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ABSTRACT

Although many types of fast neutron spectrometers capable of detecting and measuring the energy of neutrons which arrive at the spectrometer from any direction have been described by Wallace[1] and Kim,[2] only four have been developed to a stage at which they can be conveniently used. One of these, the threshold detector, is being described in another paper at this Symposium by A. R. Smith.[3] This paper treats the remaining three: emulsion, liquid scintillators, and ^{3}He.

THREE TYPES OF 4π NEUTRON SPECTROMETERS

EMULSION

Nuclear track emulsion offers a very simple experimental method by which neutron spectra may be measured. Neutrons incident on emulsion produce proton recoils in the emulsion, and, after appropriate development, the lengths of the proton recoil tracks can be measured to permit evaluation of the energy the proton had. Since a neutron can produce a distribution of proton energies, it is not possible to secure the energy of a single neutron by observing the random recoil of a proton which it produces, unless more facts about the geometry of this particular collision are also known. Fortunately, for neutrons below 20 MeV, the recoils are isotropic in the center-of-mass coordinate system. This fact allows the energy of a large number of monoenergetic neutrons to be evaluated by measuring the distribution of their proton recoil energies. More details of this relationship are contained in the Appendix.

The measurement of track lengths in the emulsion is quite time-consuming. The slow readout has recently been partially automated by Lehman[4-7] and others. The semiautomatic track-scanning apparatus consists of a standard research microscope fitted with a special stage. The lead screws and focus screw are connected to shaft-position encoders which resolve 1000 units per turn, or 0.36 deg of shaft rotation. The encoders produce an electrical signal, which is converted from binary to decimal units and used to drive a card punch, which enters in the card units of microns of stage translation or of focus motion. Thus the x, y, z position of the focal point of the microscope objective in the emulsion is automatically punched in the card. Four sets of xyz coordinates are punched in each card for the beginnings and endings of two tracks. The humidity and other control data are also punched. The coordinates of both ends of a single track may be conveniently recorded in 2.5 seconds. This does not include the scanning time for locating the end points; however, in practice the minimum time averaged over an hour of scanning is about 12 sec per track.

An essential feature of the method is that the tracks are selected by a "random walk" process as the observer scans the emulsion with the microscope. It has been shown that this type of sampling does not produce any bias in the data.

The computer program multiplies the z-coordinate difference between the two ends of a track by a measured shrinkage factor and then computes the straight-line length of the proton track. A correction is applied for the sampling bias, which favors short tracks because long tracks are more likely to escape from the emulsion. A distribution of proton energies is then printed out and plotted on the basis of known range-energy data for emulsion. A typical proton energy distribution for a monoenergetic source of neutrons is shown in Fig. 1. A smooth curve is then passed through the proton distribution, and the slopes are used to compute the incident neutron spectrum shown in Fig. 2 by the relation

$$N_n(E)dE = -\frac{dN_p(E)}{dE}\,\frac{EdE}{4\pi n\sigma_{np}(E)}\ , \qquad (1)$$

where $N_n(E)$ is the neutron spectrum, $N_p(E)$ is the proton spectrum (converted from track lengths), n is the number of target protons per cm^2, and $\sigma_{np}(E)$ is the n-p elastic cross section.

The experimentally determined resolution for a 14-MeV source, including all the various sources of error, for several thousand tracks scanned, is between 5 and 10%. This result is more precise than the direct measurement of track length and scattering angle, although it requires that a fairly large number of tracks be scanned.

This emulsion technique has been used on several neutron sources, both monoenergetic and with broad spectra, as well as on accelerator field measurements. It has also been extensively used to measure the spectra inside a tissue-equivalent phantom.[8]

Recently an attempt has been made to extend the useful energy range of emulsion for the detection of neutrons of more than 20 MeV. Individual proton recoil tracks become too long to follow conveniently and too diffuse to see at energies of more than about 30 MeV. Remy[9] has looked at stars produced in emulsion by neutrons from 20 to 300 MeV and has shown, as seen in Fig. 3, that the average number of grey prongs per star is proportional to the incident neutron energy. This technique does not seem to be capable of giving any spectral information other than the average energy, but its convenience makes it the method of choice in this energy range, where measuring even the average energy was difficult before.

