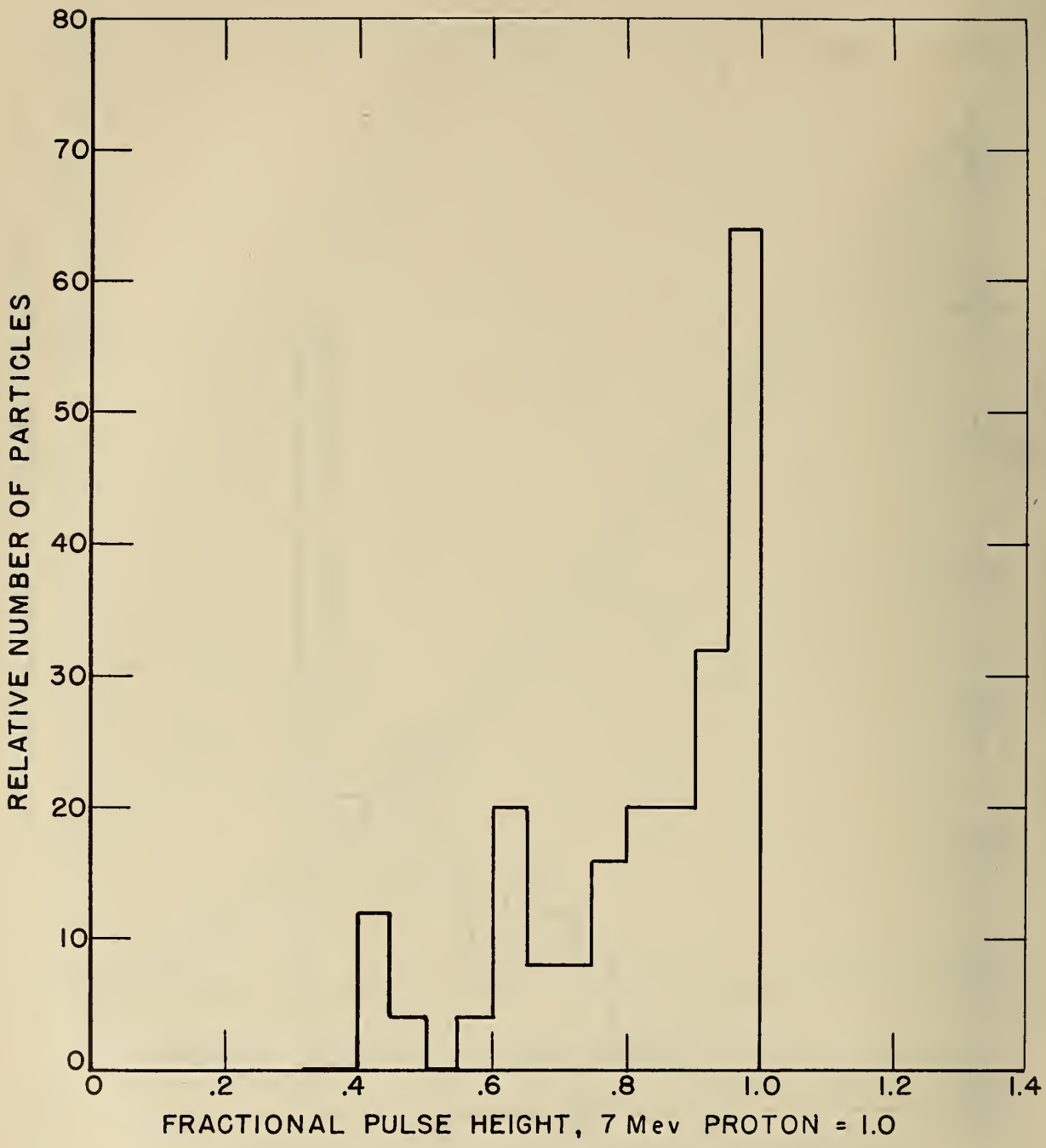
FRACTIONAL PULSE HEIGHT, 7 Mev PROTON = 1.0

Fig. 3(a)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RELATIVE NUMBER OF PARTICLES
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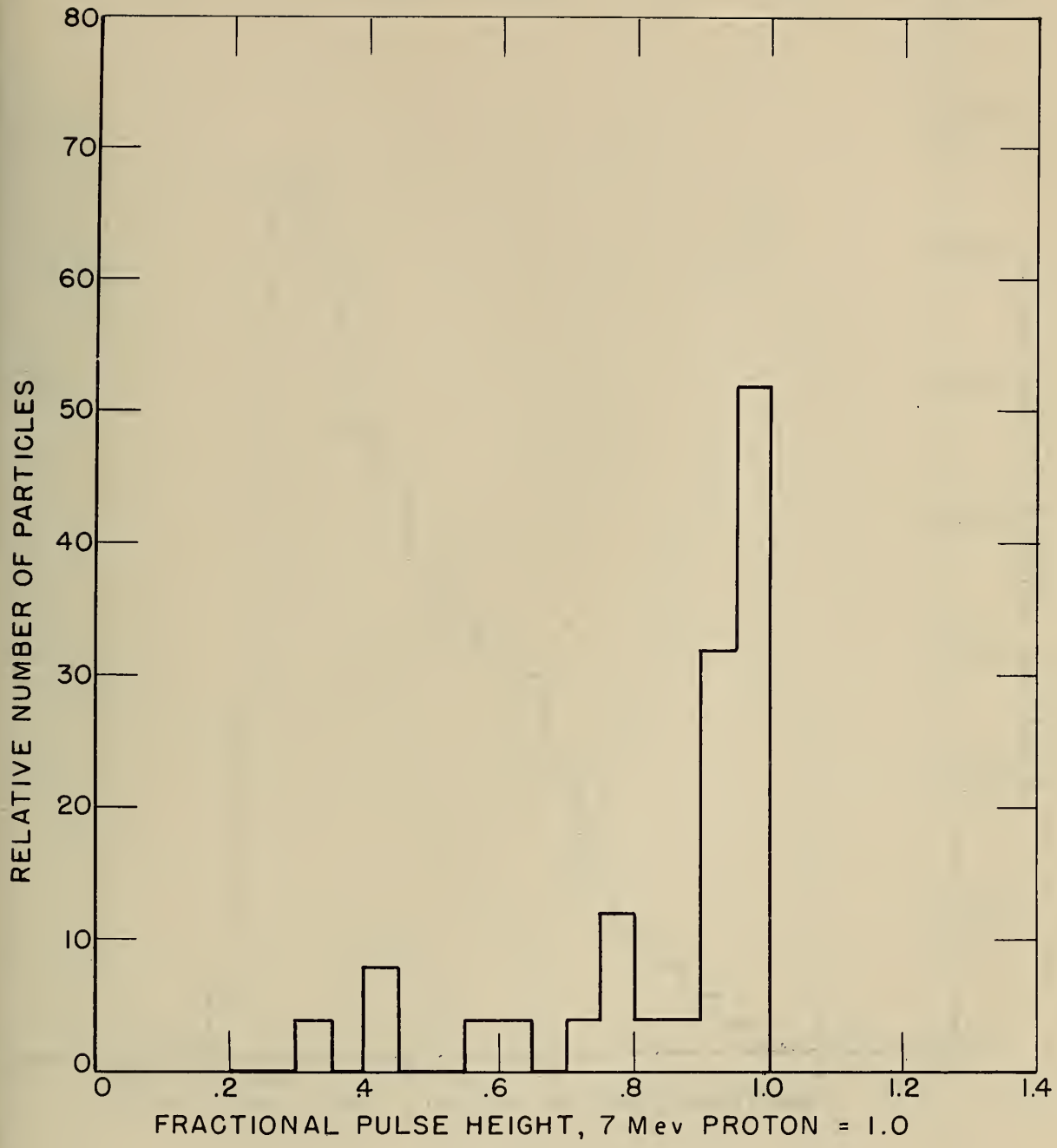
FRACTIONAL PULSE HEIGHT, 7 Mev PROTON = 1.0

