MEASUREMENT OF BEAM ENERGY AND ENERGY DISTRIBUTION ON AN INTERNAL CYCLOTRON TARGET

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ABSTRACT

The energy and energy distribution of protons striking an internal target on the ORNL 86-inch cyclotron was measured by two methods: (1) measuring density on a photographic film placed behind a stepped aluminum absorber; and (2) measuring the excitation function for the (p,n) reaction on copper. Details of the methods and typical results are given. The energy was found to be sensitive, within several hundred kilovolts, to various cyclotron parameters.

MEASUREMENT OF BEAM ENERGY AND ENERGY DISTRIBUTION ON AN INTERNAL CYCLOTRON TARGET

Most fixed-frequency cyclotrons are equipped with deflection apparatus for producing an external beam. Consequently, the problem of determining the energy of an internal beam with good precision has not often been encountered. Experimenters have usually been satisfied with determinations calculated from the strength of the magnetic field and the radius of curvature of the path, with the center of curvature assumed to be at the ion source.

Measurements of the internal beam of the ORNL 86-inch cyclotron very early indicated that the energy of the proton beam might vary as much as ±10% from $H\rho$ calculations. For nuclear physics experiments it was necessary to determine the proton energy with greater precision. A photographic method and a copper activation method for measuring energy have both been used successfully. Both are absorption methods and are thus limited essentially by knowledge of range-energy relationships and straggling. These factors limit the accuracy of determination of the most probable energy to a few hundred kilovolts. The high energy portion of the energy distribution can be determined with almost equivalent accuracy, but the shape of the low energy portion involves considerably greater uncertainty.

The energy of maximum intensity was found to vary by as much as several hundred kilovolts with minor adjustments of the ion source position, dee voltage, magnetic field tuning, and oscillator frequency.

Photographic Film

A photographic film is covered with a stepped absorber (made by folding an aluminum foil), wrapped in aluminum foil, and exposed directly in the cyclotron beam. The current is monitored by a neutron counter placed near the target and may be controlled to as low as 0.1 μa with the ion source arc turned off. In all cases, considerable detuning of the magnetic field is necessary to maintain low currents. Exposures of about 0.1 μa-sec have been found suitable for Weston Speed 5 film. Figure 1 shows a typical film. The strip at the top was not covered by the absorber; it is used to correct for variations in the beam intensity across the film.

The density of development behind each absorber step is measured with a densitometer and then plotted as the antilog of the density versus thickness of the covering aluminum, Figure 2. If it is assumed that the antilog of the density is proportional to the energy lost by protons in going through the emulsion, a beam of 18.5 Mev protons should produce a density curve as shown by the dot-dash line. Figure 2 also contains a secondary abscissa, Scale II, which is the energy of a proton with the range given by Scale I.

To determine the theoretical curve for another energy, the dot-dash curve need only be displaced horizontally so that its high energy side ends at that energy on the abscissa, Scale II. To the extent that the theoretical curve is a delta-function, the experimental curve is an energy spectrum when read on Scale II. This is a fair approximation in the region where the high energy side of the experimental curve is decreasing rapidly. Where the high energy side decreases slowly with increasing energy, its ordinates must be considerably larger than those of the energy spectrum. The width of the peak in the energy spectrum is approximately the difference between the widths of the peaks

