ICANS - VI

INTERNATIONAL COLLABORATION ON ADVANCED NEUTRON SOURCES

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CASCADE NEUTRON YIELDS FROM ENERGETIC HEAVY ION INTERACTIONS

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ABSTRACT

Experimental data on heavy ion production of cascade neutrons (neutron energy above 20 MeV) is collected and reviewed. Cascade neutron production figures per unit solid angle are given as a function of emission angle for projectiles up to Ar 40 and incident energies up to 2100 MeV/AMU. Total cascade neutron yields per event are derived and found not to increase when going to heavier projectiles.

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1. NEUTRON DIFFERENTIAL PRODUCTION CROSS-SECTIONS.

There has been numerous measurements of neutron production by protons, light, and heavy ions, which are in part reported in the bibliography. In order to compare them, we have plotted the cascade neutron single differential cross-sections

$$\frac{d\sigma}{d\Omega} = \int_{20\,MeV}^{\infty} \frac{d\sigma}{dE\,d\Omega}\,dE \quad \text{barn/sterad}$$

as a function of neutron emission angle θ in fig. 1. In the forward direction (θ= 0) there is generally a peak, whereas between 15^{o} and 150^{o} the data can in most cases be approximated by an exponential with angle of the form exp $(-k\theta)$, where k (rad^{-1}) can be found from the figure.

Fig. 2 groups recent data collected by measurement at the Berkeley Bevalac. Some of these curves are proton production measurements, upgraded by the neutron proton ratio in the target nucleus. One sees that as the energy and the masses of the projectile and target increase, there tends to be more cascade neutrons produced, and more neutrons are produced at larger emission angles.

2. NUCLEAR REACTION CROSS-SECTIONS.

Is is useful to have a value for the nuclear interaction cross-section, which is approximately the inelastic one σ_{inel}, as this serves to calculate the yield at each angle, which is the neutron differential cross-section $d\sigma/d\Omega$ divided by σ_{inel}. We have used the values published by Barshay, Dover and Vary and drawn by extrapolation the graph given in fig. 3 which gives approximative values of σ_{inel} as a function of projectile and target masses Ap and A_T.