Fig. 3(b)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RELATIVE NUMBER OF PARTICLES
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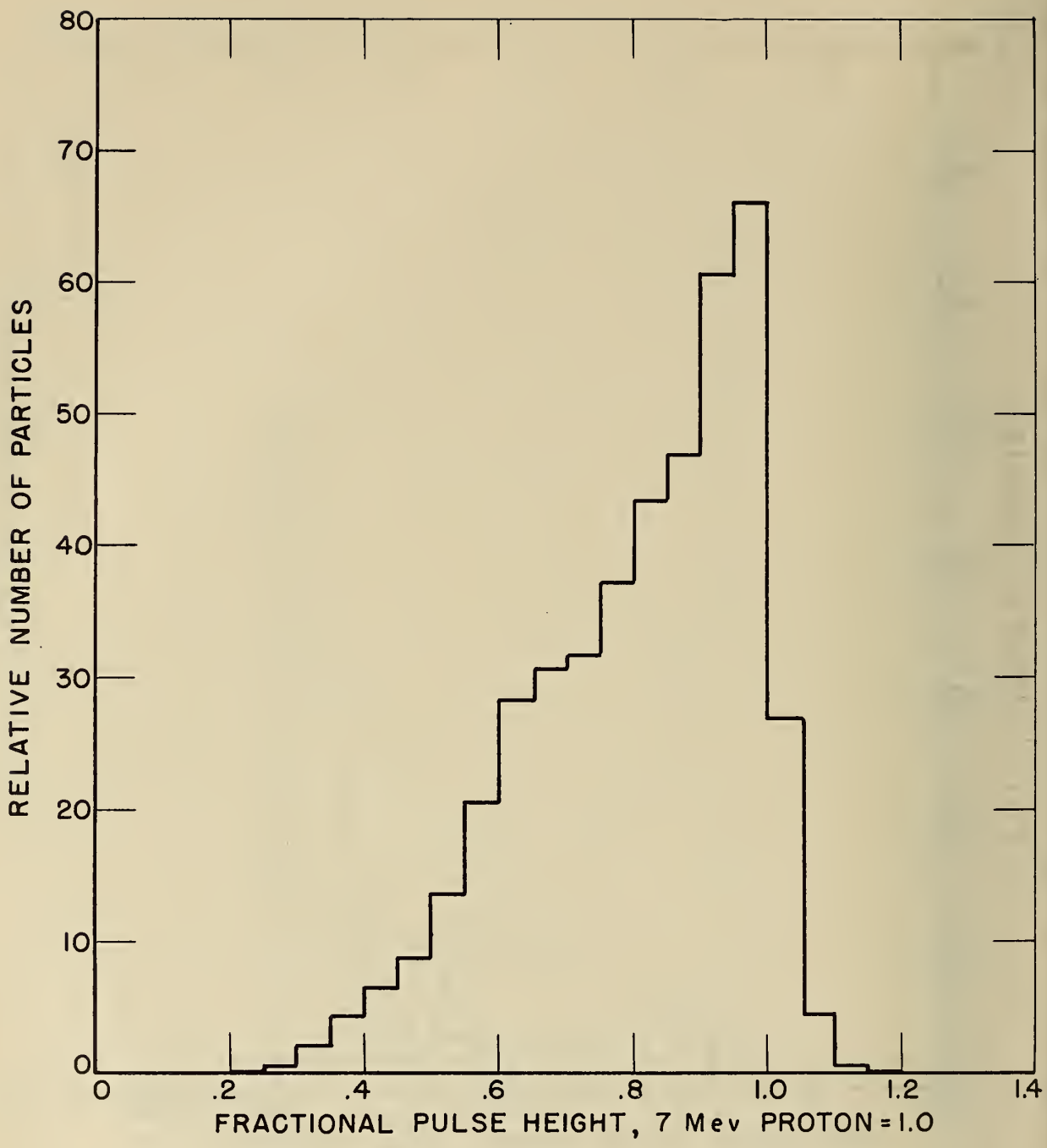
FRACTIONAL PULSE HEIGHT, 7 Mev PROTON = 1.0

Fig. 3(c)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1.0
1.2
1.4
FRACTIONAL PULSE HEIGHT, 7 Mev PROTON = 1.0

Fig. 4(a)

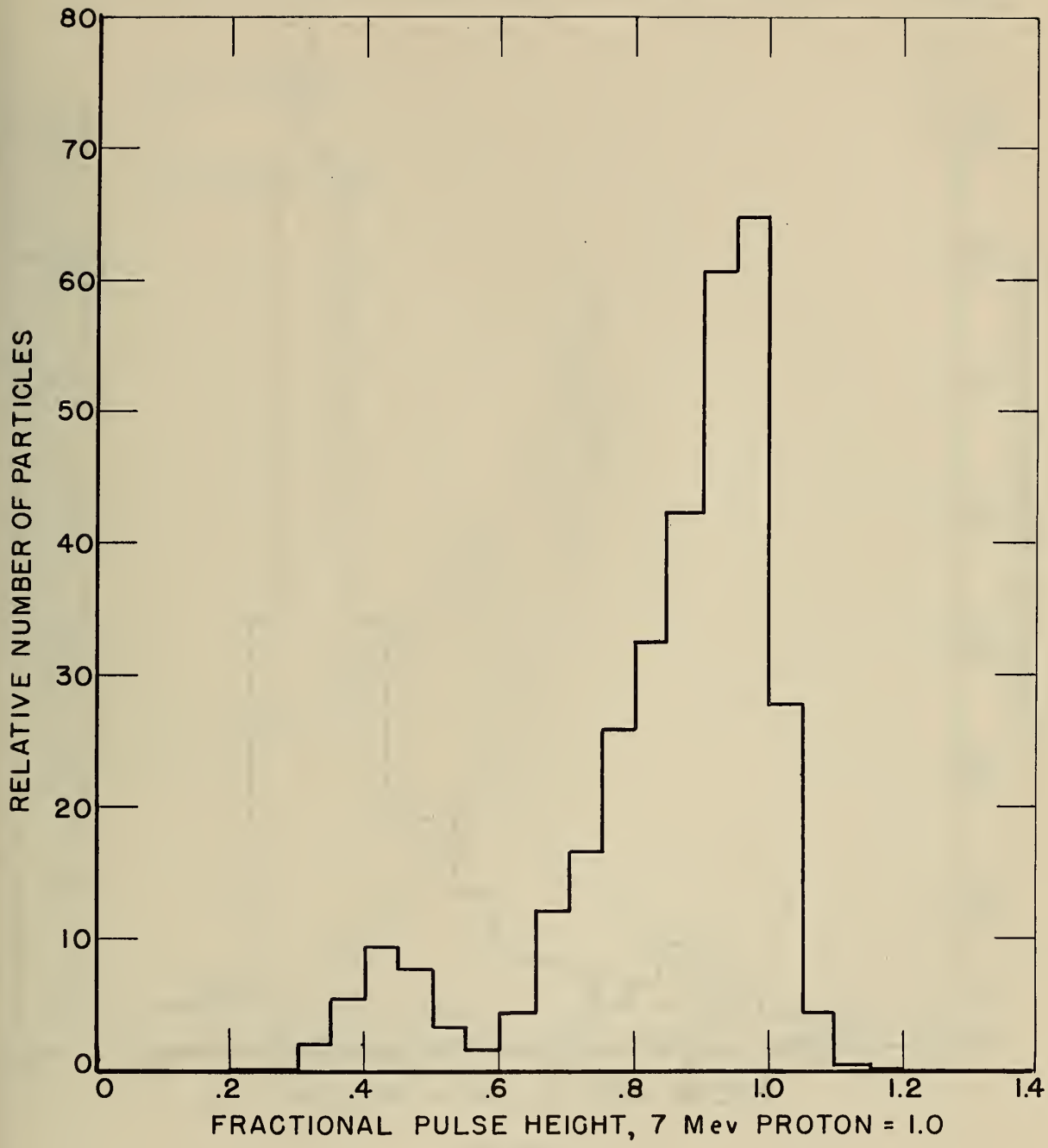
80
70
60
50
40
30
20
10
0
RELATIVE NUMBER OF PARTICLES
0
.2
.4
.6
.8
1.0
1.2
1.4
FRACTIONAL PULSE HEIGHT, 7 Mev PROTON = 1.0