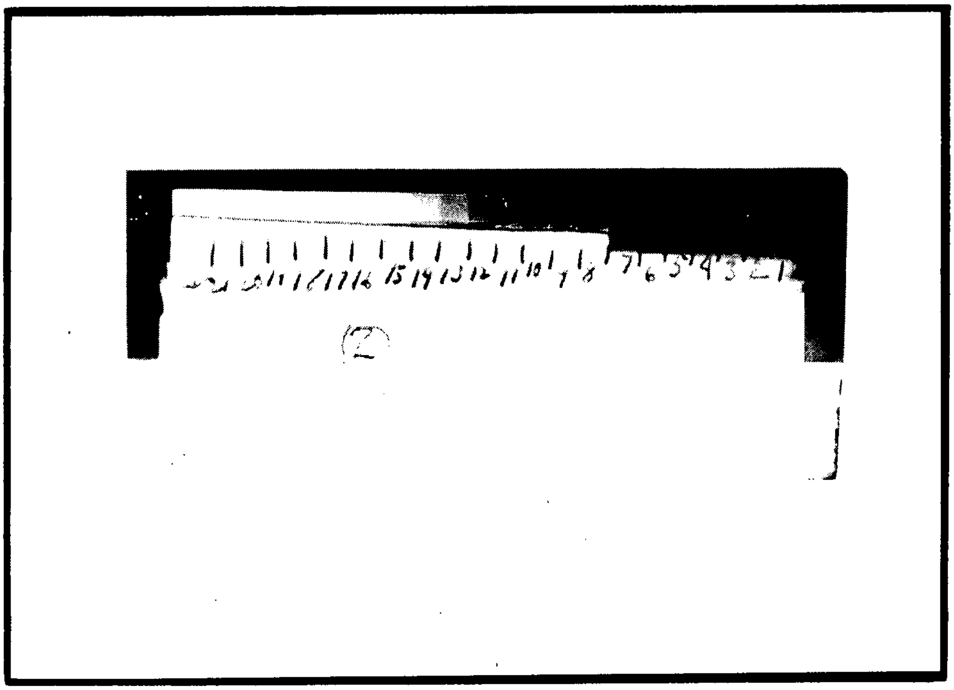

FIGURE I. TYPICAL FILM EXPOSED TO PROTON BEAM

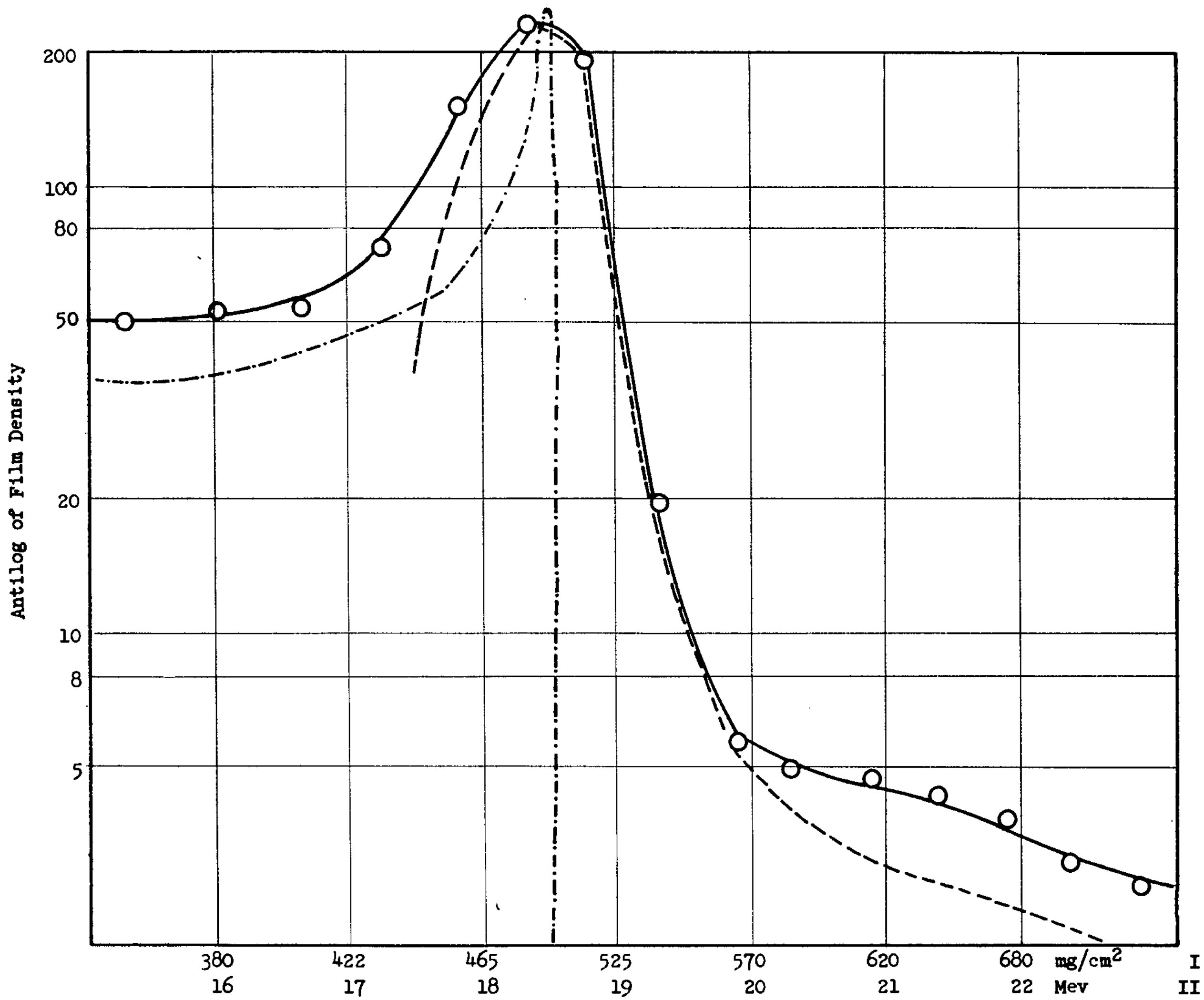

FIGURE 2. A TYPICAL ENERGY SPECTRUM, obtained by the photographic film method. Circles are experimental points. Dashed lines are the theoretical curves for 18.5 Mev. The solid line is the approximate true proton energy spectrum.

of the experimental and the theoretical curves. Other than this, the details of the low energy portion of the spectrum can only be guessed at. In Figure 2 the dashed line shows a semi-quantitative estimate of the true proton energy spectrum based upon the principles outlined above.

The chief disadvantage of the photographic film method is that the cyclotron operating conditions are so different from those used in normal operation that it may well be that the energy distribution is not the same. The most important advantage other than the simplicity of the method is that it is suitable for determining the radial width of the beam for various energies; note in Figure 1 that the radial width for low energies is greater.

Copper Excitation Function

Since the excitation function for Cu 63(p,n)Zn 63 $\rightarrow$ Cu 63 + β^+ (38 min) has recently been measured* with high precision and thin copper foil is readily available, the energy distribution of protons in the cyclotron beam is readily determined by measuring this excitation function and comparing it with the published data. The measurements consist of bombarding a stack of thin ($\sim$6 mg/cm^2) copper foils in the cyclotron beam, and counting the 38-minute beta activity under a thin-window Geiger counter. This yields a curve of activity, A, vs r, the foil thickness through which the beam has passed, Figure 3. But,

$$A(r) \propto \int \sigma(R-r)\, I(R)dR \qquad (1)$$

where R is the total range of the protons striking the front foil, I(R) is the spectrum of these ranges in the cyclotron beam--this is equivalent to the proton energy spectrum -- and σ(R-r) is the cross section for production

* Blaser, J. P., et. al., Helv Phys Acta, 24, 3 (1951).