LIQUID SCINTILLATOR

Now that proton- and electron-produced pulses in a liquid scintillator can be distinguished easily by electronic methods, the proton recoils from incident neutrons can be rapidly measured by observing these recoils in a special liquid scintillator with a photomultiplier tube. The sensitivity of such a spectrometer is very high compared with all other spectrometers. Several problems that arise in this detector have been solved recently by Young.[10] He has used a model which takes both single and double recoils into consideration. In addition to the escape of recoil protons from the surface of the detector, carbon recoils and nonlinear scintillator light output must also be taken into consideration. Young has developed a method by which the measured pulse-height spectrum can be inverted and corrected for these effects, thus producing the incident-neutron spectrum. He has provided a method for calibrating a scintillator by locating the Compton edge of a monoenergetic γ ray. He has also carried out an experimental investigation of the effect on the resolution of changing the dimensions of the liquid scintillator.

The spectrometer works well from 1.5 to 15 MeV. The detector may be quite small, since it has been found that the highest resolution occurs for a liquid thickness of 0.5 cm. The liquid scintillator spectrometer lends itself to more rapid accumulation of data and much better statistics than the emulsion method, but it is more complex to set up, and thus far the resolution is not so high

HELIUM-3

The use of ^{3}He as the counting gas in a proportional counter for neutron spectroscopy was first suggested by Batchelor.[11, 12] The reaction produced by neutrons is

$$^3\mathrm{He}(n, p)T + 764 \text{ keV}.$$

The proton receives most of the neutron's energy and the 764 keV. At energies above about 1 MeV several competing effects must be considered. The energy of the tritons, the escape of the proton from the sensitive volume, the production of deuterons, and multiple processes make corrections necessary. The first problem to be attacked was that of protons hitting the walls. Brown[13] made a proportional counter with a wall which was actually a ring of anticoincident proportional counters all in a single envelope. Although this does work, the construction is very complex. Wang[14] showed that the effect of the wall could be more efficiently eliminated by a mathematical correction to the measured pulse-height spectrum. This correction also eliminated the loss of protons through the ends of the counters, which the anticoincidence counters could not do.

One of the principal advantages of the ^{3}He proportional counter is that because of its low Z it is quite insensitive to γ rays. Thus the remaining problem of eliminating ^{3}He elastic recoils is the last remaining major problem of this detector. Sayres[15-17] has made a very important contribution to neutron spectroscopy by showing that the longer rise time of the desired proton pulses than the competing ^{3}He can be used to electronically discriminate between them. The energy resolution of a monoenergetic neutron source measured by this method may be better than 5%. The ^{3}He recoils are almost completely eliminated for energies below 5 MeV. The end effects and γ-ray counts are also greatly reduced by the pulse-shape discrimination. The sensitivity of the counter to proton recoils is about 60% of its value without this discrimination. Combining the electronic techniques of Sayres and the computations of Wang will probably make it possible to extend the effective upper energy limit of the ^{3}He technique to 15 or 20 MeV.

The ^{3}He spectrometer has the advantage that its electronics are simple and widely available. The results are immediately available, since no computer program is involved in using the Sayres method. It is not necessary to count a large number of events, as in the case of the emulsion and liquid scintillator methods, since no curve smoothing and subsequent differentiation are required. This advantage offsets the lower sensitivity of the ^{3}He counter due to its lower density than emulsion or liquid scintillator. The ^{3}He spectrometer has been used on the PuF_4 spectrum to demonstrate the technique of eliminating the wall effect at this Laboratory. Sayres[15] at Columbia has measured the spectra, among many others, of ^{24}Mg(d, n)^{25}Al,

^{28}Si(d, n)^{29}P, ^{32}S(d, n)^{33}O, and several monoenergetic sources with better than 5% energy resolution.

