of resonant coupling is probably not so important as for the quinols. The included molecules are much smaller than the cavities and are so well attached to the walls that they behave as a single particle subject to forced oscillation.

In principle the rate at which the molecule jumps about the cage can be measured, but in the present work only preliminary estimates of this quantity were obtained.

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ENERGY DEPENDENCE OF PROTON-PROTON BREMSSTRAHLUNG*

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Recent development in experimental techniques has made possible the measurement of the proton-proton bremsstrahlung cross section and thus has offered an insight into the nuclear interaction off the energy shell. It was hoped that these data would help to differentiate between various nuclear potentials. The measurements recently performed at 200,[1] 158,[2] and 48 MeV[3] disagree strongly with the theoretical predictions.[4-6] This disagreement has focused attention on the bremsstrahlung process, making a careful investigation of both theories and measurements imperative. The problems are particularly acute at lower energies where apparently the disagreement is more serious. A considerable effort is being made to clarify various theoretical inadequacies, e.g., the effect of the terms containing nuclear interactions in final and initial states, Coulomb effects, and additional terms in the T matrix off the energy shell.[5] The measurements are difficult and prone to many systematic errors. The bremsstrahlung cross section is only 10^{-4} as large as the proton elastic scattering and 10^{-2} as large as the $(p, 2p)$ reaction on possible contaminants. Even the measurement which is kinematically overdetermined does not completely discriminate bremsstrahlung events from the background. The background is caused by $(p, 2p)$ reactions on the contaminants, accidental coincidences due to gamma rays and neutrons, and accidentals involving elastically scattered protons which undergo reactions in the detector or elastically scattered protons associated with the low-energy components in the incident beam. The accidentals associated with the elastic scattering can be reduced by introducing a third counter in anticoincidence at the conjugate angle. The neutron and gamma background is decreased by using thin passing counters. Although both methods reduce background and, therefore, allow a considerably faster accumulation of the data, they may cause losses of real events.

The purpose of the present work was to provide an accurate measurement of the cross section which could be compared with the independent measurement at 48 MeV,[3] to investi-

Table I. Results of various measurements of the cross section $d\sigma/d\Omega_1 d\Omega_2$.

Energy (MeV)	$\theta_{\min}$, $\theta_{\max}$ (deg)	$\Delta\varphi$ (deg)	$d\sigma/d\Omega_1 d\Omega_2$ (μb/sr^2) Uncorrected	Corrected Nonrelativistic	Corrected Relativistic
46	25, 35	±4	3.6 ± 1.1	3.6 ± 1.1	3.4 ± 1.0
46	27.2, 32.8	±10.5	2.7 ± 0.8	3.6 ± 1.1	3.7 ± 1.1
46	27, 33	±3.8	3.5 ± 1.5	3.5 ± 1.5	3.3 ± 1.4
33.5	27.2, 32.8	±10.5	2.0 ± 0.6		3.0 ± 0.8

gate the energy dependence of the cross section, and to investigate the angular distribution of gamma rays for a fixed pair of proton angles.

Beams of 33.5- and 46-MeV protons, monochromatic to better than 1:10^5, were produced by the University of California, Los Angeles, spiral-field cyclotron. The incident protons bombarded a gas target, and the two outgoing protons were detected by scintillation counters in coincidence at $\theta_1 = \theta_2 = 30°$ and $\varphi = 180°$. The remarkably low background in the experimental area[7] has enabled us to dispense with the passing counters and thus eliminated a possible source of error. The coincident pulses from the two counters were stored in an on-line computer simultaneously with the accidental coincidences obtained by delaying pulses from one counter by 35 nsec. After subtracting the accidental events (which in the bremsstrahlung region represent about 25% of all events), two-dimensional energy plots revealed a pronounced $H(p, 2p)$ group, a $D(p, 2p)$ group, and a few events due to other contaminations (7% of all events in the region of interest). The main contaminant was air, and the corresponding $(p, 2p)$ events were subtracted on the basis of measurements made using the gas cell filled with air.

In the performance of the experiment, continuous monitoring was made for possible gain shifts, possible lateral beam drifts, contamination build-up, and possible counting losses in the electronics. Additionally, checks were made on changes in beam profile, performance of the coincidence circuitry, and the counting rate when the cell was evacuated.

The kinematics of the bremsstrahlung causes near coplanarity of nucleon momenta; thus, the effective solid angle can differ from the apparent one.[8] Correction for this effect and for the variation of the phase-space factor were calculated nonrelativistically[9] and relativistically. The maximum deviation from $\varphi = 180°$ for outgoing protons at $\theta_1 = \theta_2 = 30°$, $E_{\text{inc}} = 46$ MeV is approximately 12°. In this experiment three different geometries and two gas cells were used. The operating pressures were 1 and 2 atm, respectively.

