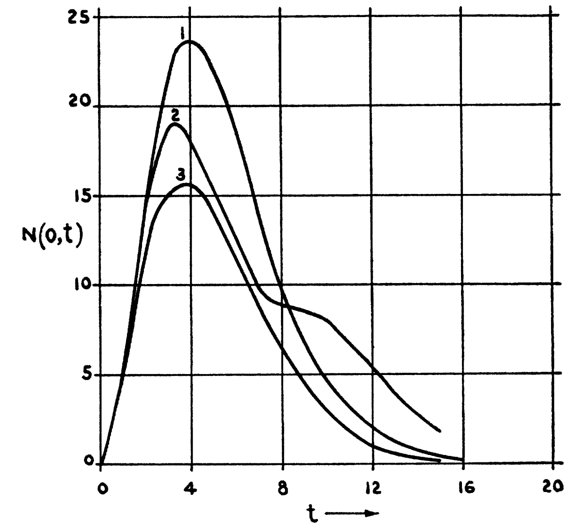

FIG. 2. $N(0, t)$, the average number of electrons induced by an incident electron of energy E_0, plotted against the depth t in cascade units. We have marked the curve given by Snyder's solution 1, that given by Bernstein for lead 2, and that by B.C. 3. In each case $\ln E_0/\beta = 5$.

found by Bernstein, Snyder, and B.C. for $N(0, t)$ for $\ln E_0/\beta = 8$ and 5. The curves taken from Bernstein are those for lead.

It becomes immediately evident that the B.C. solutions (which can be used with ease) are not as inaccurate as hitherto made out. We also wish to point out that Bernstein, like Snyder, has failed to take into account the facts given in the quotation above. When this is taken into consideration, it appears likely that the pronounced "tail" of the curves given by Bernstein, beyond the cascade maximum, will be decreased to a value close to that given by B.C. It thus now appears that the series solution of B.C. can be used with confidence.

I am indebted to Professor H. J. Bhabha for valuable discussion of the above.

[1] H. J. Bhabha and S. K. Chakrabarty, Phys. Rev. **74**, 1352 (1948).
[2] H. S. Snyder, Phys. Rev. **76**, 1563 (1949).
[3] I. B. Bernstein, Phys. Rev. **80**, 995 (1950).
[4] Reference 1, henceforth shortened to B.C.
[5] L. Jánossy and H. Messel, Proc. Phys. Soc. (London) **A64**, 1 (1951).

Photonuclear Stars in Emulsions*

RICHARD D. MILLER
Radiation Laboratory, Department of Physics, University of California, Berkeley, California
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ILFORD C2 emulsions, 200 microns thick, were exposed in the collimated x-ray beam from the Berkeley 322-Mev synchrotron. Exposures were made at synchrotron energies of 322, 242, and 161 Mev, and the monitor ionization chamber was calibrated relative to pair production cross sections at each of the three energies by the method described by Blocker, Kenney, and Panofsky.[1]

The complete area covered on each plate by the beam ($\frac{3}{8}$-in. circle) has been scanned for stars with two and more prongs. Because of the impossibility of distinguishing between a two-prong star and a scatter in the track of a single particle in a large number of cases, two-prong stars were classified as either possible or probable. Because of the arbitrariness and the difficulty of setting sufficiently precise criteria for this distinction, the two-prong data are regarded as essentially qualitative. All events within 5.5 microns of either surface of the emulsion after processing were discarded, and the minimum prong range counted was 3 microns.

TABLE I. Relative yields of stars.

No. prongs \ X-ray energy	322 Mev	242 Mev	161 Mev
possible 2	73±7	81±8	34±5
probable 2	91±8	70±7	36±5
3	137±6	109±9	39±5
4	88±5	57±6	29±4
5	37±3	14±3	8±2
6	13±2	3.6±1.6	0.6±0.6
7	3±1		
8	0.9±0.5		
≥3	280±9	184±12	77±9
≥5	54±4	18±4	9±2

The yields of stars with various numbers of prongs are shown in Table I. The 322-Mev yields are normalized to an emulsion thickness before processing of 200 microns, and to an exposure of 10^8 "equivalent quanta," or 322×10^8-Mev total energy in the complete bremsstrahlung spectrum. The yields at the other energies are normalized to the same thickness and to exposures that contain the same number of quanta per Mev interval at 32 Mev. The uncertainties indicated in the table are the standard deviations due to counting statistics only. The prong spectrum of the 322-Mev yield is similar to that reported by Kikuchi;[2] the difference in the minimum prong length counted probably accounts for the discrepancies.