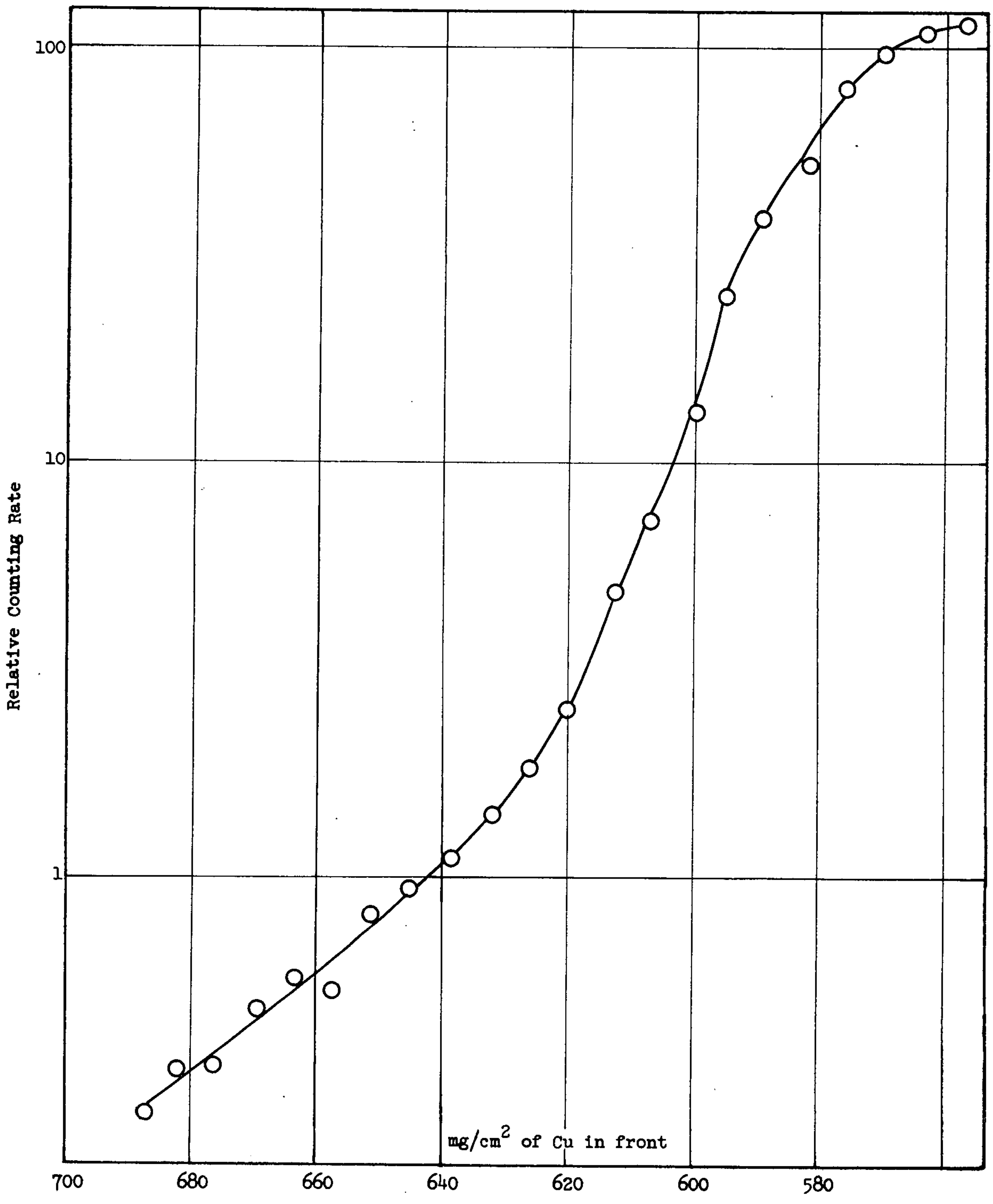

FIGURE 3. A TYPICAL EXCITATION FUNCTION
for 38-min activity in copper

of the 38-minute activity for a proton with residual range R-r. A(r) is measured, $\sigma(R-r)$ is readily obtainable* and the problem is to compute I(R).