CONCLUSIONS

A qualitative comparison of these three spectrometers is shown in Fig. 4. These curves contain several assumptions made by Kim[2] of a practical nature, and should be regarded as only qualitatively related. It is seen that the efficiencies of all three decline with increasing energy. Only the ^{3}He spectrometer can detect thermal and epithermal neutrons. An experienced observer can see ^{14}N(n, p)^{14}C reactions in emulsion. When proton recoils are used the minimum energy detectable is about 300 keV. The hump in the ^{3}He curve at about 2 MeV is caused by the neutron cross section. Since both the ^{3}He and emulsion methods have sufficient sensitivity to be used in a human dosimetric measurement, and offer in the emulsion method great experimental simplicity and in the ^{3}He method great resolution and immediate readout, it would seem that these are the most promising methods for further development work.

APPENDIX

Four-π neutron spectrometers, in contrast with the many other types of neutron spectrometers (which depend on a prior knowledge of the neutron-source point or the beam line of the neutrons striking the spectrometer), have been developed relatively recently. For the time-of-flight proton-recoil, ranger, chopper, or crystal types of spectrometer, the source point and perhaps the zero time of origin of the neutrons must be known in order to measure the flight time or to allow the measurement of a recoil angle and associated proton energy. If the point of origin of a neutron is not known, a new approach must be made to measuring neutron-energy spectra. It is conceivable that a collimator could be used to define the incident direction in order to make the resulting proton-recoil angle meaningful. The use of such a collimator would largely defeat the purpose of such a measurement in that it would introduce a large mass around the detector and consequently distort the neutron spectrum.

To avoid this distortion other approaches can be made. If we analyze the statistical distribution of proton-recoil energies resulting from the recoil of monoenergetic neutrons of a few MeV, we find that all energies, from that of the primary neutron on down to zero, are equally probable. This rectangular distribution (shown in Fig. 1) is naturally somewhat distorted by the range-energy relation for these protons and by other instrumental considerations. Nevertheless, in principle, if one assumes that the relation between the incident monoenergetic neutron energy and the resulting proton-recoil spectrum is known for a variety of incident neutron energies, then the pulse-height spectrum produced by an unknown incident-neutron spectrum can be unfolded by a simple differentiation if the ideal rectangular shape is actually or assumed to be present.

If the modified nonrectangular shape is to be taken into consideration, then a matrix inversion process will allow the desired result to be achieved with considerably more effort and less precision. This latter process may introduce some practical but surmountable difficulties, such as negative probability values, which are of course meaningless. These considerations are indicated in Fig. 1 for a δ-function neutron energy distribution and for three mixed δ functions. The extension of this basic idea to more complex spectra is the basis for several of the instruments that we discuss. The actual relation between the proton-recoil distribution and the neutron spectrum is that given in Eq. (1).

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FIGURE LEGENDS

Fig. 1. The proton-recoil energy distribution from a 14-MeV monoenergetic source. The geometric corrections have already been made. The curve is drawn to smooth the data. The two peaks at 0.7 MeV due to $^{14}N(n,p)^{14}C$ events and at 1.4 MeV due to natural α-particle activity in the emulsion have been omitted from the smooth curve, since they do not represent actual elastic proton recoils from neutrons. About 2500 protons are included.

Fig. 2. The points are calculated from the smooth curve in Fig. 1 by use of Eq. (1). The smooth curve is drawn through these points. The scatter in the 5- to 13-MeV region is to be expected since there are few neutrons in this region. The peak from 2 to 4 MeV is probably caused by spurious (d, d) reactions in the target as it picks up deuterons from the beam as the (d, t) reaction proceeds.

Fig. 3. Average number, A, of grey prongs per star versus incident-neutron average energy E_n. Errors shown in A are statistical errors due to counting. Errors shown in E_n are values of $\Delta E_{1/2}$.

Fig. 4. Efficiency vs energy relations for special cases of organic liquid scintillator, nuclear emulsion, and ^{3}He proportional-counter spectroscopes as computed by Kim.[2]

Fig. 5. Idealized scintillator response.