Fig. 4(b)

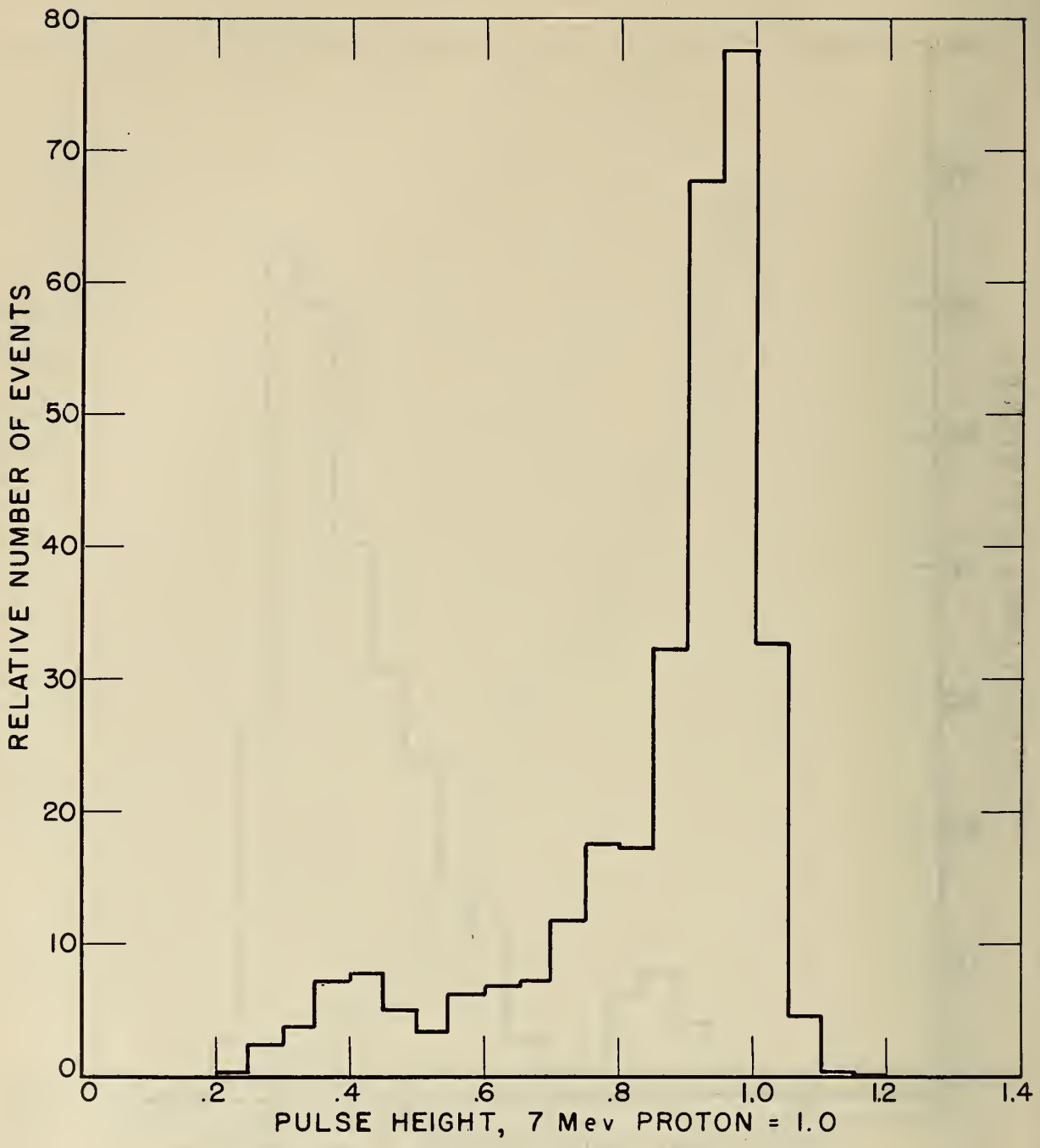
80
70
60
50
40
30
20
10
0
RELATIVE NUMBER OF EVENTS
0
.2
.4
.6
.8
1.0
1.2
1.4
PULSE HEIGHT, 7 Mev PROTON = 1.0

Fig. 4(c)

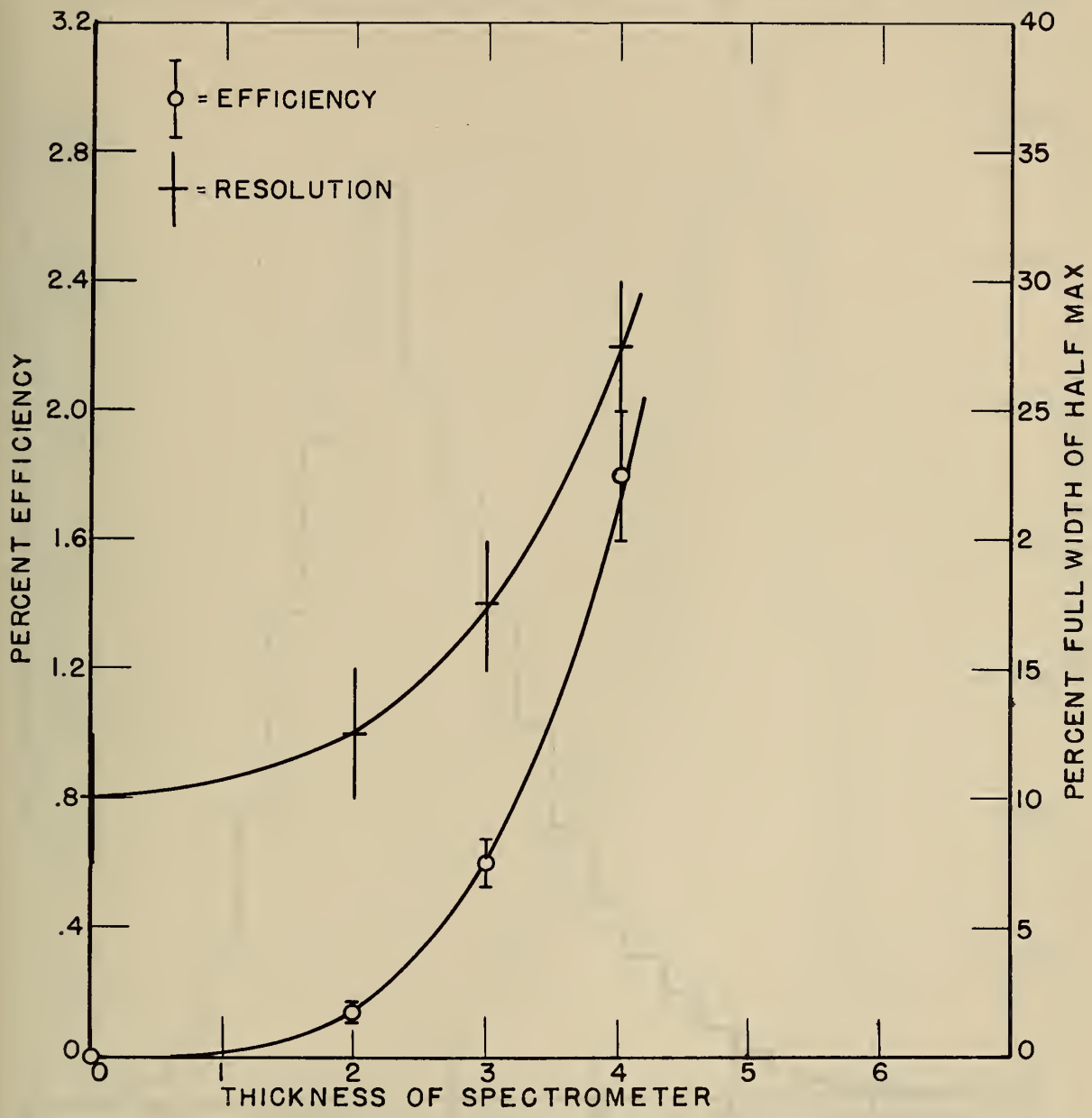
= EFFICIENCY
= RESOLUTION
PERCENT EFFICIENCY
PERCENT FULL WIDTH OF HALF MAX
THICKNESS OF SPECTROMETER
3.2
2.8
2.4
2.0
1.6
1.2
.8
.4
0
40
35
30
25
2
15
10
5
0
0
1
2
3
4
5
6

