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PROTON-PROTON BREMSSTRAHLUNG AT 204 MeV*

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Extensive nucleon-nucleon elastic-scattering experiments[1] are accounted for by various theoretical[2] pictures: potentials, both phenomenological[3] and meson-theoretic[4]; boundary-condition models[5]; and dispersion-theoretic calculations.[6] The implications of these pictures transcend elastic N-N scattering; they describe the two-nucleon interaction off the mass shell as well as on the mass shell. Beyond its intrinsic interest, the off-mass-shell behavior is relevant to few- and many-nucleon calculations based on two-nucleon interactions. The off-mass-shell aspect of the various theoretical descriptions of the N-N interaction is essentially untested by experimental data. The nucleon-nucleon bremsstrahlung reaction $N+N\to N+N+\gamma$ should provide the much-needed test.

Proton-proton bremsstrahlung was treated theoretically first by Ashkin and Marshak,[7] and more recently by Sobel and Cromer,[8] and others[9-12] who utilize a N-N potential, and by Ueda[13] who performed a dispersion-theoretic calculation. Nuclear bremsstrahlung, from targets of complex nuclei, was first observed by Wilson[14] who attributed the γ rays to n-p bremsstrahlung.

Free p-p bremsstrahlung has been observed by Gottschalk, Shlaer, and Wang,[15] Warner,[16] Richardson et al.,[17] and ourselves.[18] These initial measurements indicated the general magnitude of the bremsstrahlung process (low compared to Sobel and Cromer's calculations by a factor of 4-10), but showed little of its functional dependence, and ignored spin. Here we present the γ-ray energy spectra, distributions in the two-nucleon c.m. scattering angles, and γ-ray and p-p asymmetries due to an initially polarized proton beam.

Experimental method.—The experiment was performed by bombarding a liquid-hydrogen target with a 90% polarized, 204-MeV proton beam. (See Fig. 1.) The γ rays were detected by two threshold counters which gave good direction information.[19] The two final-state protons were caught in a spark-chamber array covering essentially the complete angular region into which they could scatter. A coincidence between a γ ray and two protons (signaled by scintillation counters in front of the chambers) triggered the spark chambers. The direction of all three final-state particles and the energies (by range) of the two protons were thus determined. Since the reaction was three

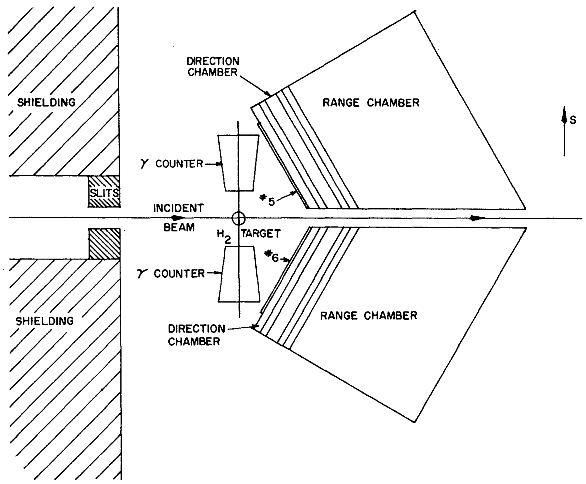

FIG. 1. Plan view of the experiment.

times overdetermined, background rejection was good. A total of 513 p-p bremsstrahlung events were obtained with the γ detectors at laboratory angles 45, 90, and 135°.

Kinematical variables. – The following five variables are used to specify the final-state kinematics: $\theta_\gamma, \varphi_\gamma, E_\gamma$ (the polar angle, azimuthal angle, and energy of the γ ray in the three-particle center of mass), $\theta_{\text{c.m.}}$ and $\varphi_{\text{c.m.}}$ (the polar angle and azimuthal angle of the vector $\vec{P}_1 - \vec{P}_2$ formed by taking the difference of the momenta of the two final-state protons in the three-particle center-of-mass system). Polar angles are defined so that $\theta = 0°$ along the beam line; azimuthal angles are defined so that $\varphi = 0°$ in the horizontal plane. θ_γ and φ_γ are appropriate to multipole expansion treatments of bremsstrahlung.[12] E_γ is a measure of how far the interaction is off the mass shell. $\theta_{\text{c.m.}}$ and $\varphi_{\text{c.m.}}$ reduce to the conventional center-of-mass scattering angles for N-N elastic in the limit as $E \to 0$.

Results. – The distributions shown in Figs. 2(a), 2(b), and 2(c) refer to $\theta_\gamma = 108°$ ($\theta_{\gamma\,\text{lab}} = 90°$), after adding data from $\varphi_\gamma = 0$ and 180°. Data for $\theta_\gamma = 59$ and 146° ($\theta_{\gamma\,\text{lab}} = 45$ and 135°) indicate the same features as 108°, but with poorer statistics. All quantities not specified have been summed over, weighted by the experimental detection efficiencies. Symmetries including those resulting from the identical nature of the two protons have been utilized to "fold" the angular distributions into smaller ranges.