The integral equation, (1), may be solved by assuming I(R) to be a block spectrum, i.e.,

$$I = I_n \quad (R_n > R > R_{n-1}) \tag{2}$$

in which case (1) becomes

$$A(r_i) = \sum_{n=1}^{N} \sigma\left(\frac{R_n + R_{n-1}}{2} - r_i\right) \cdot I_n \left[R_n - R_{n-1}\right] \tag{3}$$

or a line spectrum, i.e.,

$$I = \sum_{n=1}^{N} W_n \, \delta(R - R_n) \tag{4}$$

in which case

$$A(r_i) = \sum_{n=1}^{N} \sigma(R_n - r_i) \, W_n \tag{5}$$

(3) is equivalent to (5) for

$$W_n = I_n \left[R_n - R_{n-1}\right] \tag{6}$$

Equation (5) is a set of linear, simultaneous equations which may be solved for the W_n. While this may seem quite tedious at first, it turns out that since $\sigma(R-r)$ is a very rapidly decreasing function the system of simultaneous equations includes one with only W_N, one with W_N and W_{N-1}, etc., so that only rarely is it necessary to solve as many as two equations simultaneously. As a result, the whole process can be carried out in about

*Blaser, J. P., et. al., Helv Phys Acta 24, 3 (1951).

thirty minutes. Some care in choice of the R_n's is necessary in order to avoid large oscillations and negative W's, or alternatively, these may be recognized as due to small errors in the measurements and averaged over. Figure 4 shows the points obtained from a typical block spectrum and the continuous proton spectrum surmised from it.

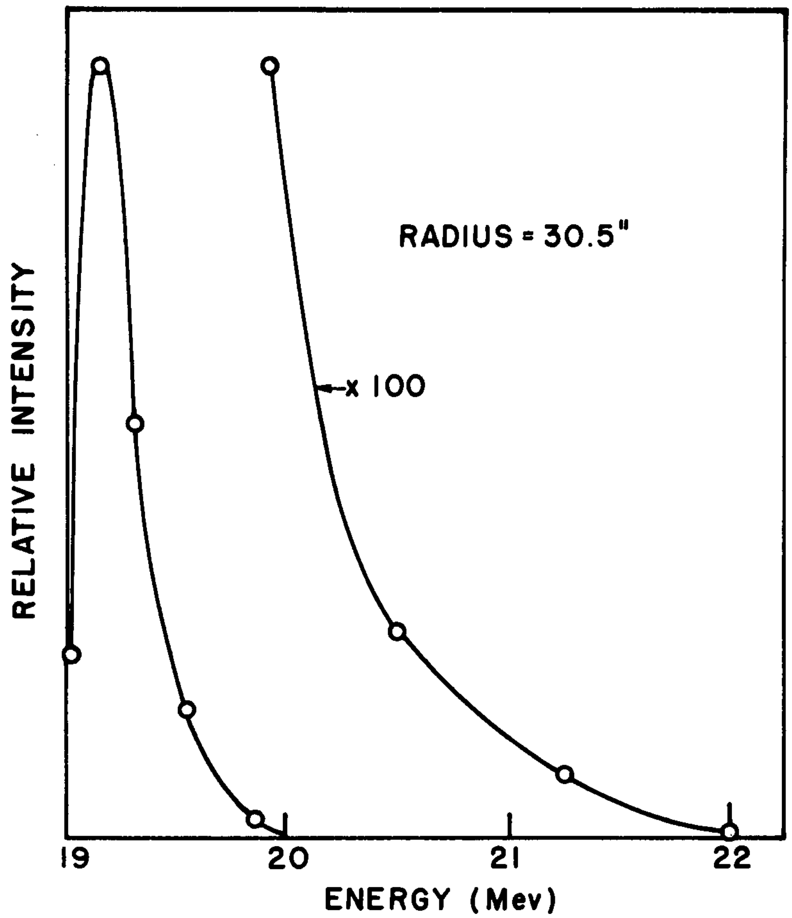

FIGURE 4. TYPICAL ENERGY DISTRIBUTION obtained by the copper excitation function method.