Fig. 5

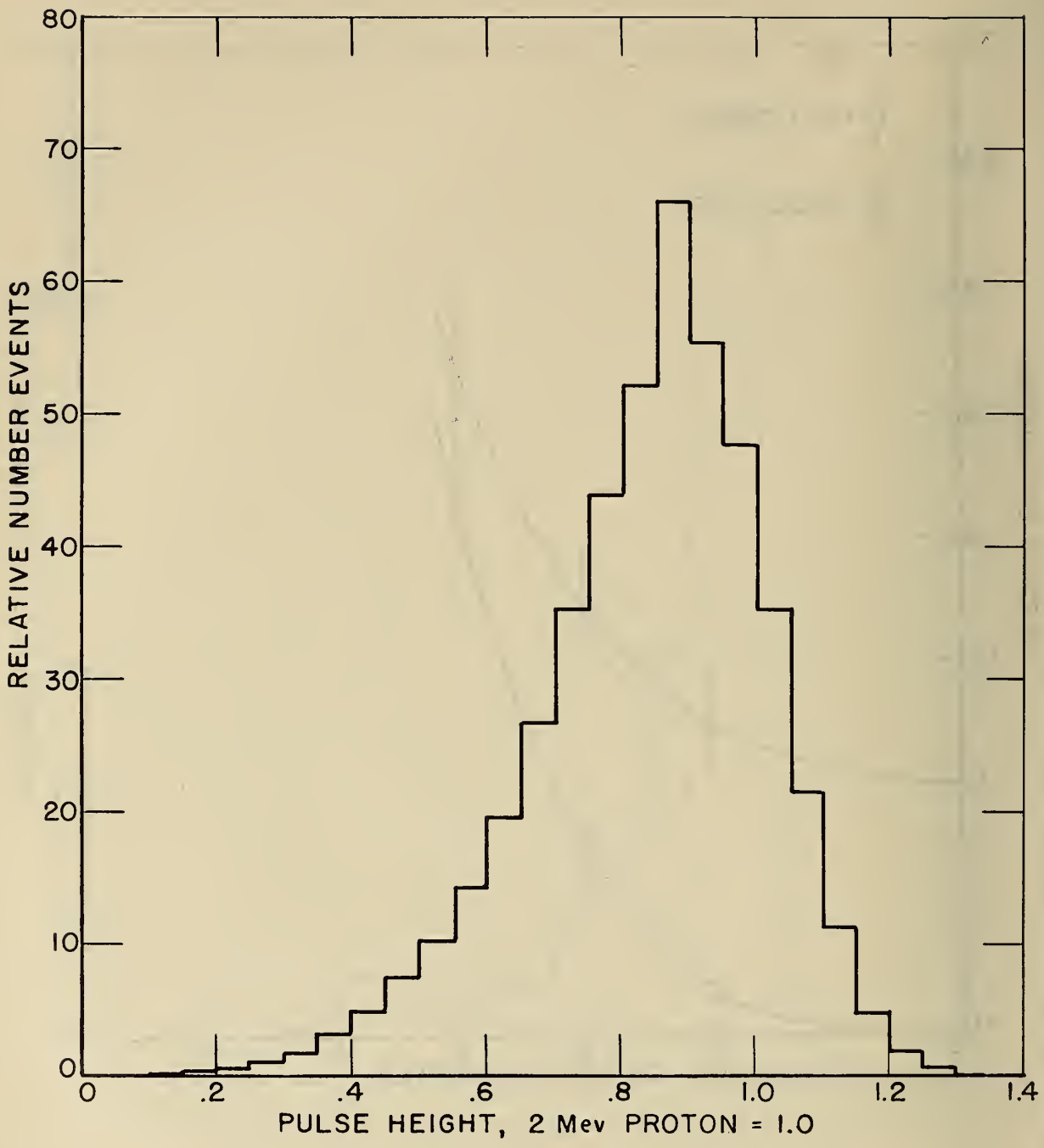
80
70
60
50
40
30
20
10
0
RELATIVE NUMBER EVENTS
0
.2
.4
.6
.8
1.0
1.2
1.4
PULSE HEIGHT, 2 Mev PROTON = 1.0

Fig. 6(a)

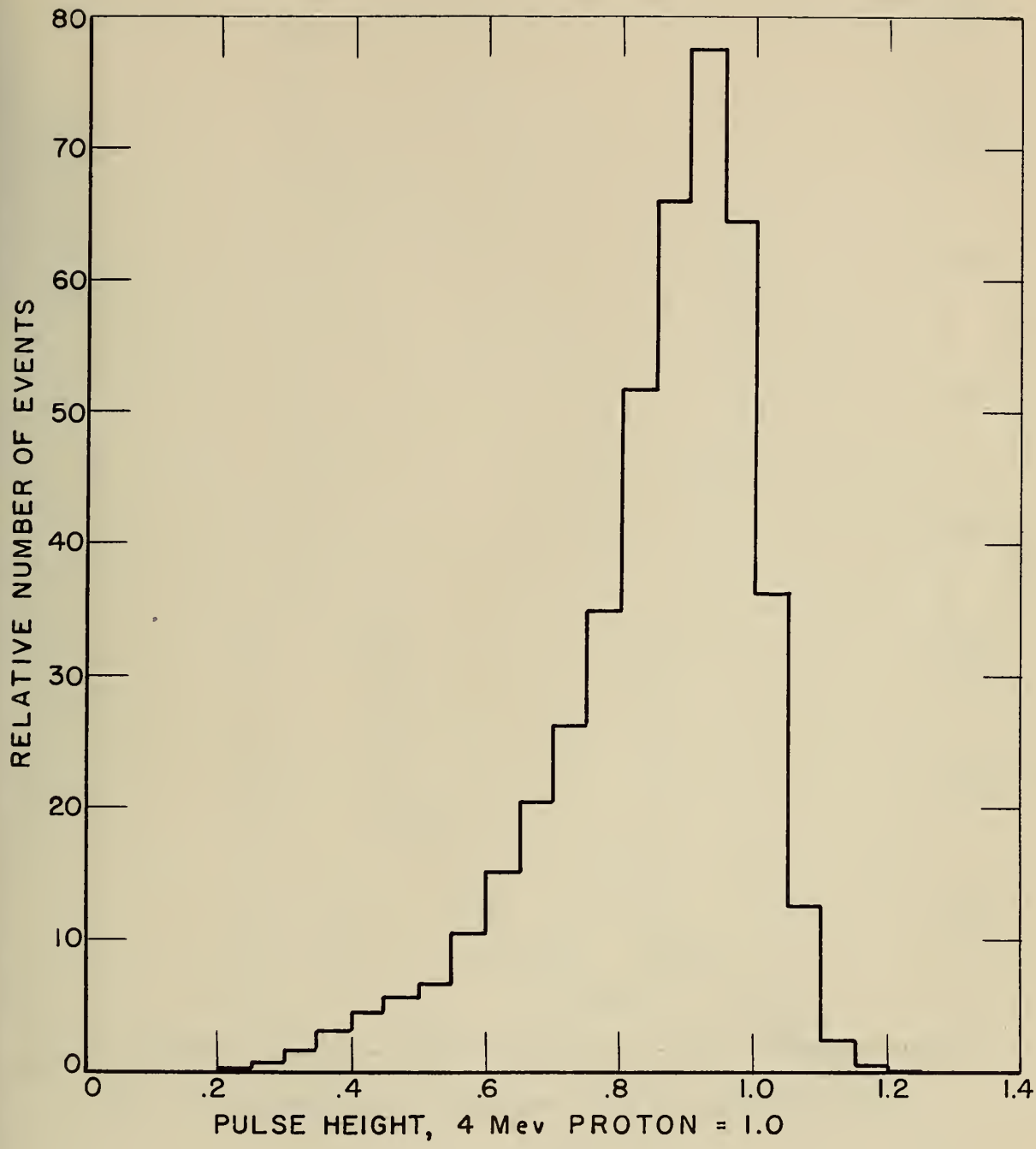
80
70
60
50
40
30
20
10
0
RELATIVE NUMBER OF EVENTS
0
.2
.4
.6
.8
1.0
1.2
1.4
PULSE HEIGHT, 4 Mev PROTON = 1.0