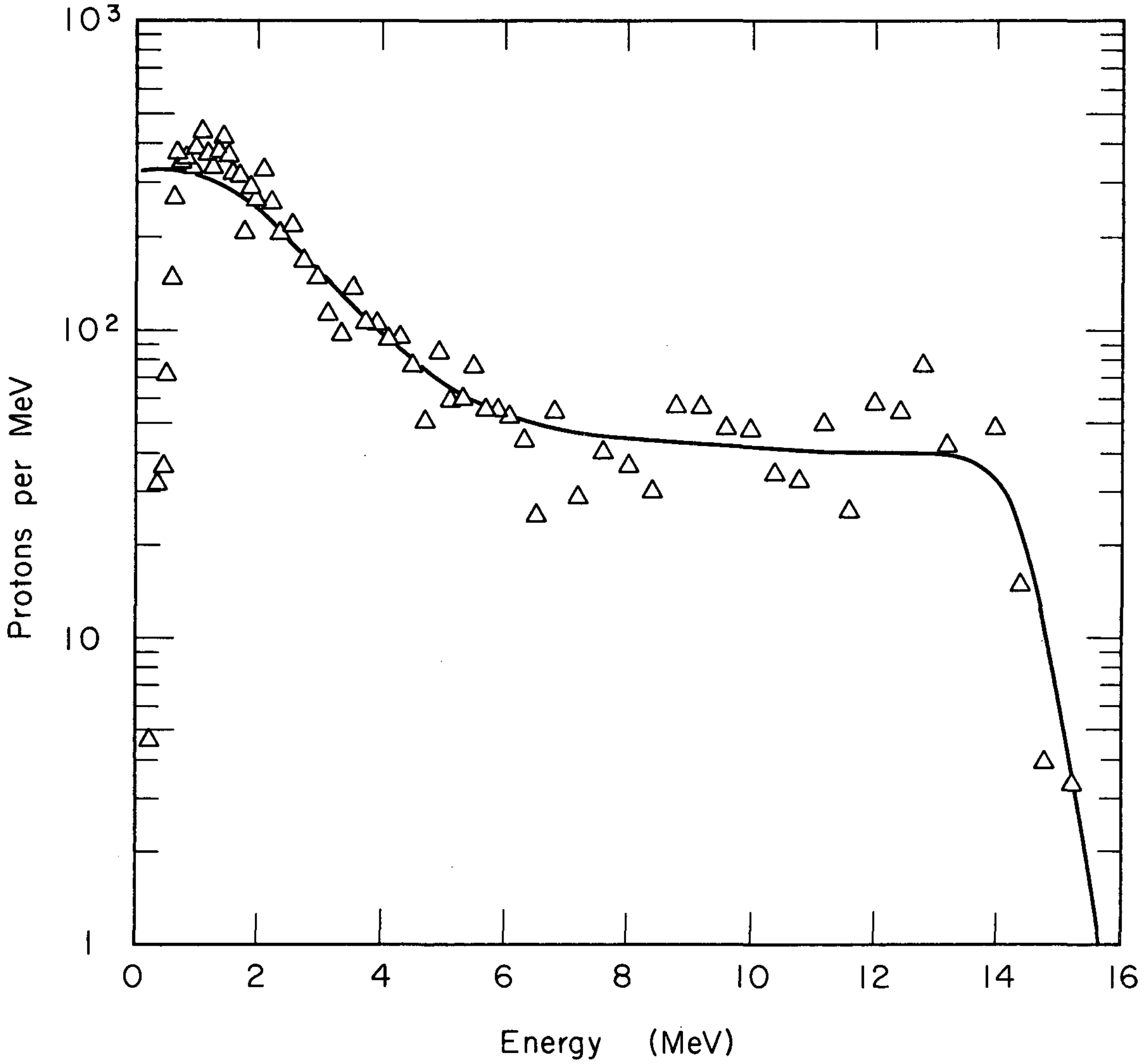

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