NEUTRON-PROTON BREMSSTRAHLUNG AT 197 MeV*

P. F. M. Koehler†, K. W. Rothe,‡ and E. H. Thorndike
Department of Physics and Astronomy, University of Rochester, Rochester, New York
(Received 17 April 1967)

A knowledge of off-mass-shell behavior of the nucleon-nucleon interaction is very desirable, both as a test of various theoretical pictures[1] of the N-N interaction, and as input information for nuclear structure calculations. Nucleon-nucleon bremsstrahlung, $N+N\rightarrow N+N+\gamma$, is a promising way to study such behavior, and for this reason p-p bremsstrahlung (hereafter $pp\gamma$) has received much attention in recent years, both experimental[2-6] and theoretical.[7-10]

Although equally interesting, n-p bremsstrahlung (hereafter $np\gamma$) has received much less attention. Calculations by Ashkin and Marshak[11] and by Cutkosky[12] suggest that the $np\gamma$ cross section is several times larger than the $pp\gamma$ cross section; however, calculations by Duck and Pearce[13] predict that the two cross sections are comparable. Experiments[14-16] studying the production of high-energy (>20-MeV) γ rays from proton bombardment of complex nuclei have been interpreted in terms of $np\gamma$ inside the nucleus. However, Beckham[17] found that the extraction of the free $np\gamma$ cross section from such data is very uncertain and model dependent. The present work was undertaken to provide a more reliable $np\gamma$ cross-section measurement.

The experiment was performed with a proton beam and a target of "almost free" neutrons in deuterium. (The alternative of using a neutron beam and a hydrogen target was discarded because a neutron beam combining sufficient intensity and energy definition was not available.) The proton-deuteron radiative processes are interpreted by the following extension of the spectator model.[18] The incident proton interacts with one of the nucleons in the deuteron, which has a momentum distribution given by the deuteron wave function. The γ ray is produced in this initial interaction, and does not interact further. On occasions the spectator nucleon will interact with the incident or struck nucleon. These final-state interactions will distort the kinematics from those of the simple quasifree process, and sometimes cause binding of the interacting particles.

The model just described leads to the six processes listed in Table I. The constants K_1, K_2, and K_3 allow for the reduction of the quasifree cross sections below the free ones due to Glauber shielding,[19] and to final-state interactions, which either distort the kinematics (6), or bind particles (4, 5). The likelihood of deuteron binding (4) is given by a spin factor of $\frac{3}{4}$, and the square of the deuteron form factor $|F(q^2)|^2$.

Experimental method.—A 2-in. diam liquid-deuterium target was bombarded with a 90% polarized proton beam whose energy at the target center was 197± 5 MeV. The γ rays were detected in a counter whose efficiency[20] rose smoothly from zero near $E_\gamma = 40$ MeV to 0.10 at $E_\gamma = 110$ MeV. The charged particles (one

Table I. Proton-deuteron radiative processes, according to a spectator model with final-state interactions.

Reaction	Name	Cross section
(1) $p+d\rightarrow n_s+p+p+\gamma$	Quasifree $pp\gamma$	$K_1\sigma_{pp\gamma}$
(2) $p+d\rightarrow p_s+n+p+\gamma$	Quasifree $pn\gamma$	$K_2\sigma_{np\gamma}$
(3) $p+d\rightarrow p_s+d+\gamma$	Quasifree pn radiative capture	$K_3\sigma_{\text{cap}}$
(4) $p+d\rightarrow p+d+\gamma$	$pd\gamma$	$(\sigma_{pp\gamma}+\sigma_{np\gamma})\frac{3}{4}\lvert F(q^2)\rvert^2$
(5) $p+d\rightarrow He^3+\gamma$	$He^3\gamma$	...
(6) $p+d\rightarrow p+n+p+\gamma$	Multiple scattering term	...

or two) emerging in coincidence with a γ ray were noted in large-area scintillation counters and observed in spark chambers. These were located symmetrically about the beam and provided good direction and fair range information, but did not distinguish between protons and deuterons. Figure 1 shows the two differerent spark chamber arrangements used. Neutrons, spectator nucleons, and He^3 particles were not detected.

Identification of events.—Two-prong events were candidates for Reactions (1), (4), and (6). Those that failed to fit (4) (a three-constraint fit) were assumed to be (1) (a zero-constraint fit). Examples of Reaction (6) thus classified as (1) will be characterized by an anomalously high spectator momentum. In fact, the neutron momentum spectrum calculated for those two-prong events which failed to fit (4) was in good agreement with the expected spectator neutron spectrum. Hence Reaction (6) is small compared to (1) in the region studied. Reaction cross sections (1) and (4) were fitted with functional forms to allow extrapolation to regions where only one, or none, of the two charged particles was detected.