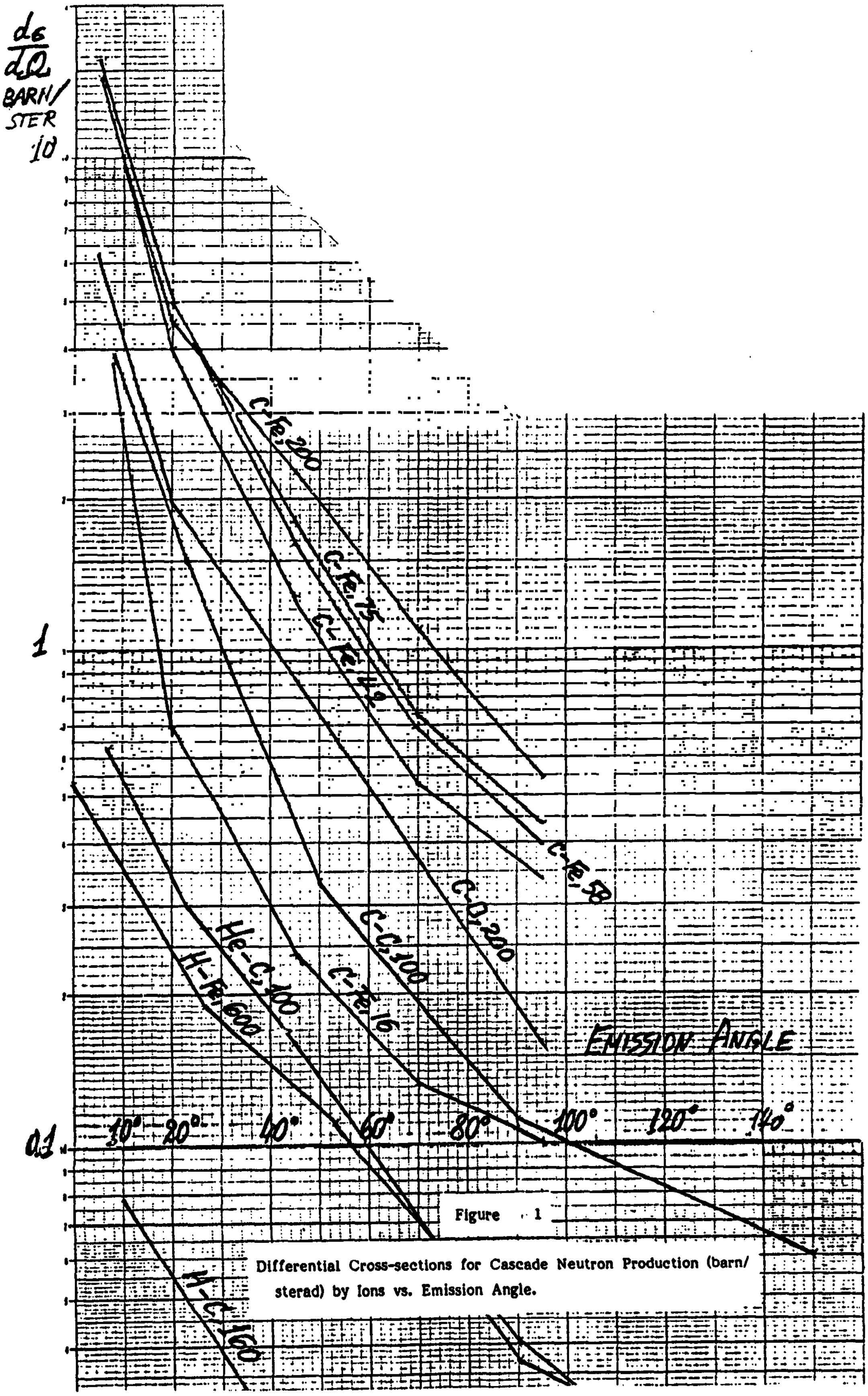


Figure 1

Differential Cross-sections for Cascade Neutron Production (barn/sterad) by Ions vs. Emission Angle.