Using the nominal partial densities of emulsion elements given by the manufacturer, and assuming that star production cross sections are proportional to mass number, the 322-Mev yield of 3 and more prong stars gives a cross section for silver, integrated over the bremsstrahlung spectrum, of 6.5×10^{-27} cm² per "equivalent quantum." This figure is reduced to 5.6×10^{-27} if the cross section is assumed proportional to $A^{\frac{2}{3}}$.

The energy distribution of the quanta responsible for the differences in yields from the different energy exposures is shown in Fig. 1. Also shown, at one-tenth the scale for the difference

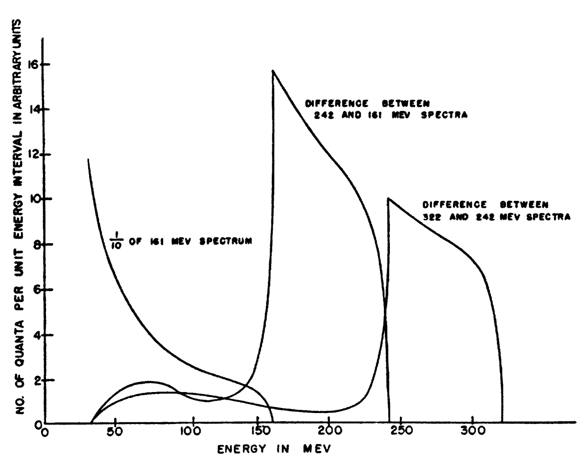

FIG. 1. Differences between spectral distributions of bremsstrahlung from electrons of 322, 242, and 161 Mev, when the spectra have been normalized to contain the same number of quanta per unit energy interval at 32 Mev. The 161-Mev bremsstrahlung spectrum is shown at one-tenth the ordinate scale for the difference spectra.

spectra, is the spectrum of 161-Mev bremsstrahlung. Because most of the difference quanta are in the energy range between the two upper limits of the bremsstrahlung spectra, it is possible to calculate a cross section averaged over this energy interval. Estimating that that part of the yield due to the low energy tail in the 161- to 242-Mev difference spectrum is 10 percent of the 161-Mev yield, and making similar corrections for the yield from the tail in the 242- to 322-Mev difference spectrum, the average cross

TABLE II. Meson photoproduction cross sections of silver, integrated over 322-Mev bremsstrahlung, in units of 10^{-27} cm² per equivalent quantum.

π^+	0.7
π^-	1.1
π^0	4.0
sum	5.8

sections of silver for the production of three or more prong stars are

$$\int_{242}^{322}\sigma(E)N_{322}(E)dE \Big/ \int_{242}^{322}N_{322}(E)dE=(8\pm1)\times10^{-27}\ \text{cm}^2,$$

$$\int_{161}^{242}\sigma(E)N_{242}(E)dE \Big/ \int_{161}^{242}N_{242}(E)dE=(7\pm1)\times10^{-27}\ \text{cm}^2,$$

where $N_{322}(E)$ is the number of quanta per Mev in 322-Mev bremsstrahlung, etc.

The integrated meson production cross sections of silver listed in Table II have been calculated from the measured carbon cross sections,[3,4] assuming the $A^{-\frac{1}{3}}$ dependence of the yield per nucleon found for π^+ meson production.[5] It seems likely that some of the stars observed are associated with meson production. The star yield is probably too large to be accounted for by this process alone, however, since only about $\frac{1}{4}$ of the low energy π^- mesons found which were produced in the emulsion had as many as 3 other prongs associated with their production.

Another possible mechanism for star production by high energy photons is suggested by the π^+ meson relative yield data of Mozley.[5] The implication of the $A^{-\frac{1}{3}}$ dependence of the yield per nucleon is that only the surface nucleons are effective in producing mesons. Since none of the known photonuclear reactions have cross sections comparable to nuclear area at these energies, this effect is probably not due to nuclear opacity to photons. If, however, this effect is due to nuclear opacity to mesons, one might expect that there should be stars produced by meson production and reabsorption in the same nucleus, with cross sections several times that for meson production.

I wish to thank Professor E. M. McMillan for suggesting this problem and for his helpful discussions, Mrs. W. R. Gaffey for assistance in scanning the plates, Dr. R. S. Christian for calculations of the bremsstrahlung spectra, Mr. R. Kenney and Mr. W. Blocker for the use of equipment and assistance in calibration of the ionization chamber, and Mr. G. C. McFarland and the synchrotron crew for assistance in making the exposures.