One-prong events were candidates for Reactions (2) and (3), in addition to (1), (4), and (6). Reaction (3) exhibits two-body kinematics smeared by the spectator momentum, so that deuterons emerge in a narrow forward cone. The excess events in this cone, compared with nearby regions, were assumed to be examples of Reaction (3). In a separate run, the charged particles which emerge near the center of the forward cone in coincidence with a γ ray were identified as deuterons by their time of flight and total energy. Those one-prong events left after processes (1), (3), and (4) had been subtracted were assumed to be examples of Reactions (2) and (6). Here, spark-chamber information was not used, but rather coincidence rates of a single charged particle with a γ ray, obtained with counters as shown in Fig. 1(a).

Reaction (5) gave rise only to zero-prong events (γ rays). Measurements[21] at 156 MeV showed this cross section to be small.

Results: Quasifree $pp\gamma$, (1).—Angular distributions and the γ-energy spectrum were found to be in good agreement with predictions based on the results of the free $pp\gamma$ experiment,[5] after the motion of the target nucleon and the experimental resolutions had been folded in. After correcting for the constraints imposed

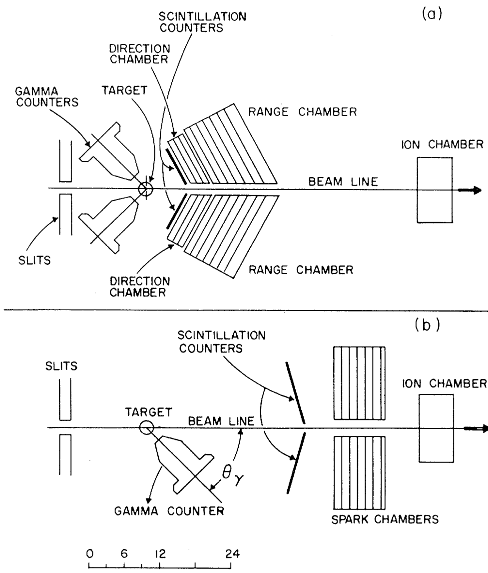

FIG. 1. Top view of the apparatus. (a) The spark chambers used for the detection of two-prong events from processes (1) and (4). (b) The spark chambers used for the detection of one-prong events from process (3).

by the apparatus and the identification procedure, we found that the average ratio of the quasifree $pp\gamma$ to the free $pp\gamma$ differential cross sections (K_1) was 0.46 ± 0.10.

Quasifree pn radiative capture, (3).—The differential cross sections showed the same angular distribution as the prediction from deuteron photodisintegration.[22] The average ratio of quasifree to free radiative capture (K_3) was 0.75 ± 0.15. The right-left γ-ray asymmetries due to the polarized proton beam were in good agreement with calculations for the proton polarization in deuteron photodisintegration.[22]

Quasifree $pn\gamma$, (2).—Upper and lower limits for the free $np\gamma$ cross section were obtained from the quasifree $pn\gamma$ results. To obtain the upper limit, processes (1), (3), and (4) were subtracted from the single charged-particle coincidences, and the remainder, (2) and (6), was assumed to be only (2). K_2 was taken as 0.65, as suggested by the measured values of K_1 and K_3. To obtain the lower limit, we imagined the final-state interactions turned off. Then Reactions (4), (5), and (6) would vanish, and K_1, K_2, and K_3 would be near 1. Free $pp\gamma$ and free np radiative capture processes were subtracted from the single charged-particle coincidences, and the remainder was taken as

Table II. Inferred free *n-p* bremsstrahlung cross sections. The differential cross section $d\sigma/d\Omega_\gamma(E_\gamma > 40$ MeV) and the γ-ray direction θ_γ are expressed in the $np\gamma$ center of mass. E_γ is the γ-ray laboratory energy. The error bars on the cross sections inferred from quasifree $pn\gamma$ encompass the upper and lower limits (see text); experimental errors are typically ±15%. The errors listed with the cross sections inferred from $pd\gamma$ are experimental only, i.e., they do not include an estimate of the uncertainty due to theory.

Source of Result	$\frac{d\sigma}{d\Omega_\gamma}(E_\gamma > 40$ MeV) (μb/sr) $\theta_\gamma = 60°$	$\theta_\gamma = 108°$	$\theta_\gamma = 147°$	$\sigma_{tot}(E_\gamma > 40$ MeV) (μb)
Quasifree $pn\gamma$	3.4 ±1.0	2.5 ±0.8	1.8 ±0.5	35 ±12
$pd\gamma$		2.7 ±0.4	3.2 ±0.5	

free $np\gamma$, i.e., $K_2 = 1$. In both cases, the background subtraction was typically 40% of the single charged-particle coincidences, leaving 60% to be interpreted as $np\gamma$. The average of the upper and lower limits is listed in Table II, with error bars chosen to encompass both limits. Cross sections are for $E_\gamma > 40$ MeV. Integrating over all γ directions on the basis of the 3 points, a total free $np\gamma$ cross section was obtained, again for $E_\gamma > 40$ MeV.