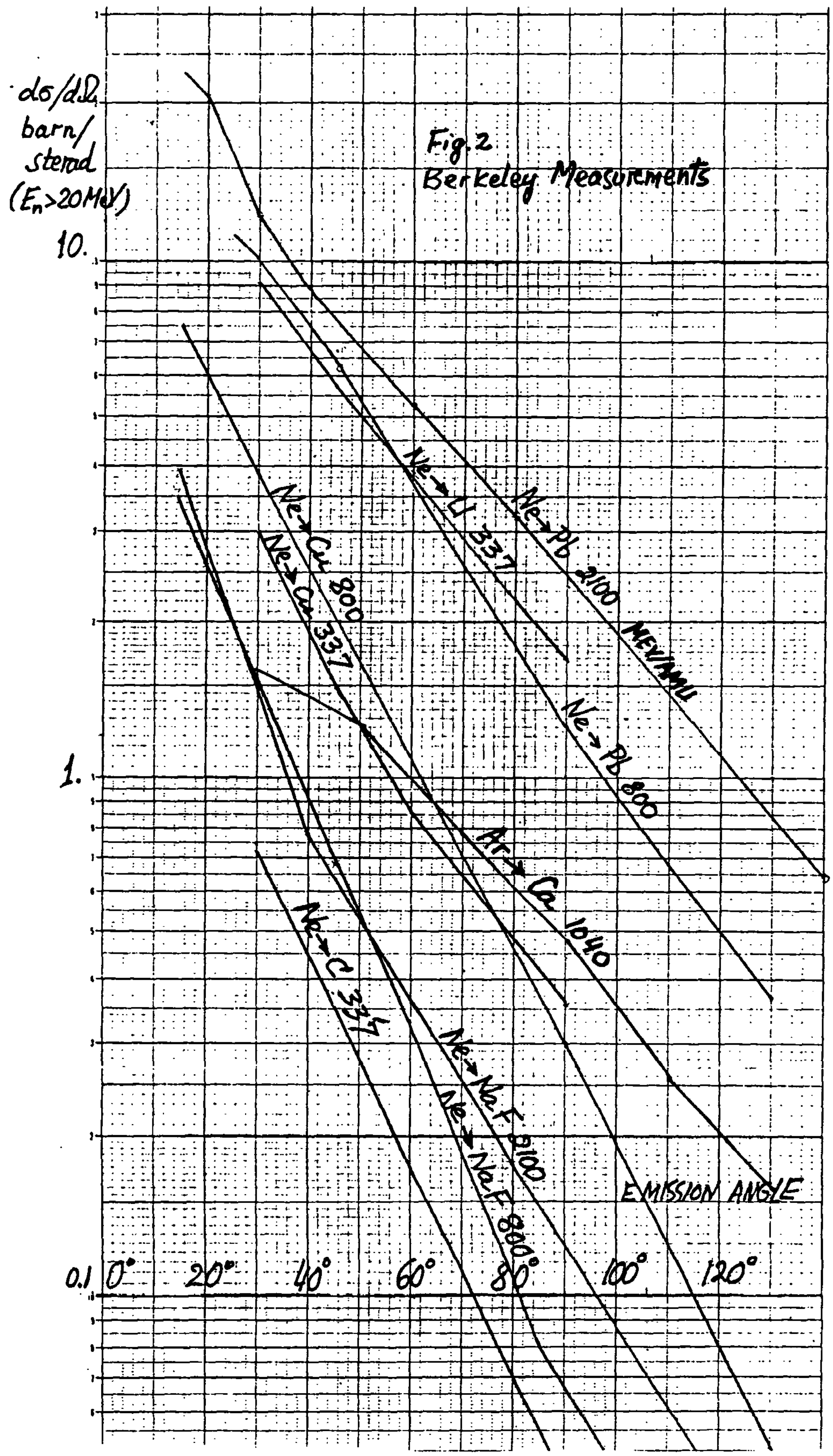
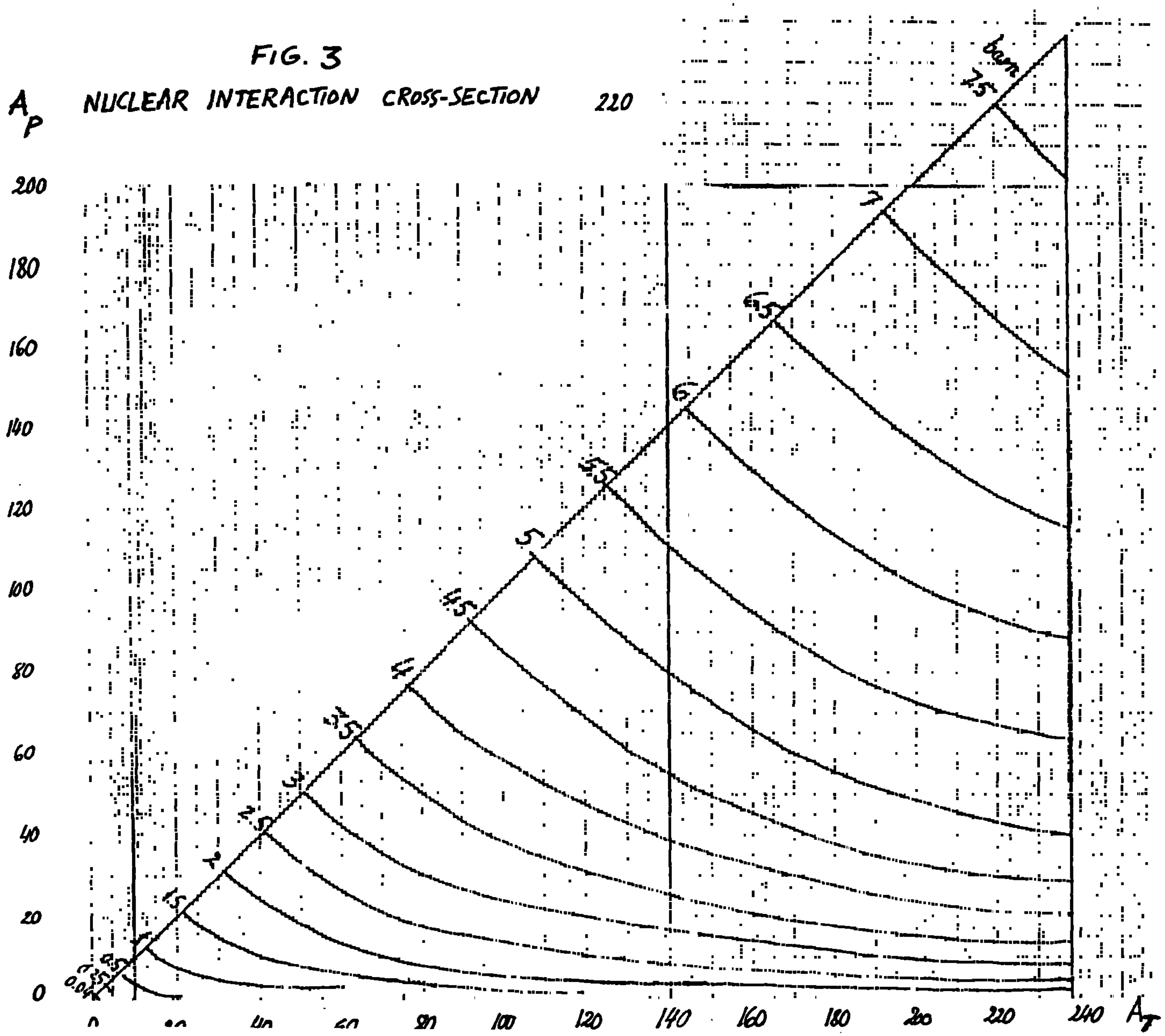

