Intermediate-energy (40 MeV $\lesssim E_\gamma \lesssim$ 400 MeV) photonuclear interactions*

T. A. Gabriel
Oak Ridge National Laboratory, Oak Ridge, Tennessee, 37830

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Comparisons between theoretical and recent experimental photoproton spectra are presented for 400-MeV bremsstrahlung on carbon, aluminum, copper, and gold. Experiments are suggested which would facilitate further theoretical considerations.

[NUCLEAR REACTIONS $C(\gamma,x)$, $Al(\gamma,x)$, $Cu(\gamma,x)$, $Au(\gamma,x)$, $E_\gamma = 40-400$ MeV, calculated $\sigma(E_p,\theta)$, $\sigma(E_\pi,\theta)$.]

In the five years since the first results on intermediate-energy ($E\gamma \gtrsim 40$ MeV) photonuclear reactions, obtained with the quasi-deuteron model and the intranuclear-cascade model,[1] were published,[2] there has been a slow but steady increase in the quantity and quality of the photonuclear-reaction data.[2-9] However, the validity of the quasi-deuteron model[2,10,11] used to describe the dominant reaction mechanism between the giant dipole resonance region and the pion threshold region, as well as the value of the quasi-deuteron "constant" is still in a state of uncertainty. In this paper, some comparisons with recent experimental data[3] are made, some data which hopefully can be used by experimentalists in designing new experiments are presented, and some additional experimental measurements which would help answer questions concerning high-energy photonuclear reactions are suggested.

Since the calculational details are described elsewhere,[1,2] only a brief discussion is presented here. The calculations are based entirely on Monte Carlo methods and depend upon the intranuclear-cascade concept; i.e., the interaction between a high-energy particle and a nucleus can be described on the basis of free particle-particle collisions within the nucleus. The location of the first collision, and subsequent collisions, and the direction of the collision products following the collisions are determined from free particle-particle total and differential cross sections. Experimental cross sections are used wherever possible; otherwise, theoretical cross sections are depended upon.

The size of the nuclear target and the nucleon-density distribution were determined from the experimental work of Hofstadter.[12] The nucleon-momentum distribution for each region inside the target was assumed to be a zero-temperature Fermi distribution. The binding energy of the most loosely bound nucleon, i.e., the nucleon at the top of the Fermi sea, was taken to be 7 MeV. The Fermi exclusion principle was approximately taken into account by requiring that all hadron particles have energies above the appropriate Fermi energy.

The initial interaction of the photon within the nucleus is described by the use of the quasi-deu-

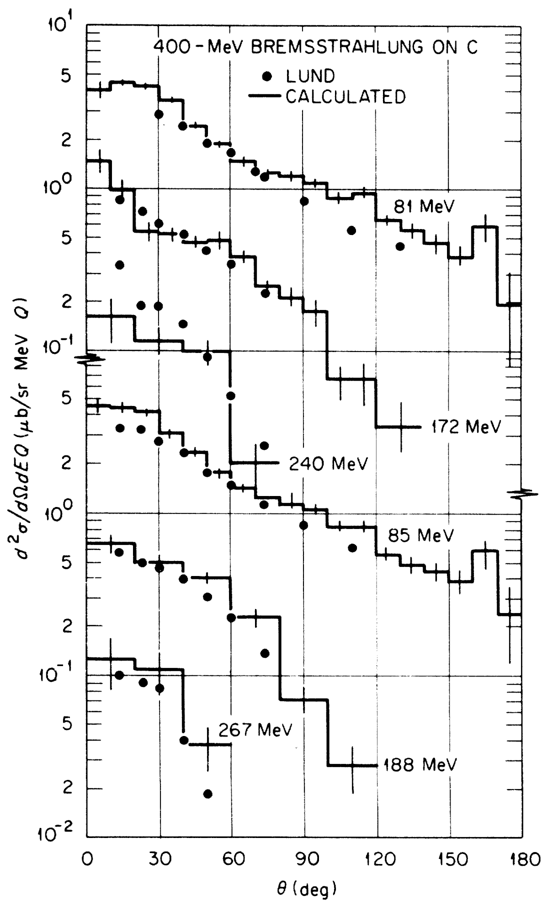

FIG. 1. Photoproton angular distributions for 400-MeV bremsstrahlung on C.

teron model, i.e., absorption by a neutron-proton pair within the nucleus, or, when energetically possible, by one of the four pion-nucleon states formed in photon-nucleon interactions. The probability of which reaction occurs is determined by free-particle cross sections for photopion production[13] and by the expression of Levinger[10] for quasi-deuteron absorption:

$$\sigma_{qd} = (NL/A)\sigma_d,$$

where N is the number of quasi-deuteron pairs, A is the atomic number, σ_d is the photodeuteron cross section,[14] and L is the quasi-deuteron constant. Levinger obtained 6.8 for L while Gabriel and Alsmiller[2] used a value of 10.3. In the present work and in more recent measurements, a value in between these limits seemed more appropriate for light- and intermediate-weight nuclei.