Figure 2(a) shows the γ-ray energy spectrum. Note that it is not the $1/E_\gamma$ spectrum typical of purely electromagnetic bremsstrahlung processes. The curve is due to Ueda[13] and has been normalized to the same area as the data for $E_\gamma \geq 35$ MeV. Agreement is good.

Figure 2(b) shows the angular distribution versus $\cos\theta_{\text{c.m.}}$. It is not isotropic, and implies that the final two-proton system contains substantial p state, or higher L.

Figure 2(c) shows the angular distribution versus $\varphi_{\text{c.m.}}$. It is not isotropic, but indicates a strong preference for the γ ray to lie in the two-proton scattering plane.[20] We are unable to give a theoretical explanation of this anisotropy.

Figure 2(d) shows the two-proton asymmetry

$$\epsilon = \frac{N(270° < \varphi_{\text{c.m.}} < 90°, \theta_{\text{c.m.}}) - N(90° < \varphi_{\text{c.m.}} < 270°, \theta_{\text{c.m.}})}{N(270° < \varphi_{\text{c.m.}} < 90°, \theta_{\text{c.m.}}) + N(90° < \varphi_{\text{c.m.}} < 270°, \theta_{\text{c.m.}})}$$

(normalized to a 100% polarized incident beam) versus $\theta_{\text{c.m.}}$. Data from all γ-ray directions have been combined in this figure. A minimum near $\theta_{\text{c.m.}} = 50°$ is suggested. The curve is the asymmetry (or polarization parameter P) for elastic p-p scattering.[1] There is agreement in sign and general magnitude.

Left-right asymmetries for the γ rays (normalized to a 100% polarized incident beam) are listed in Table I. The sign convention is such that a positive asymmetry implies that $\vec{P}_{\text{inc}} \times \vec{K}_\gamma$ is parallel to the incident polarization, where $\vec{P}_{\text{inc}}$ and $\vec{K}_\gamma$ are the momenta of the incident proton and the γ ray, respectively. These asymmetries agree in sign and general magnitude with those predicted[21] and observed[22] in radiative n-p capture, $n + p \to d + \gamma$, at comparable energy. Table I also lists differential cross sections $d\sigma/d\Omega_\gamma$, together with the calculations of Ueda,[13] which are typically a factor of 2.5 high.

Other laboratories[15-17] have measured the cross section

$$\left(\frac{d^3\sigma}{d\Omega_{\text{proton 1}}\, d\Omega_{\text{proton 2}}\, dE_{\text{proton 1}}}\right)_{\text{lab}},$$

Table I. Gamma-ray asymmetries normalized to 100% incident-beam polarization, together with measured and predicted values for the differential cross section $d\sigma/d\Omega_\gamma$.

		$(d\sigma/d\Omega_\gamma)_{E_\gamma \geq 35 \text{ MeV}}$	
θ_γ	Asymmetry	Measured (nb/sr)	Predicted[a] (nb/sr)
59°	0.110 ± 0.175	27.0 ± 5.2	99.3
108°	−0.192 ± 0.061	30.1 ± 3.5	77.1
146°	−0.135 ± 0.091	47.6 ± 6.8	129.0
All	−0.162 ± 0.049	•••	•••

[a]Ref. 13.

where the two protons are observed at equal angles to the beam and in a coplanar geometry. In terms of the variables defined above, $\varphi_{\text{c.m.}} = 0°$, $\varphi_\gamma = 0°$, and $\theta_{\text{c.m.}}$ is near 90°. These experiments are thus much more restricted than ours, although these limitations could be circumvented by observing the protons at unequal angles and in a noncoplanar geometry. We can compare that portion of our data near $\varphi_{\text{c.m.}} = 0°$, $\theta_{\text{c.m.}} \approx 90°$ with the measurements of the other laboratories. We find $(d^2\sigma/d\Omega_{p1}d\Omega_{p2}) = 13$, 14, and 29 μb/sr^2 (±20%) at $\theta_{p1} = \theta_{p2} = 30$, 35, and 40°, respectively. These results lie a factor of 0.8 to 1.4 above the 158-MeV measurements.[15,23]

The finite vertical extent of proton counters in coplanar-geometry experiments necessitates a correction which is sensitive to the angular distribution in $\varphi_{\text{c.m.}}$. If the behavior shown in Fig. 2(c) persists at 158[23] and 48 MeV, then the measurements of Gottschalk, Schlaer, and Wang[15], and Warner[16] should be corrected upwards by amounts varying between 20% and 100%. Future experiments utilizing this geometry must be prepared to take account of this behavior.