dσ/dΩ barn/sterad (E_n>20MeV)
Fig.2
Berkeley Measurements
10.
1.
0.1
0°
20°
40°
60°
80°
100°
120°
EMISSION ANGLE
Ne→Pb 2100 MEV/AMU
Ne→U 337
Ne→Pb 800
Ne→Cu 800
Ne→Cu 337
Ar→Ca 1040
Ne→C 337
Ne→NaF 2100
Ne→NaF 800

FIG. 3

NUCLEAR INTERACTION CROSS-SECTION



The σ_{inel} values given are smaller than the geometric cross-sections. It is a recognized fact that grazing incidence (tangential nuclei) is not enough for inelastic interactions to take place: there must be a volume common to both nuclei.

3. CASCADE NEUTRON YIELD.

The cascade neutron yield at a given angle, as mentioned previously, is given by:

$$Y(\theta) = \frac{1}{\sigma_{inel}} \frac{d\sigma}{d\Omega} \qquad \text{neutron/sterad}$$

The division of the $d\sigma/d\Omega$ values by σ_{inel} has the advantage of grouping the numerical values together. Excepting the forward direction, where neutron emission is always enhanced, the yield then takes the form:

$$Y(\theta) = Y_0 \, e^{-k\theta} \qquad \text{neutron/sterad}$$

where Y_0 is a mathematical quantity describing the practically exponential decay with θ between 15° and 150°. Practically, it is the intersection of the straight line on linear-log paper with the ordinate axis at $\theta = 0$.

4. TOTAL NUMBER OF CASCADE NEUTRONS PER INTERACTION.

To compare cascade neutron production from various projectiles, targets and energies, it is convenient to take in a simplistic fashion the total neutron production as a figure of merit. This is obtained by integrating the yield multiplied by the proper solid angle differential at each angle over all angles:

$$N = \int Y(\theta)\, d\theta = 2\pi Y_0 \int_0^{\pi} e^{-k\theta} \sin\theta \, d\theta$$

$$= 2\pi Y_0 (1 - e^{-k\pi}) / (1 + k^2) \simeq 2\pi Y_0 / (1 + k^2)$$

The values obtained are plotted in fig. 4 as a function of projectile incident energy for various projectiles and targets.

5. ENERGY DEPENDENCE.

A pattern seems to emerge from fig. 4. which suggests an energy dependence following the expression $E^{0.3}$ in most cases.

6. PROJECTILE, TARGET DEPENDENCE.

The total neutron production N extrapolated or intrapolated from fig. 4 at a common energy of 1,000 MEV/AMU is shown for all targets as a function of projectile mass up to Ar 40 in fig. 5. Neutron production, which begins to increase with projectile mass up to carbon 12, shows a systematic decrease for all targets when going to projectile mass 20 (Neon). This could be explained by the fact that channels involving creation of charged fragments carrying neutrons with them (such as deuterons, alphas and other light atoms) tend to be favored when the projectile mass increases.

