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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An Interpretation of Nuclear Cross Sections for High Energy Neutrons*

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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

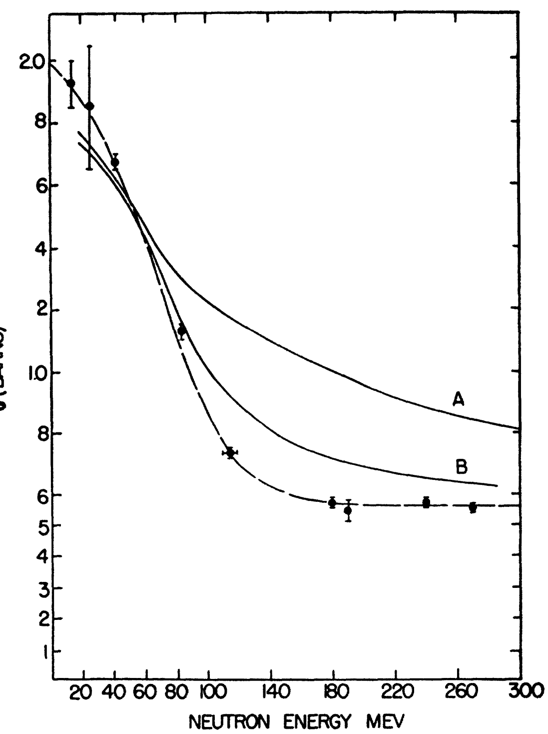

FIG. 1. Cross section of Al for high energy neutrons. The dashed curve is fitted to the experimental points of Dejuren and Moyer. Curves A and B are calculated from the optical model with and without, respectively, a central repulsion in the nucleon-nucleon interaction.

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

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

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)

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

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 that $f(0)$ decreases rapidly with increasing energy above 100 Mev. A potential consisting of a strong repulsion surrounded by an attractive well possesses this characteristic, owing to the circumstance that interference between the repulsion and the surrounding well causes the S phase shift, and hence its contribution to the scattering amplitude, to become negative at high energies.

An interaction of this type, containing a singlet central repulsion of radius 0.60×10^{-13} cm, has already been suggested[3] in connection with high energy p-p scattering measurements. We have calculated the neutron cross sections using forward scattering amplitudes obtained from this potential, with results for aluminum given in curve B of Fig. 1. We conclude from Fig. 1 that if one is restricted to a simple model for the nucleon interaction, the sharp drop in the observed neutron cross section at high energies requires that this model contain a strong central repulsion.

It is important to note that this argument sheds no light on the tensor component of the interaction, since tensor forces of any kind will make only small contributions to $f(0)$.

A more detailed account is in preparation, including a discussion of the effect of the presence of other nucleons on the two-body nucleon cross sections.

* This work was carried out under the auspices of the AEC.
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The $T+T$ Reactions

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THE interaction of tritons with tritons may lead to three nuclear reactions:

$$T+T\rightarrow He^4+2n+\ \ 11.3\text{ Mev} \quad (1)$$

$$\rightarrow He^5+n\ +\sim 10.5\text{ Mev} \quad (2)$$

$$\downarrow$$

$$He^4+n\ +\sim\ 0.8\text{ Mev}^1$$

$$\rightarrow He^4+n^2. \quad (3)$$

The first reaction is a 3-body disintegration resulting in continuous energy distributions for the α-particles and neutrons. The second reaction is a two-stage process recognizable by a neutron group at $\sim$8.8 Mev. Reaction (3) postulates the formation of a di-neutron which, if its lifetime were sufficiently great, would be accompanied by an α-particle group of small energy spread. To distinguish these reactions measurements have been made of the energies of the disintegration products emitted at 90° to the triton beam.