The effect on the nucleus of the cascading pions and/or nucleons following the initial interaction is treated through the use of the intranuclear-cascade model developed by Bertini.[1] This model has been utilized to yield reasonable agreement with a variety of experimental data.

The number of bremsstrahlung photons per unit energy as a function of photon energy was obtained from the Schiff spectrum.

In Figs. 1–4 comparisons are made with experimental data[3] consisting of photoproton angular distributions for 400-MeV bremsstrahlung incident on four elements, C, Al, Cu, and Au. The ΔE energy boxes were chosen to be consistent with those used experimentally. In contrast to the first paper[2] in which the quasi-deuteron constant was set at 10.3, the values employed here are 7.1 for C, Al, and Cu, and 12.5 for Au. These values were chosen because they yielded the "best fit" to this particular set of data. Considering the fact that no detailed nuclear structure is included, the agreement is good for all elements.

The disagreement with the C data at the larger angles is primarily due to an overestimate of the

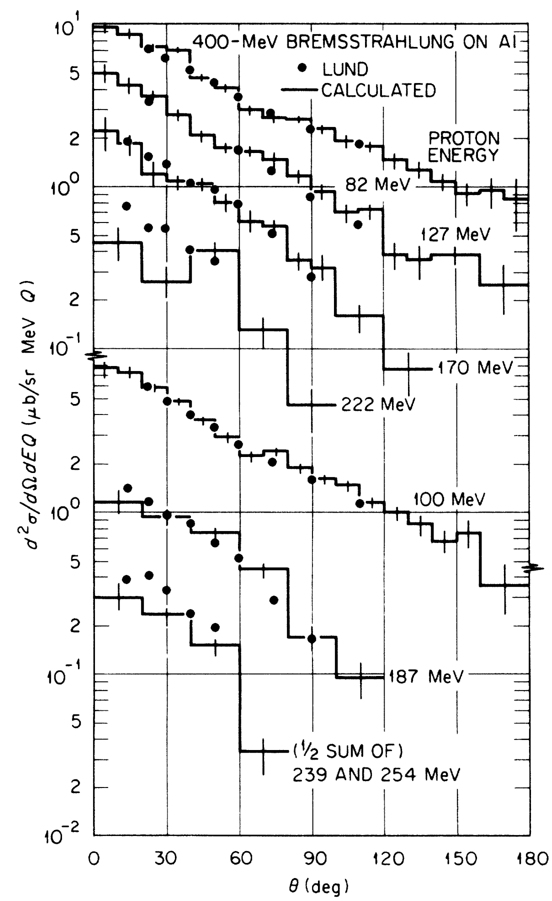

FIG. 2. Photoproton angular distributions for 400-MeV bremsstrahlung on Al.

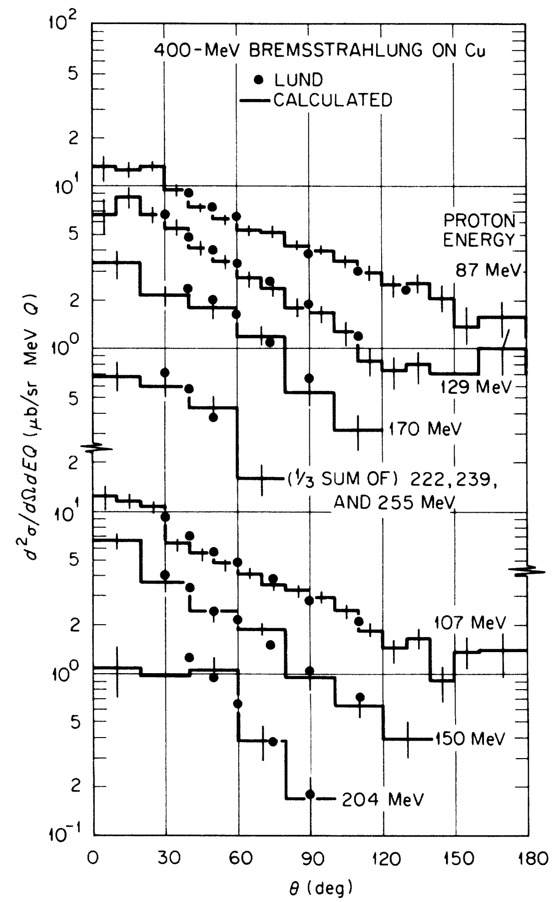

FIG. 3. Photoproton angular distributions for 400-MeV bremsstrahlung on Cu.