$pd\gamma$, (4). –By taking $\sigma_{pd\gamma} = (\sigma_{pp\gamma} + \sigma_{np\gamma})\frac{3}{4}|F(q^2)|^2$, the $pd\gamma$ data were used to obtain a free $np\gamma$ cross section. The results are listed in Table II. The errors quoted do not include an estimate of the uncertainty in the theory. As the form factor was small (typically $|F|^2 = 0.04$) in the region where the reaction $pd\gamma$ could be detected, this method of obtaining $\sigma_{np\gamma}$ is considered less reliable than that using Reaction (2). Note that the two methods are in fair agreement.

Discussion. –We have found that the total *n-p* bremsstrahlung cross section, for $E_\gamma > 40$ MeV, lies between 23 and 47 μb, implying that the ratio[5] $\sigma_{np\gamma}/\sigma_{pp\gamma}$ lies between 30 and 70. These numbers are to be compared with theoretical estimates of $\sigma_{np\gamma} \approx 22$ μb, by Cutkosky[12] (fair agreement), and of $\sigma_{np\gamma}/\sigma_{pp\gamma} \approx 1$ to 2, by Pearce and Duck[13] (poor agreement). (It should be noted that Pearce and Duck's calculation is not of total cross section, but for a restricted kinematical region.)

The only related experiment was done by Edgington and Rose[16] at 140 MeV. They employed a D_2O-H_2O subtraction and obtained a poor-resolution γ-energy spectrum; charged particles were not observed. No evidence was found for the existence of the quasifree radiative-capture process ($K_3 < 0.1$), in marked contrast to our result ($K_3 = 0.75 \pm 0.10$). They found 8 μb for the $np\gamma$ total cross section using a method of interpretation comparable to the one that gave us 47 μb (our upper limit). The two experiments are clearly incompatible; the difference cannot be explained by the difference in incident energy. We believe ours to be correct, though we cannot pinpoint an error in the other one.

The large value found here for $\sigma_{np\gamma}$ makes a measurement of the free $np\gamma$ process, using a neutron beam, decidedly more feasible than previously believed.

*Work supported by the U. S. Atomic Energy Commission.

†Now at the University of Maryland, College Park, Maryland.

‡Now at the University of Pennsylvania, Philadelphia, Pennsylvania.

[1]M. J. Moravcsik, The Two-Nucleon Interaction (Clarendon Press, Oxford, England, 1963); E. Lomon, to be published; D. Wong, to be published.

[2]B. Gottschalk, W. J. Shlaer, and K. H. Wang, Phys. Letters 16, 294 (1965); Nucl. Phys. 75, 549 (1966).

[3]R. E. Warner, Can. J. Phys. 44, 1225 (1966).

[4]I. Šlaus, J. W. Verba, J. R. Richardson, C. F. Carlson, W. T. H. van Oers, and S. L. August, Phys. Rev. Letters 17, 536 (1966).

[5]K. W. Rothe, P. F. M. Koehler, and E. H. Thorndike, Phys. Rev. (to be published).

[6]M. L. Halbert, D. L. Mason, and C. L. Northcliffe, in Proceedings of the International Conference on Nucleon-Nucleon Interactions, Gainesville, Florida, March 1967 (unpublished).

[7]M. I. Sobel and A. H. Cromer, Phys. Rev. 132, 2698 (1963).

[8]I. Duck and W. A. Pearce, Phys. Letters 21, 669 (1966).

[9]P. Signell and D. Marker, in Proceedings of Williamsburg Conference on Intermediate Energy Physics, February, 1966 (unpublished), Vol. II, p. 667.

[10]Y. Ueda, Phys. Rev. 145, 1214 (1966).

[11]J. Ashkin and R. E. Marshak, Phys. Rev. 76, 58, 989 (1949).

[12]R. E. Cutkosky, Phys. Rev. 103, 505 (1956).

[13]W. A. Pearce and I. Duck, in Proceedings of the

International Conference on Nucleon-Nucleon Interactions, Gainesville, Florida, March 1967 (unpublished)

[14]R. Wilson, Phys. Rev. 85, 563 (1952).

[15]D. Cohen, B. J. Moyer, H. C. Shaw, and C. N. Waddell, Phys. Rev. 130, 1505 (1963).

[16]J. A. Edgington and B. Rose, Nucl. Phys. 89, 523 (1966).