As of now there are no known production measurements with projectiles above Ar 40. It would be useful to do such measurements, with heavier atoms in the future.

Pending such measurements, theoretical calculations such as the fire streak and fireball calculations can be applied. Dr. Walt Schimmerling at Berkeley has told me that he is working with Professor Meadey of Kent University on deriving theoretically a formula which will give the inclusive neutron production as a function of projectile and target masses. Inclusive refers in this case to the total number of reaction channels which produce at least one neutron (and in some cases more).

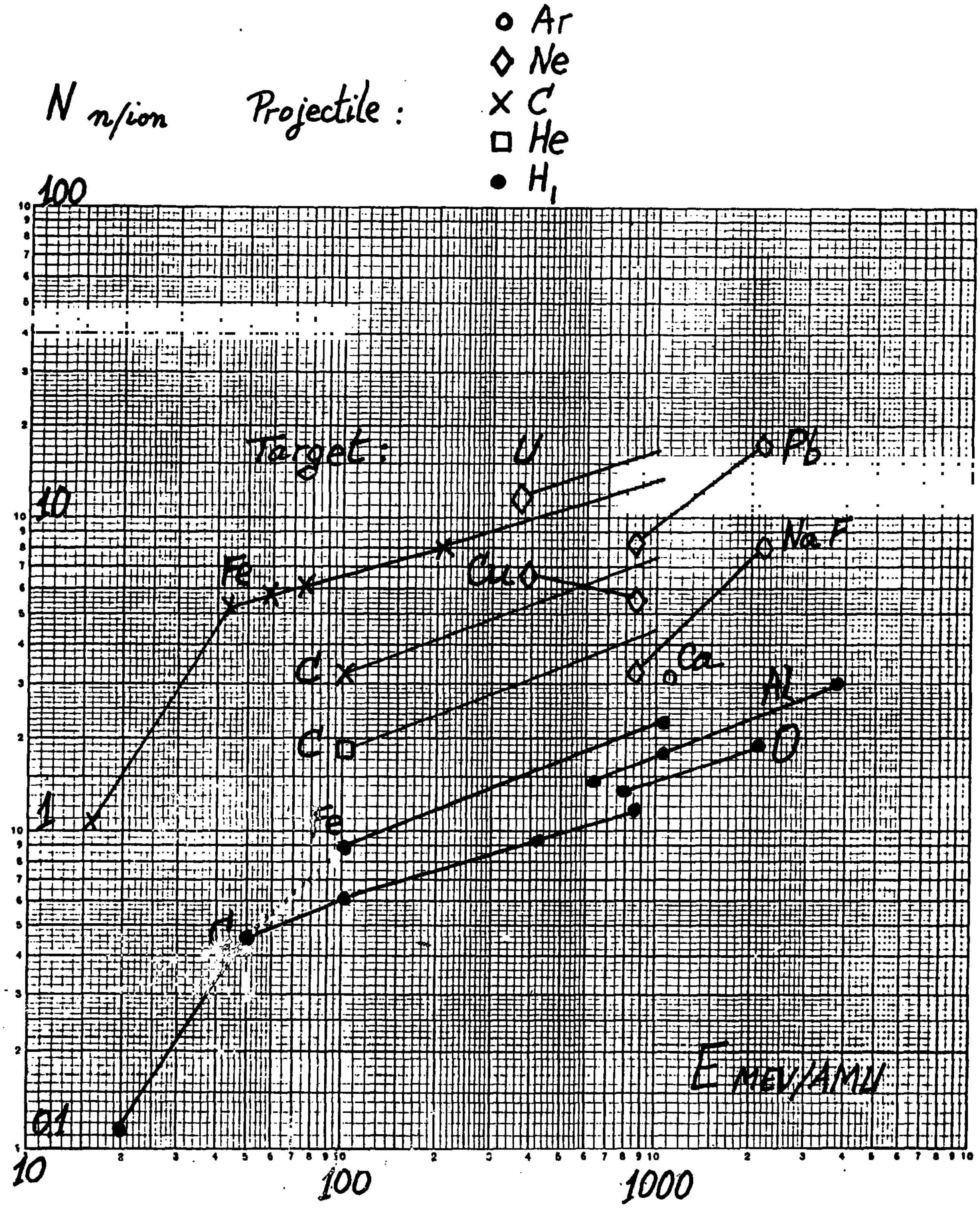


Fig. 4. Cascade neutron production vs projectile energy for various projectiles and targets.