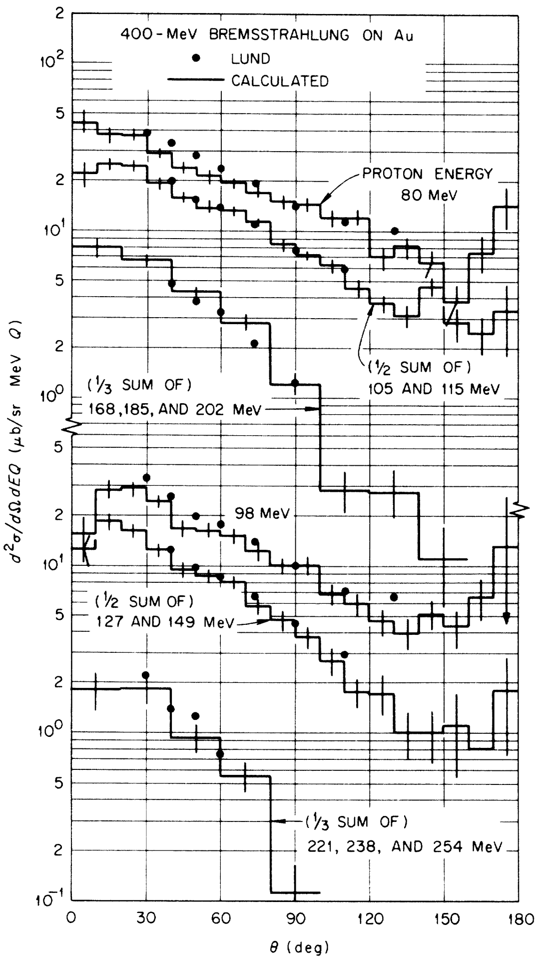

FIG. 4. Photoproton angular distributions for 400-MeV bremsstrahlung on Au.

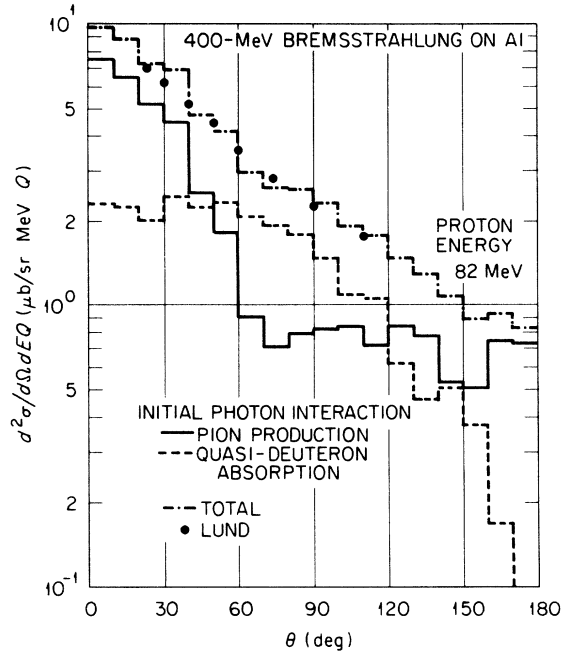

FIG. 5. Quasi-deuteron and pion-production contributions to the total photoproton angular distribution at 82-MeV proton energy for 400-MeV bremsstrahlung on Al.

average relative momentum associated with the neutron-proton pair which absorbed the incident photon. In addition, it is presently suspected that the size of the target nucleus for low A number ($A \lesssim 27$) targets is too large. This, of course, would lead to an overestimate of the cross sections. The disagreement at the higher proton energies for

TABLE I. Positively charged pion spectra from 400-MeV bremsstrahlung photons on a thin Al target.