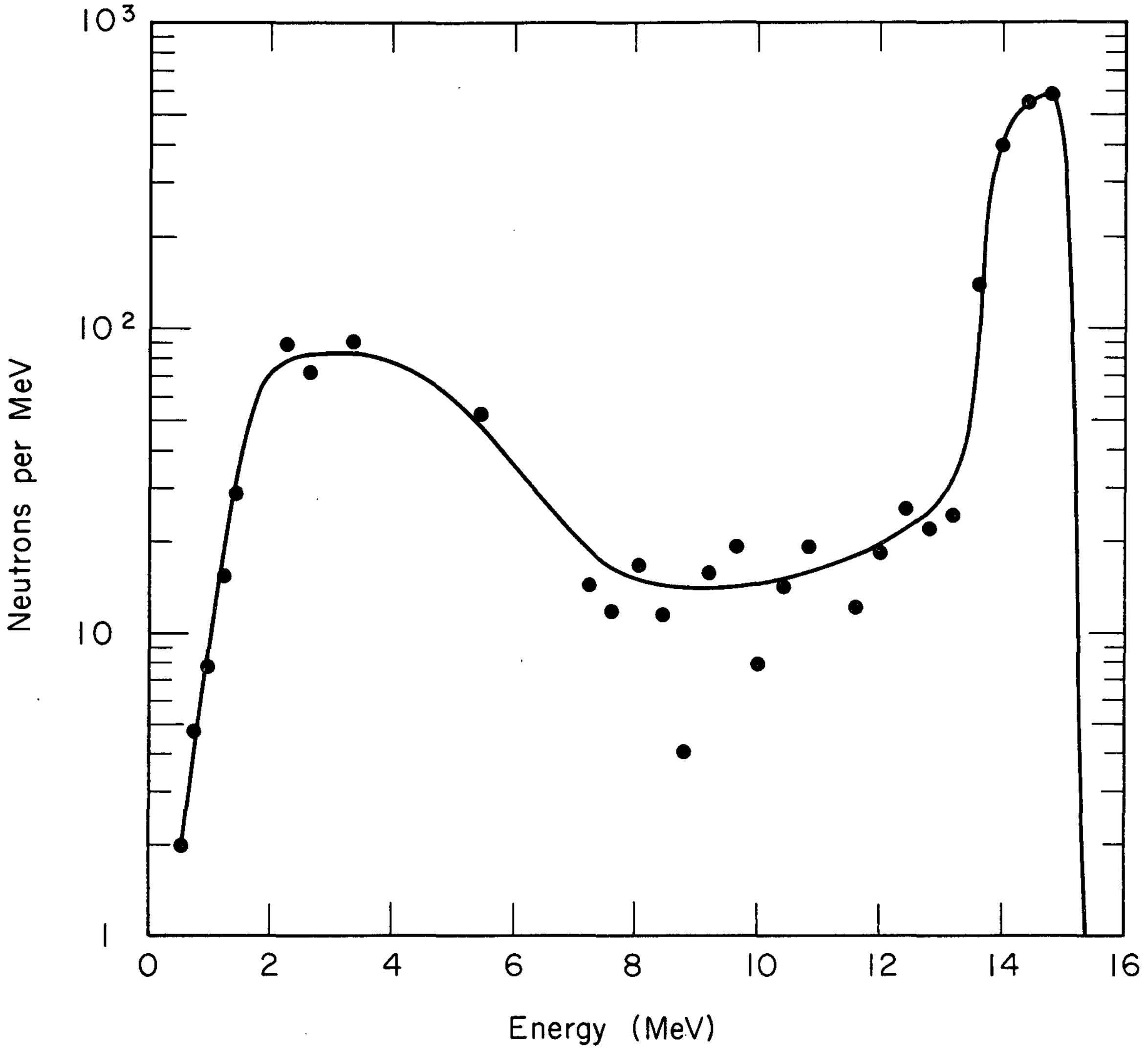
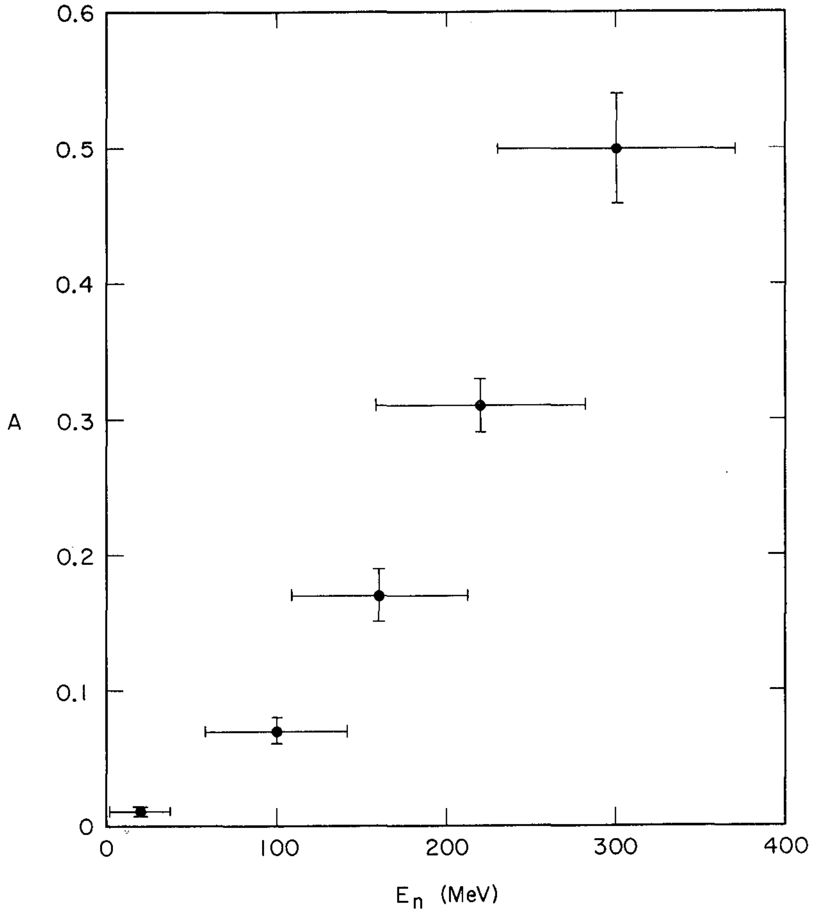
Fig. 1