Fig. 6(b)

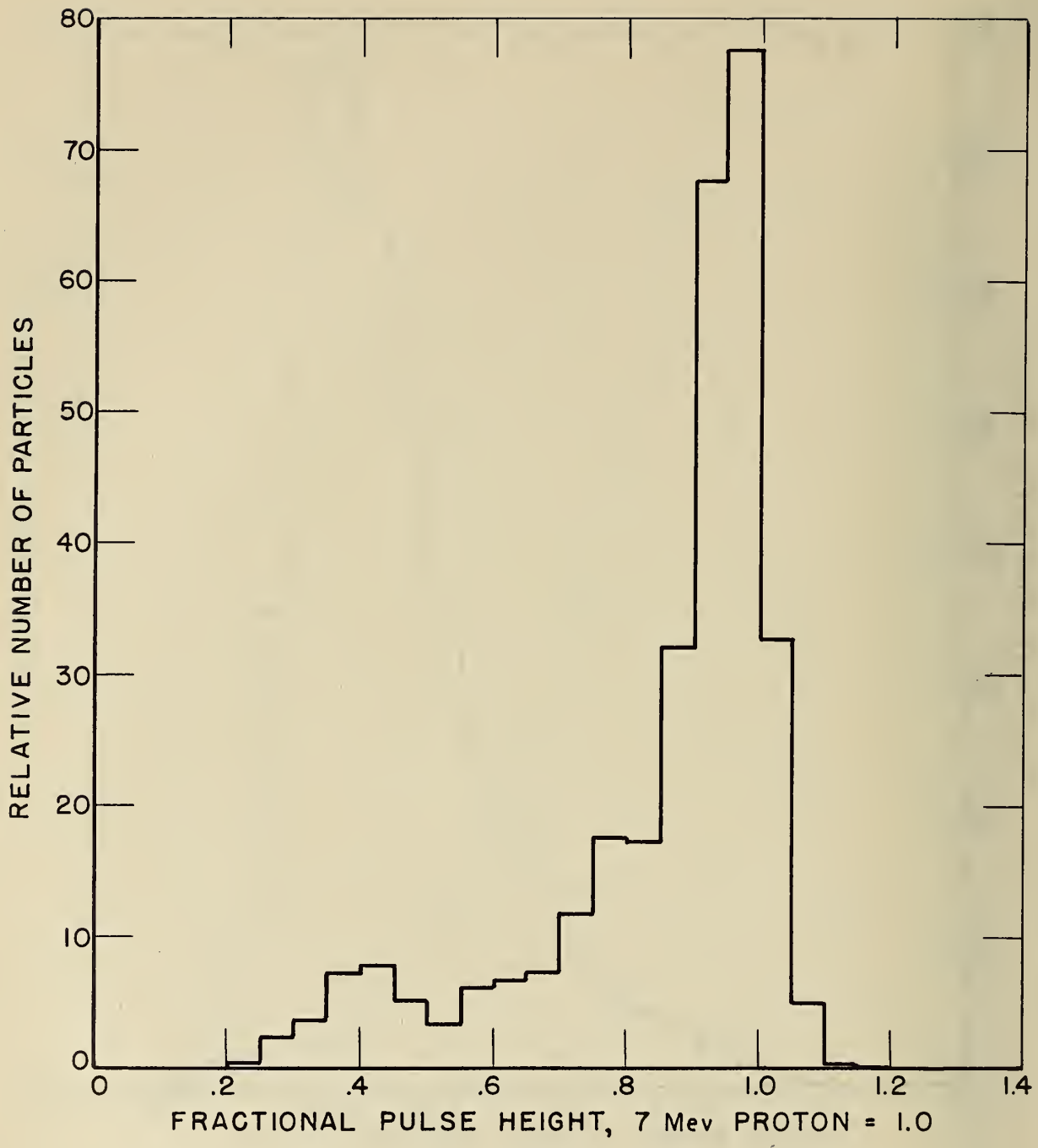
80
70
60
50
40
30
20
10
0
RELATIVE NUMBER OF PARTICLES
0
.2
.4
.6
.8
1.0
1.2
1.4
FRACTIONAL PULSE HEIGHT, 7 Mev PROTON = 1.0

Fig. 6(c)

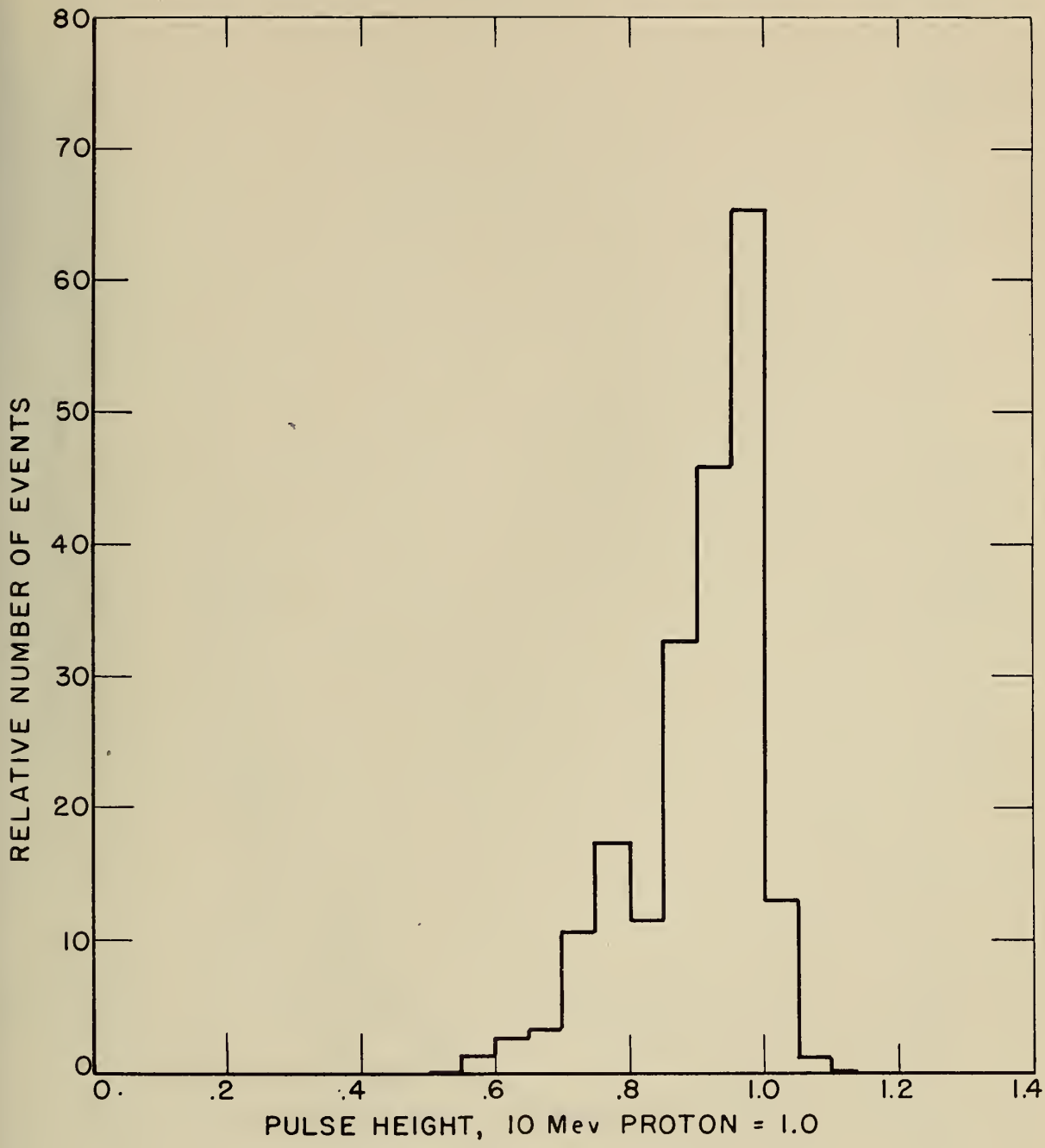
80
70
60
50
40
30
20
10
0
RELATIVE NUMBER OF EVENTS
0.
.2
.4
.6
.8
1.0
1.2
1.4
PULSE HEIGHT, 10 Mev PROTON = 1.0