Angular interval (deg)	$d\sigma/d\Omega$ (mb/sr Q) Energy interval (MeV) 0–40	40–80	80–120	120–160	160–180
0–20	5.77×10^{-2} (0.14)	4.52×10^{-2} (0.24)	2.76×10^{-2} (0.30)	1.76×10^{-2} (0.38)	2.01×10^{-2} (0.35)
20–40	7.75×10^{-2} (0.11)	4.44×10^{-2} (0.14)	1.92×10^{-2} (0.21)	1.22×10^{-2} (0.27)	1.75×10^{-2} (0.22)
40–60	7.04×10^{-2} (0.09)	5.23×10^{-2} (0.10)	2.95×10^{-2} (0.14)	2.10×10^{-2} (0.16)	1.02×10^{-2} (0.24)
60–80	6.35×10^{-2} (0.09)	5.65×10^{-2} (0.09)	1.72×10^{-2} (0.16)	1.11×10^{-2} (0.20)	4.17×10^{-3} (0.33)
80–100	7.97×10^{-2} (0.07)	5.53×10^{-2} (0.09)	2.39×10^{-2} (0.13)	4.79×10^{-3} (0.30)	2.17×10^{-3} (0.45)
100–120	8.02×10^{-2} (0.08)	6.02×10^{-2} (0.09)	1.44×10^{-2} (0.18)	3.24×10^{-3} (0.38)	9.27×10^{-4} (1.00)
120–140	7.95×10^{-2} (0.08)	5.51×10^{-2} (0.10)	1.25×10^{-2} (0.21)	5.68×10^{-4} (1.00)	...
140–160	9.14×10^{-2} (0.10)	4.78×10^{-2} (0.13)	1.30×10^{-2} (0.26)	...	...
160–180	9.00×10^{-2} (0.18)	6.00×10^{-2} (0.20)	7.50×10^{-3} (0.58)	...	...

TABLE II. Negatively charged pion spectra from 400-MeV bremsstrahlung photons on a thin Al target.

Angular interval (deg)	$d\sigma/d\Omega$ (mb/sr Q) Energy interval (MeV) 0–40	40–80	80–120	120–160	160–180
0–20	7.02×10^{-2} (0.19)	5.02×10^{-2} (0.22)	1.25×10^{-2} (0.45)	7.52×10^{-3} (0.58)	2.51×10^{-2} (0.32)
20–40	9.06×10^{-2} (0.10)	5.05×10^{-2} (0.13)	2.70×10^{-2} (0.18)	2.09×10^{-2} (0.20)	1.92×10^{-2} (0.21)
40–60	9.38×10^{-2} (0.08)	5.80×10^{-2} (0.09)	3.47×10^{-2} (0.13)	2.22×10^{-2} (0.13)	1.25×10^{-2} (0.21)
60–80	1.05×10^{-1} (0.07)	6.88×10^{-2} (0.08)	2.97×10^{-2} (0.12)	1.16×10^{-2} (0.20)	4.17×10^{-3} (0.33)
80–100	9.75×10^{-2} (0.07)	6.56×10^{-2} (0.08)	1.91×10^{-2} (0.15)	7.37×10^{-3} (0.24)	4.35×10^{-4} (1.00)
100–120	9.87×10^{-2} (0.07)	6.90×10^{-2} (0.08)	1.16×10^{-2} (0.20)	4.17×10^{-3} (0.33)	...
120–140	9.94×10^{-2} (0.08)	5.51×10^{-2} (0.10)	1.76×10^{-2} (0.18)	...	...
140–160	8.87×10^{-2} (0.10)	5.31×10^{-2} (0.13)	7.83×10^{-3} (0.33)	...	...
160–180	1.25×10^{-1} (0.14)	6.00×10^{-2} (0.20)	1.25×10^{-2} (0.45)	...	...

C and Al is due primarily to poor statistics.

The individual contributors to the total proton angular distribution, i.e., those protons produced when the initial photon is absorbed by a quasi-deuteron and those protons produced when the initial photon produces a pion, at a proton energy of 82 MeV, are shown in Fig. 5. It is quite apparent that the shape of the spectra could not be predicted without an excellent balance between the initial interactions.

Even though this set of data indicates a possible "A" dependence of L, it is still possible within reasonable limits to modify parts of the calculational model (i.e., nuclear radius, momentum distributions, etc.) such that L would be A independent. However, such modifications are at present unwarranted until more data become available. To facilitate this, the following experimental measurements are suggested: (1) photon-proton or neutron spectra resulting from 100- to 400-MeV bremsstrahlung photons on elements spanning the Periodic Table. This would help determine the energy and A dependence of L. (2) Photopion spectra resulting from the same bremsstrahlung photons. This would indicate whether or not the protons resulting from pion production in the initial interaction are overestimated, thereby reducing the actual value of L. In order to aid in the design of the second experiment, Tables I and II give the expected charged-pion yield from 400-MeV bremsstrahlung on Al. The quantity below each number represents the standard error.

The code system used to calculate photonuclear interactions is available from the Radiation Shielding Information Center of the Oak Ridge National Laboratory.

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