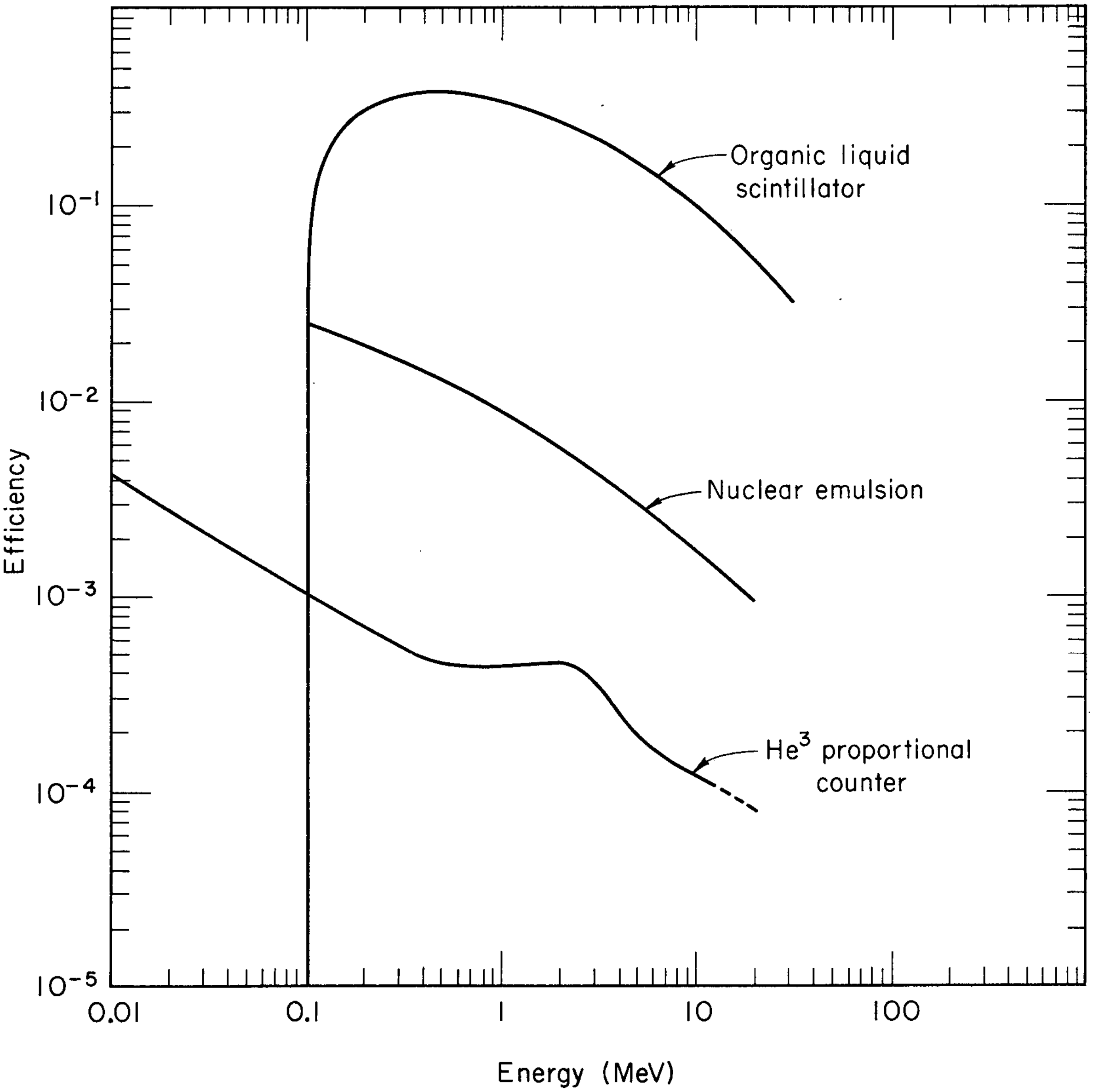
MUB-8433

Fig. 2



MU-36583

Fig. 3



MUB.8432

Fig. 4