Fig. 6(d)

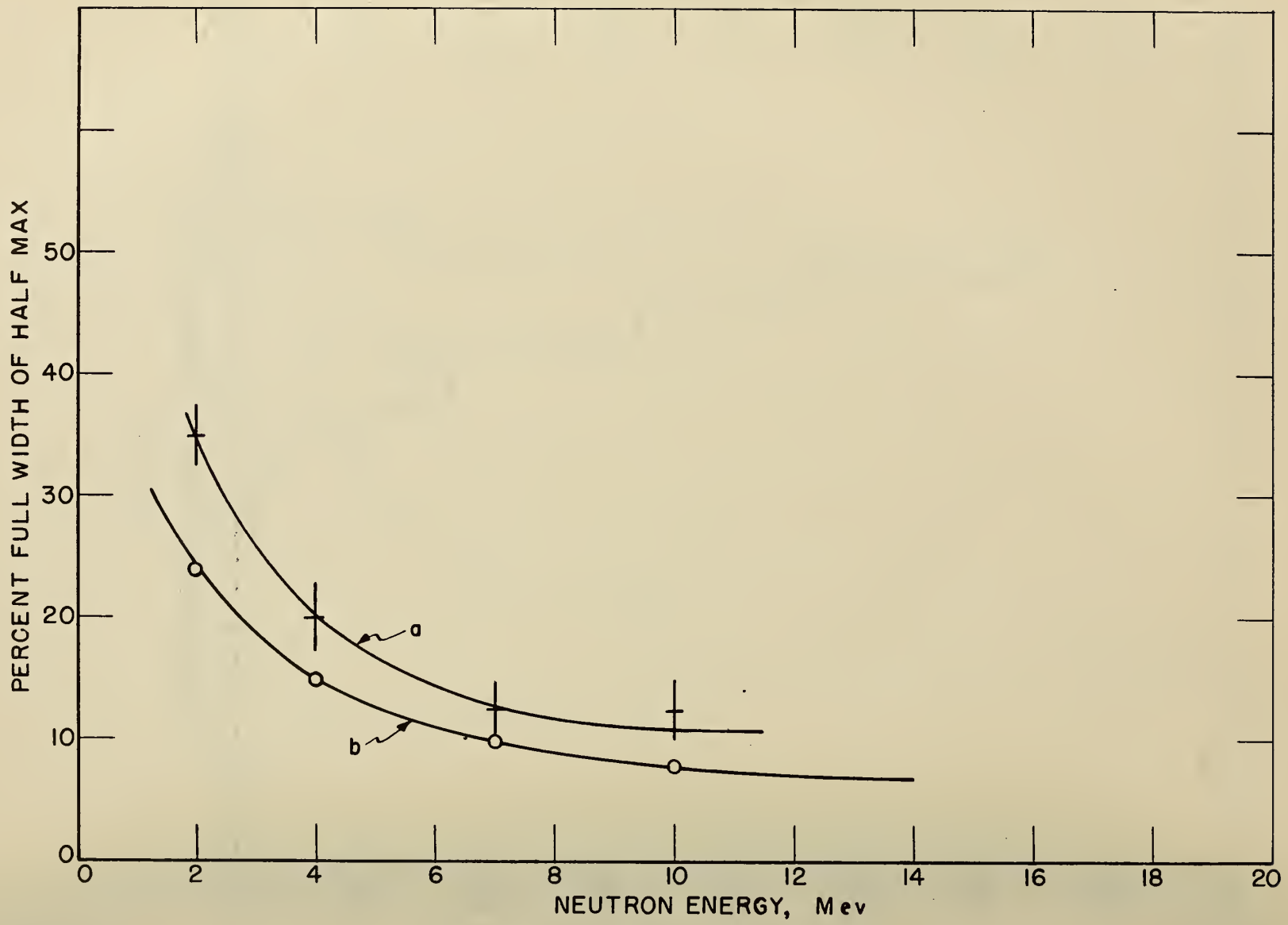
PERCENT FULL WIDTH OF HALF MAX
0
10
20
30
40
50
0
2
4
6
8
10
12
14
16
18
20
NEUTRON ENERGY, Mev
a
b

Fig. 7

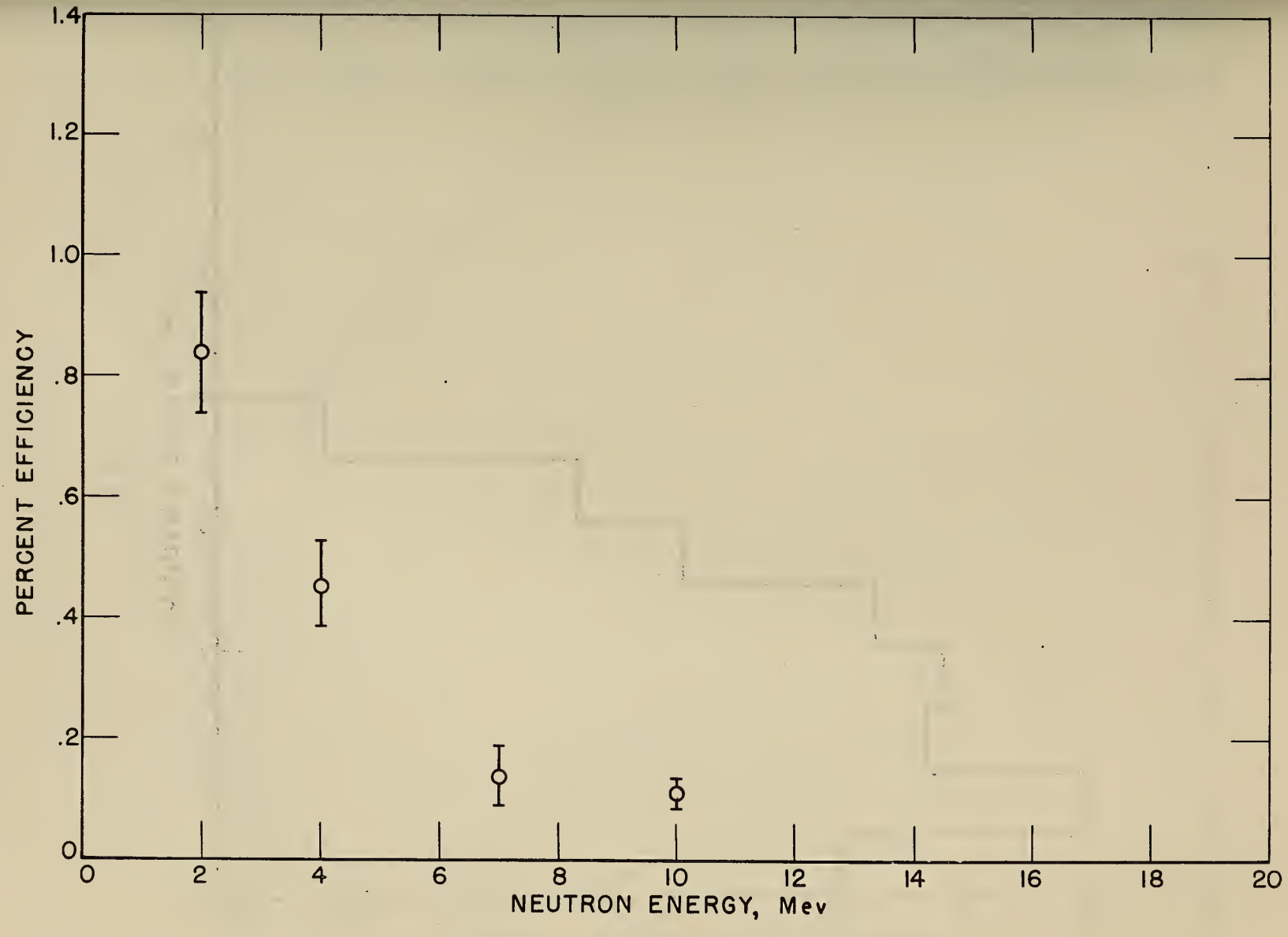
1.4
1.2
1.0
.8
.6
.4
.2
0
PERCENT EFFICIENCY
0
2
4
6
8
10
12
14
16
18
20
NEUTRON ENERGY, Mev