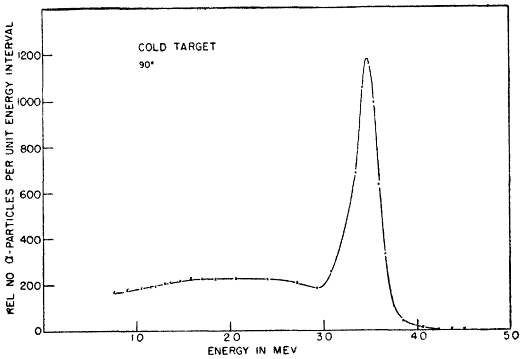

FIG. 1. The $T+T$ α-particle energy distribution. Triton energy = 220 kev.

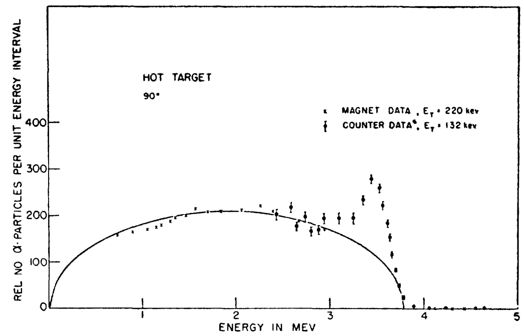

FIG. 2. The $T+T$ α-particle energy distribution. The solid line is the theoretical distribution based on classical statistical mechanics. Probable errors are indicated. E_T is triton energy.

The momentum distribution of the α-particles was investigated using a 90° analyzing magnet[2] with a resolution of 3 percent in momentum. The α-particles were detected by their scintillations in a ZnS screen. Sufficient intensity was obtained by bombarding a brass block with a 200 μa unresolved beam containing 10 percent tritons, some of which were absorbed on the brass and acted as a target. The bombarding energy was 220 kev. The relative number of α-particles per unit energy interval in the range 0.7–4.5 Mev is shown in Fig. 1. Scattered tritons from the beam prevented measurements below 0.7 Mev. The intensity of low energy α-particles has been corrected for the effect of charge exchange in the target.[3] Superimposed on the continuous distribution from reaction (1) is a group of α-particles at 3.5 Mev from the $T+D$ reaction. The high intensity of this group can be explained by the large yield of this reaction at low energies[4] and the natural deuterium content in the beam and in traces of oil on the target.

As the $T+D$ peak might obscure a small group of α-particles associated with the formation of an unstable di-neutron, it was necessary to reduce the deuterium contamination. Best results were obtained by bombarding a metal strip, maintained at a dull red heat, with a resolved beam of mass 5 ions [$H\ H\ T^+$]. Heating the target prevented deposition of oil vapor. An extended investigation of the upper portion of the α-particle distribution was made under these conditions with a proportional counter and thirty-channel pulse analyzer.[5] The complete energy distribution is shown in Fig. 2.

The α-particle distribution shows no group corresponding to the formation of a di-neutron, unless such a group coincides in energy with that of the $T+D$ α-particles. The absence of an α-particle group at an energy greater than 3.8 Mev, the energy corresponding to a di-neutron of zero binding energy, leads to the conclusion that a bound state of the di-neutron, if it exists at all, is formed in fewer than 1 percent of the disintegrations. If the di-neutron exists in a virtual state with a mass exceeding that of two neutrons by an amount equivalent to an energy E, an α-particle group with energy $3.8-E/3$ Mev will be observed whose width will depend on the lifetime of the state. For $E\leq 0.6$ Mev an upper limit of 1 percent of the disintegrations may be placed on the existence of an α-particle group of width $\sim$0.2 Mev corresponding to a di-neutron of lifetime $\sim 3\times 10^{-21}$ sec.

The neutron energy distribution shown in Fig. 3 was obtained from measurements of proton recoils in Ilford C2 100μ-emulsions placed at 90° to the triton beam. A light target assembly was used to reduce the neutron scattering. Since no correction has been made for the small effect of scattering, the distribution may be distorted so as to increase the apparent number of low energy neutrons. Recoil protons from monoenergetic 14-Mev $T+D$ neutrons were observed, but have not been included in Fig. 3. There is some evidence for a peak at $\sim$8.8 Mev corresponding to