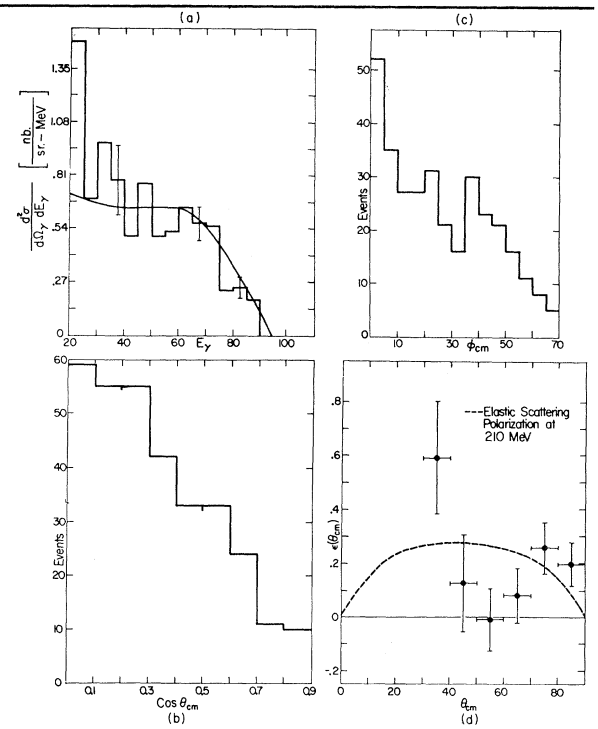

FIG. 2. (a) Gamma-ray energy spectrum for $\theta_\gamma = 180°$. (b) Distribution of events as a function of $\cos\theta_{\text{c.m.}}$ for $\theta_\gamma = 180°$. The ordinate is proportional to $(d^2\sigma/d\Omega_\gamma d\Omega_{\text{c.m.}})$. (c) Distribution of events as a function of $\varphi_{\text{c.m.}}$, for $\theta_\gamma = 108°$. The ordinate is proportional to $(d^2\sigma/d\Omega_\gamma d\Omega_{\text{c.m.}})$. (d) Proton asymmetries (normalized to 100% incident-beam polarization) as a function of $\theta_{\text{c.m.}}$ for all events.

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OBSERVATIONS ON THE PROPAGATION OF SOLAR-FLARE ELECTRONS IN INTERPLANETARY SPACE*

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Recently, Van Allen and Krimigis[1] measured fluxes of electrons with energies of 40 to 150 keV in interplanetary space following solar chromospheric flares. The flux-versus-time profile of these events strongly suggests that the electrons had undergone propagation by diffusion in some spatial region. These authors assume that the diffusion took place in interplanetary space and showed that the flux-versus-time behavior could be empirically fitted to a simple, isotropic diffusion equation. The purpose of this Letter is to report additional examples of solar-flare electron events and to show that the propagation of electrons in the neighborhood of the earth is highly anisotropic in two respects. The observations were made from the first and third interplanetary monitoring platform satellites during 1964, 1965, and 1966. The University of California experiment consists of two Geiger-Müller tubes and an ionization chamber. One of the counter tubes is used in conjunction with a high atomic number scattering foil so that its directional response is to electrons only. With this apparatus it is possible to identify and measure fluxes of protons and electrons in pure or mixed beams provided that the counting rates due to the particle fluxes are comparable with or larger than the counter backgrounds. A description of this apparatus has been previously published.[2]

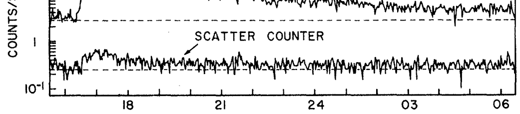

FIG. 1. The solar-flare electron event of 8 October 1965.

We have identified a total of eight solar-flare electron events to date. These include two of the events observed on Mariner IV and already reported by Van Allen and Krimigis.[1] The general features of solar electron fluxes which have propagated to the earth are illustrated here in Figs. 1 and 2. These events are seen to be characterized by a rapid buildup of flux requiring 15 to 30 minutes followed by a slow decay over many hours. This behavior also characterized the events studied by Van Allen and Krimigis. All known solar electron events to date are summarized in Table I. Included there are not only the events by us but the events of Van Allen and Krimigis. Table I also gives information on the associated solar flares obtained from the ESSA-ITSA Bulletin, Pt. B, Solar and Geophysical Data. Inspection of this table leads to the following conclusions:

(1) All but one of the solar electron events are clearly associated with solar flares. The associated flare is often accompanied by radio noise and sometimes by x-ray emission. The appearance of the electrons is delayed from 23 to 55 minutes with respect to the radio burst, or in cases when that has not been reported, with respect to the flare maximum. These time delays are reasonable in view of the fact that the travel time of an unscattered 50-keV electron with small pitch angle from sun to earth along the interplanetary field line is 24 minutes.

(2) The importance of the flares is seen to be small in most cases. Thus 1−, 1, and 1+ flares are able to accelerate and eject large numbers of energetic electrons.

(3) The flares ejecting the electron fluxes occur in several different plage regions. Most