[17]W. C. Beckham, University of California Radiation Laboratory Report UCRL-7001 (unpublished).

[18]A. Kuckes, R. Wilson, and P. Cooper, Ann. Phys. (N.Y.) 15, 193 (1961).

[19]R. J. Glauber, Phys. Rev. 100, 242 (1955).

[20]The efficiency calibration was done by calculation and checked by measurements with a tagged photon beam. The counter is described in Ref. 5.

[21]D. Bachelier, M. Bernas, I. Brissaud, C. Détraz, J. P. Didelez, H. Langevin-Joliot, J. Lee, and P. Radvanyi, Phys. Letters 21, 697 (1966).

[22]A. Donnachie and P. J. O'Donnell, Nucl. Phys. 53, 128 (1964).

QUARK-MODEL CALCULATION OF THE Λ TO Σ RATIO IN THE ISOSPIN-1 s-WAVE $\bar{K}N$ REACTION

G. Morpurgo

Istituto di Fisica dell'Università di Genova, Istituto Nazionale di Fisica Nucleare, Sezione di Genova, Genova, Italy

(Received 3 April 1967)

It is shown that the ratio between the amplitudes of the reactions $\bar{K}_0+p\to\Lambda+\pi^+$ and $\bar{K}_0+p\to\Sigma^0+\pi^+$ in the s-wave region can be calculated by the quark model under the assumption that no nearby $J=\frac{1}{2}^-$ resonance exists affecting these amplitudes. The parameter $\mathcal{E}_{(s\ \mathrm{wave})}$ is shown to be 0.67 and is larger than this if, in addition, p waves are included. The experimental value is 0.35 ± 0.03.

The nonrelativistic quark model[1,2] has had many significant experimental confirmations. In spite of the fact that different opinions exist as to whether these successes are tests of the model in its realistic acception, or of a more abstract underlying algebraic structure, it appears useful to look for additional predictions of the model, in order to establish its limits of validity.

We shall consider here the $\bar{K}$-nucleon reactions at low energy where only the s wave is important, and show that if the s-wave $T=1$ amplitudes describing such reactions are purely direct amplitudes (that is, they are not influenced by some nearby resonance), it is possible to calculate with the quark model the ratio

$$\mathcal{E}=\left(\frac{\Lambda}{\Lambda+\Sigma}\right)_{T=1}=\frac{|N_1|^2}{|N_1|^2+|M_1|^2(q_\Sigma/q_\Lambda)}. \quad (1)$$

We obtain

$$\mathcal{E}_{(s\ \mathrm{wave})}\cong0.67 \quad (2)$$

and $\mathcal{E}\geqslant0.67$ when the p waves also enter. In the above, N_1 is the amplitude[3] for the reaction $\bar{K}_0+p\to\Lambda+\pi^+$, and M_1 is the amplitude for the reaction $\bar{K}_0+p\to(1/\sqrt{2})(\Sigma^0+\pi^+-\Sigma^++\pi^0)$; q_Λ and q_Σ are the center-of-mass momenta of the outgoing Λ and Σ, respectively. To show this, observe that, if only s waves enter, both M_1 and N_1 can be expressed in terms of the same spin-nonflip amplitude (which we call f_0) for the reaction

$$\bar{K}_0+\mathcal{P}\to\lambda+\pi^+, \quad (3)$$

where $\mathcal{P}$ is the $T_3=+\frac{1}{2}$ nonstrange quark and λ is the strange quark.

In fact, both the $\Lambda^0\pi^+$ and $\Sigma^0\pi^+$ s-wave final states are produced from the initial $\bar{K}_0p$ state when one or the other of the two $\mathcal{P}$ quarks in the proton changes into a λ quark. By using the standard wave functions[4] of p, Λ, and Σ, one easily gets

$$|N_1|^2=\tfrac{3}{2}|f_0|^2 \text{ and } |M_1|^2=|f_0|^2;$$

therefore, recalling that for absorption at rest we have $q_\Sigma/q_\Lambda=0.7$, we get the value (2) of $\mathcal{E}_{(s\ \mathrm{wave})}$, where we have neglected the possible dependence of f_0 on the momentum q_Λ or q_Σ. If p and higher waves are included, the value of $\mathcal{E}$ is, in general, larger than the value $\mathcal{E}_{(s\ \mathrm{wave})}$ calculated above. In fact, the most general amplitude of (3) can be written as $f+g\sigma\cdot\hat{n}$ where f and g are functions of the scattering angle. For an unpolarized proton, we therefore have

$$|N_1|^2=\tfrac{3}{2}(|f|^2+|g|^2) \text{ and } |M_1|^2=|f|^2+\tfrac{1}{9}|g|^2. \quad (4)$$