Fig. 8

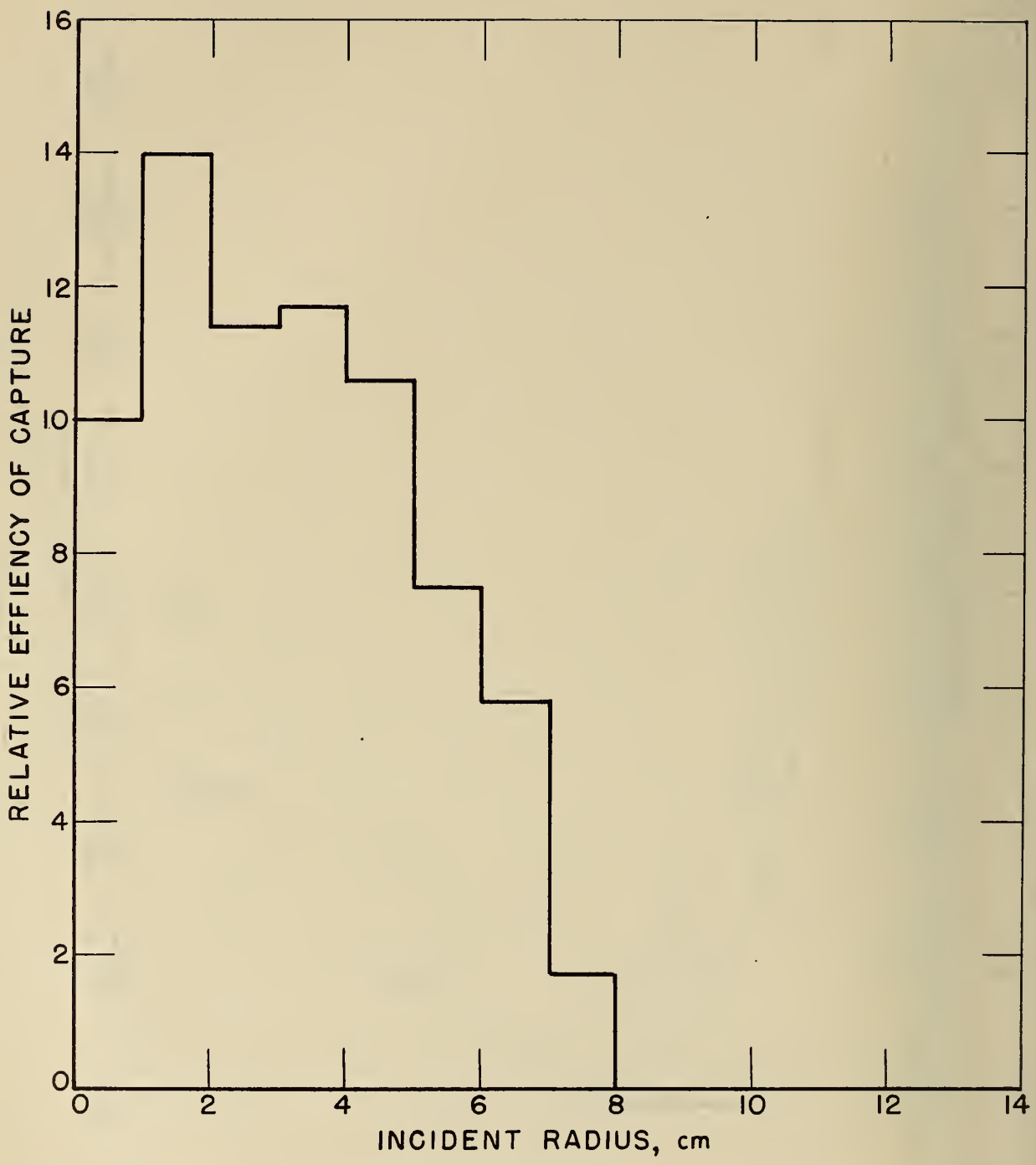
RELATIVE EFFIENCY OF CAPTURE
INCIDENT RADIUS, cm
0
2
4
6
8
10
12
14
16

Fig. 9

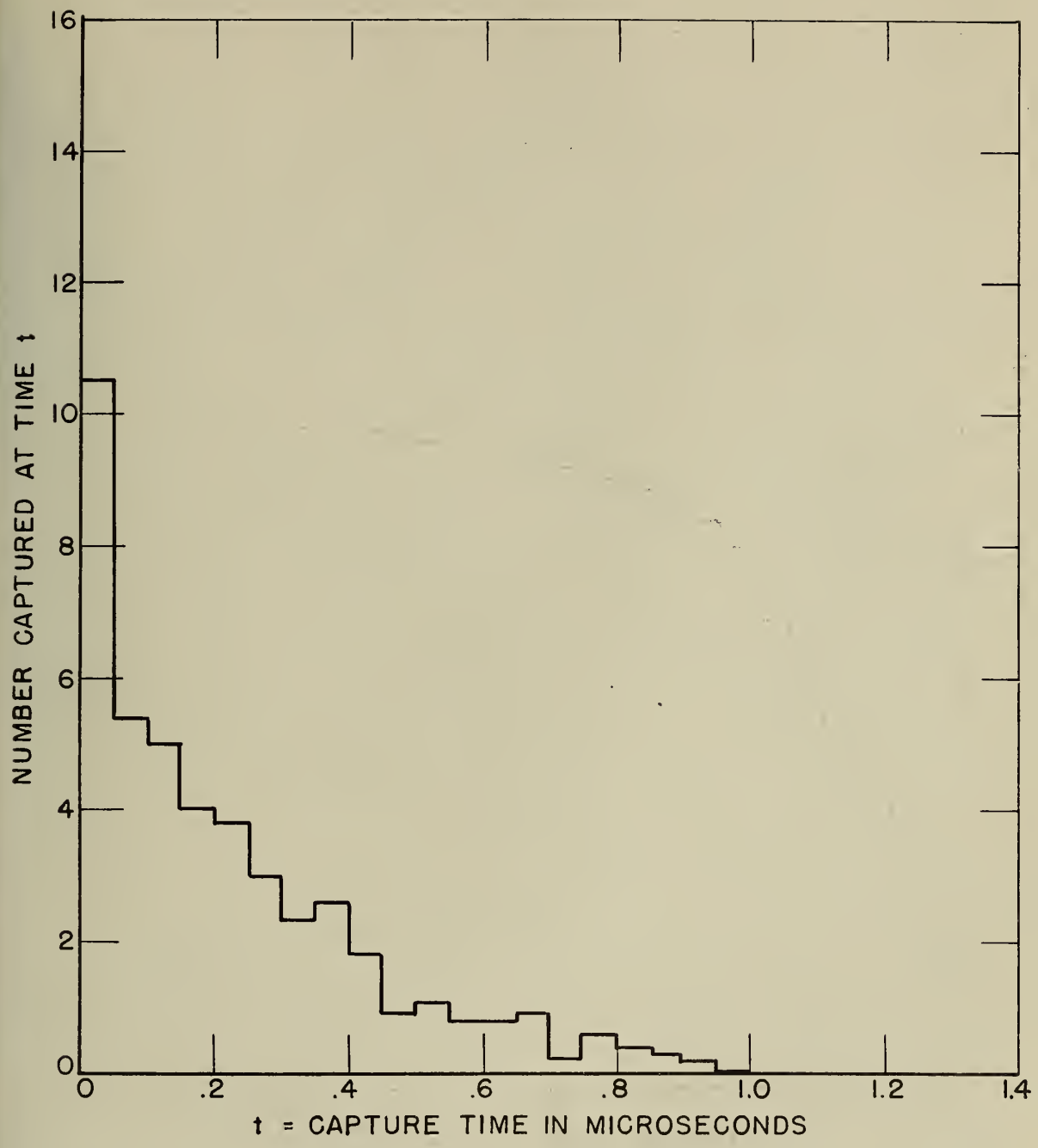
16
14
12
10
8
6
4
2
0
NUMBER CAPTURED AT TIME t
0
.2
.4
.6
.8
1.0
1.2
1.4
t = CAPTURE TIME IN MICROSECONDS