* This work was performed under the auspices of the AEC.
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[3] Peterson, Gilbert, and White, to be published.
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An Interpretation of Nuclear Cross Sections for High Energy Neutrons*

ROBERT JASTROW
Radiation Laboratory, University of California, Berkeley, California
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RECENTLY, Dejuren and Moyer have extended the measurements of neutron cross sections to fill in the energy region up to 280 Mev[1] and find two interesting features, illustrated by their data for aluminum in Fig. 1:

1. The cross sections are constant at high energies, above 150 Mev.
2. The drop to these high energy levels occurs very sharply at intermediate energies.

The constancy of the cross sections at high energies is in contrast to the continued decrease with increasing energy which would be expected if the interaction between the neutron and the particles in the nucleus were weak. It suggests the presence of a singularity in the n-n and n-p interactions, presumably the same singularity

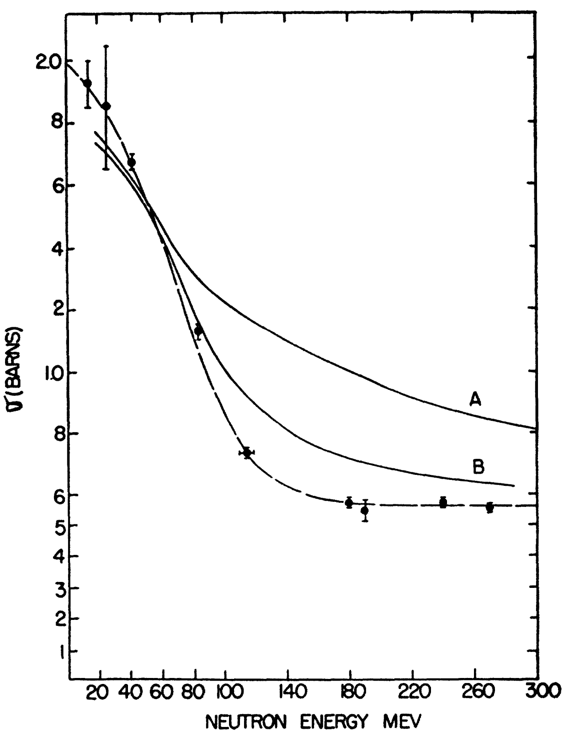

FIG. 1. Cross section of Al for high energy neutrons. The dashed curve is fitted to the experimental points of Dejuren and Moyer. Curves A and B are calculated from the optical model with and without, respectively, a central repulsion in the nucleon-nucleon interaction.

for which evidence is provided in the p-p interaction by the nearly energy-independent p-p cross section at correspondingly high energies.[2,3]

In order to test this interpretation of the energy-independent cross sections we have carried out calculations based on an optical model in which nuclear matter is described by an index of refraction and an absorption coefficient.[4] The cross section is then composed of an incoherent contribution depending only on the absorption coefficient and a coherent contribution depending on the index of refraction. The absorption coefficient is given by

$$K=\tfrac{1}{2}\rho(\sigma_{nn}+\sigma_{np}), \quad (1)$$

where ρ is the nucleon density, and σ_{nn} and σ_{np} are the total n-n and n-p cross sections. For the index of refraction, n, we have (assuming equal numbers of protons and neutrons)

$$n=1+(\pi\rho/k^2)\{f_{nn}(0)+f_{np}(0)\}, \quad (2)$$

where k is the neutron wave number and $f_{nn}(0)$ and $f_{np}(0)$ are the forward scattering amplitudes, all in the laboratory system.

If we assume that n-n and p-p forces are identical, we may insert the measured n-p and p-p cross sections in (1). The forward scattering amplitudes occurring in (2), however, are not unambiguously determined by experiment, even under the assumption of identical n-n and p-p forces, but must be calculated from the particular nucleon-nucleon interaction assumed. We have substituted in (2) scattering amplitudes derived from potentials fitted to n-p and p-p scattering by Christian and Hart[5] and by Christian and Noyes[6] and obtained the neutron cross section given by curve A of Fig. 1. This result does not reproduce the rapid fall in Dejuren's measurements at intermediate energies.

Since the absorption coefficient and the incoherent cross section are fixed by experiment, the origin of the discrepancy must lie in the coherent contribution and, therefore, in the values used for the scattering amplitudes in (2). One sees that a description of the neutron cross sections requires a nucleon-nucleon potential such