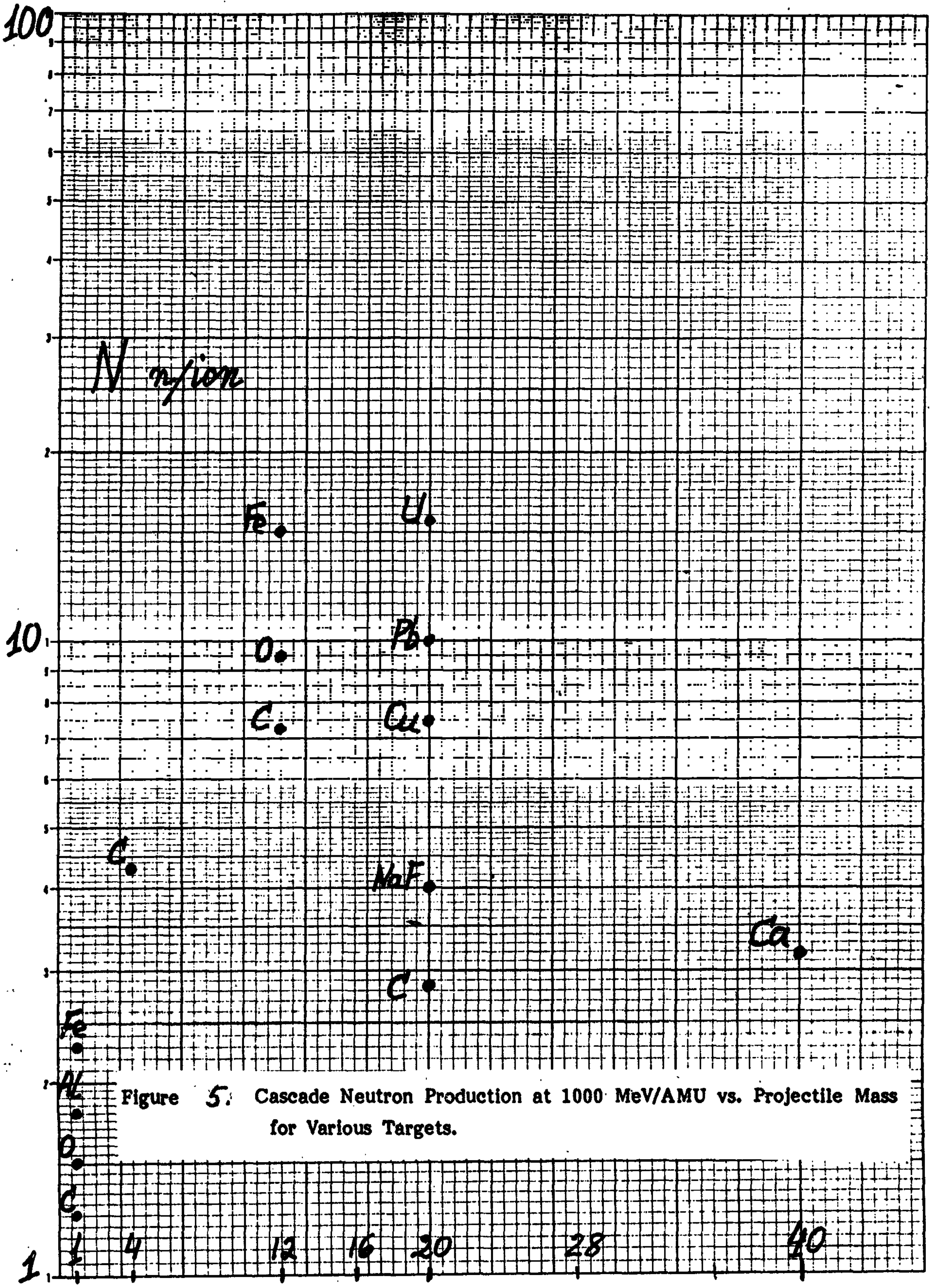


Figure 5. Cascade Neutron Production at 1000 MeV/AMU vs. Projectile Mass for Various Targets.

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