The absolute cross section was determined directly from beam integration and by comparison with the elastic proton scattering. Under the same conditions the reactions $D(p, 2p)$ and $C^{12}(p, 2p)$ were studied using the gas cell and solid targets. The measurements were always in agreement within 10%.

The results of the independent measurements are summarized in Table I, together with the characteristics of the geometries. The final value of $d\sigma/d\Omega_1 d\Omega_2$ at 46 MeV is (3.46 ± 0.6 μb/(sr)^2 and at 33.5 MeV is (3.0 ± 0.8) μb/(sr)^2. The quoted uncertainties are the over-all uncertainties. The cross section $d\sigma/d\Omega_1 d\Omega_2 dE_1$ is shown in Fig. 1(a). It is compared with the calculation[10] done for $\theta_1 = \theta_2 = 30°$ using the Hamada-Johnston potential. The finite energy and angular resolutions were not folded in. The gamma-ray angular distributions are shown in Fig. 1(b). Though the absolute value of the cross section is not reproduced by the theory, the shape is reasonably accounted for.[10]

Since the present data essentially confirm the 48-MeV data,[3] it seems that the theoretical predictions at lower energies are even less correct than at higher energies. However, the 34- to 48-MeV data represent averages over φ and are compared with the calculations done for $\varphi = 180°$. Measurements at higher energies[1,11,12] indicate that the cross sections fall off as the noncoplanarity of the final-state protons approaches the kinematical limits. Unless the φ dependence of the transition-matrix element at lower energies is much stronger than at higher energies, the discrepancy is still almost one order of magnitude. The experimental cross sections for various incident energies are compared with the theoretical

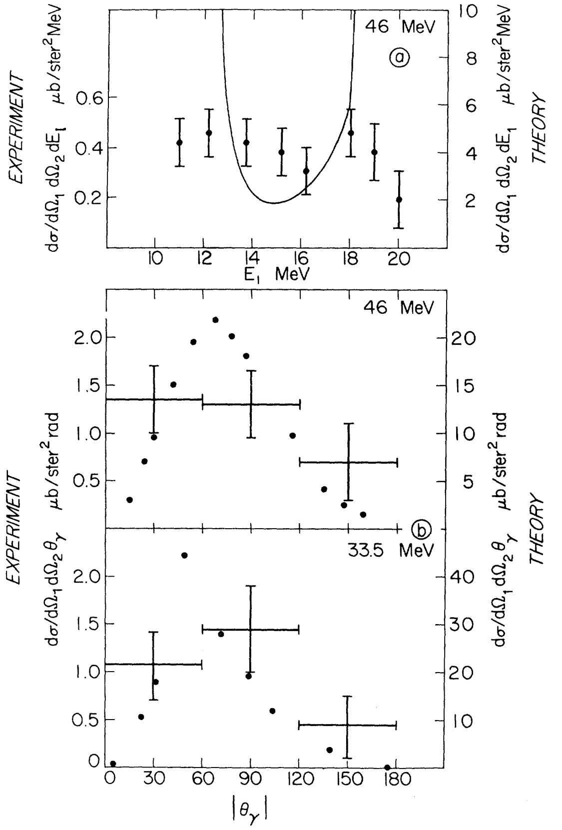

FIG. 1. (a) The cross section $d\sigma/d\Omega_1 d\Omega_2 dE_1$ ($\theta_1 = \theta_2 = 30°$) at 46 MeV compared with the theoretical calculation of Marker and Signell[10] (solid curve). (b) The angular distribution of gamma rays compared with the calculation[10] (dots) using the Hamada-Johnston potential.

calculations in Fig. 2. It seems that so far the theory predicts neither the absolute value nor the energy dependence of the cross section.

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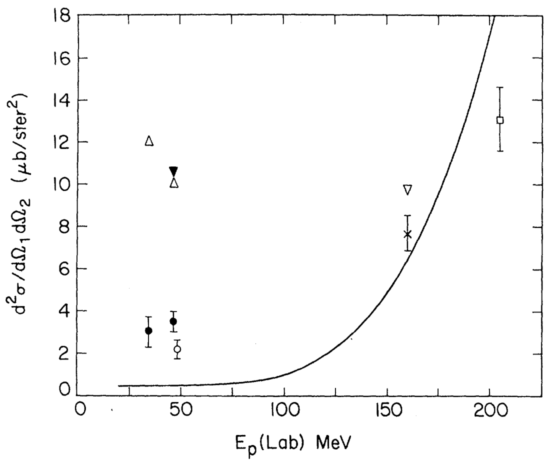

FIG. 2. The cross section $d\sigma/d\Omega_1 d\Omega_2$ ($\theta_1 = \theta_2 = 30°$) as a function of the incident energy.

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