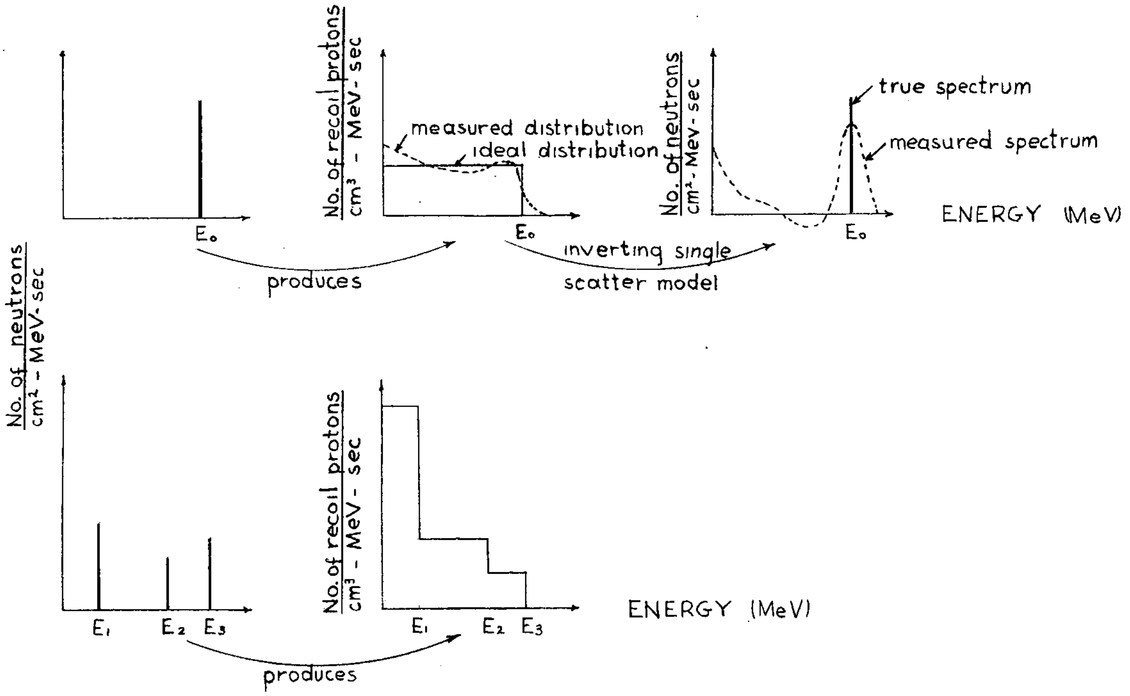


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Fig. 5