Fig. 10(a)

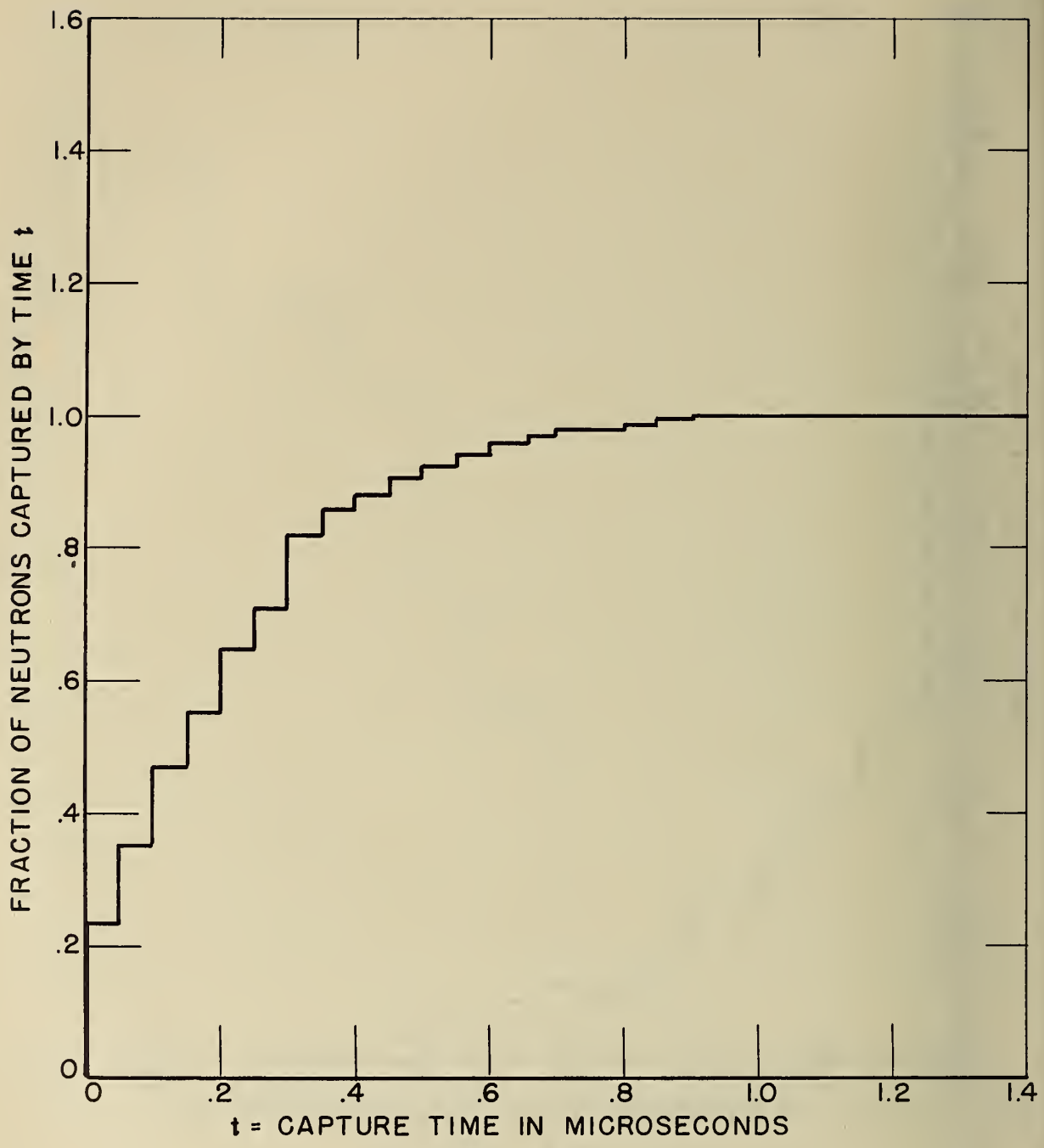
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
FRACTION OF NEUTRONS CAPTURED BY TIME t
0
.2
.4
.6
.8
1.0
1.2
1.4
t = CAPTURE TIME IN MICROSECONDS

Fig. 10(b)

U. S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS
A. V. Astin, *Director*

THE NATIONAL BUREAU OF STANDARDS

The scope of activities of the National Bureau of Standards at its headquarters in Washington, D. C., and its major laboratories in Boulder, Colo., is suggested in the following listing of the divisions and sections engaged in technical work. In general, each section carries out specialized research, development, and engineering in the field indicated by its title. A brief description of the activities, and of the resultant publications, appears on the inside front cover.

WASHINGTON, D. C.

Electricity and Electronics. Resistance and Reactance. Electron Devices. Electrical Instruments. Magnetic Measurements. Dielectrics. Engineering Electronics. Electronic Instrumentation. Electrochemistry.

Optics and Metrology. Photometry and Colorimetry. Optical Instruments. Photographic Technology. Length. Engineering Metrology.

Heat. Temperature Physics. Thermodynamics. Cryogenic Physics. Rheology. Engine Fuels. Free Radicals Research.

Atomic and Radiation Physics. Spectroscopy. Radiometry. Mass Spectrometry. Solid State Physics. Electron Physics. Atomic Physics. Neutron Physics. Radiation Theory. Radioactivity. X-rays. High Energy Radiation. Nucleonic Instrumentation. Radiological Equipment.

Chemistry. Organic Coatings. Surface Chemistry. Organic Chemistry. Analytical Chemistry. Inorganic Chemistry. Electrodeposition. Molecular Structure and Properties of Gases. Physical Chemistry. Thermochemistry. Spectrochemistry. Pure Substances.

Mechanics. Sound. Mechanical Instruments. Fluid Mechanics. Engineering Mechanics. Mass and Scale. Capacity, Density, and Fluid Meters. Combustion Controls.

Organic and Fibrous Materials. Rubber. Textiles. Paper. Leather. Testing and Specifications. Polymer Structure. Plastics. Dental Research.

Metallurgy. Thermal Metallurgy. Chemical Metallurgy. Mechanical Metallurgy. Corrosion. Metal Physics.

Mineral Products. Engineering Ceramics. Glass. Refractories. Enameled Metals. Concreting Materials. Constitution and Microstructure.

Building Technology. Structural Engineering. Fire Protection. Air Conditioning, Heating, and Refrigeration. Floor, Roof, and Wall Coverings. Codes and Safety Standards. Heat Transfer.

Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics.

Data Processing Systems. SEAC Engineering Group. Components and Techniques. Digital Circuitry. Digital Systems. Anolog Systems. Application Engineering.

- Office of Basic Instrumentation.
- Office of Weights and Measures.

BOULDER, COLORADO

Cryogenic Engineering. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Gas Liquefaction.

Radio Propagation Physics. Upper Atmosphere Research. Ionospheric Research. Regular Propagation Services. Sun-Earth Relationships. VHF Research. Ionospheric Communication Systems.

Radio Propagation Engineering. Data Reduction Instrumentation. Modulation Systems. Navigation Systems. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Radio Systems Application Engineering. Radio-Meteorology.

Radio Standards. High Frequency Electrical Standards. Radio Broadcast Service. High Frequency Impedance Standards. Electronic Calibration Center. Microwave Physics. Microwave Circuit Standards.

NBS