Proton-Proton Bremsstrahlung at 47 MeV*

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The cross section for proton-proton bremsstrahlung at 47 MeV was measured by detecting the two protons at 30° on either side of the beam. Strongly noncoplanar events were not accepted. The integrated cross section and differential cross section as a function of γ-ray polar angle are in reasonable agreement with recent theoretical predictions. A survey of all presently available (30°, 30°) measurements and predictions is given.

INTRODUCTION

THE proton-proton bremsstrahlung (PPB) reaction continues to be of interest from both the experimental and theoretical standpoint. The original stimulus for the experimental study of this process was the suggestion[1] that the model dependence of the off-energy-shell effects in this reaction might influence the PPB cross section appreciably; thus a measurement of the cross section might provide the basis for a choice between different nucleon-nucleon potentials which fit the elastic scattering data equally well. This possibility remains the primary motivation for current interest in the problem.

Earlier PPB cross-section measurements at (30°, 30°) in the Harvard geometry[2] have been reported for 48 MeV by Warner[3] and for 46 MeV by Slaus *et al.*[4] Our own (30°, 30°) measurement at 61.7 MeV[5] gave a smaller value for the cross section at the higher energy, contrary to theoretical expectation. In an effort to resolve this conflict, we undertook the present study at 47 MeV. To minimize uncertainties arising from detection of noncoplanar events, the azimuthal acceptance was limited to $\pm 2.4°$. This is much less than the maximum angle of noncoplanarity allowed by kinematics: $\Phi_m = 10.4°$. (The coordinate system used in this paper is defined in Ref. 5.) Two independent measurements were made, several months apart.

EXPERIMENTAL METHOD

The method of measurement and much of the apparatus have been described in Ref. 5 and will be discussed only insofar as there have been changes. In the first of our 47-MeV measurements the beam transport system and scattering chamber were as previously described. Prior to the second measurement, the quadrupole magnet nearest to the cyclotron was moved downstream. This change made it possible to focus the entire beam extracted from the cyclotron to a spot contained almost completely within a rectangle 0.05 in. wide and 0.12 in. high, about half the size previously obtained.

Figure 1 is a detailed view of the scattering geometry for both runs. The target volume in the hydrogen gas was determined by the intersection of the beam boundary with the regions subtended by the front slit and the ΔE counter of each telescope. This represents an improvement over our earlier design,[5] since the ΔE and E counters were close together and multiple scattering in the ΔE detectors had essentially no effect on the results. The dimensions and acceptance angles of the telescopes are given in Table I. The beam position was checked at the end of each run. It was discovered that the centroid of the beam had been about 0.1 in. below the median plane of the counters during the second run and the

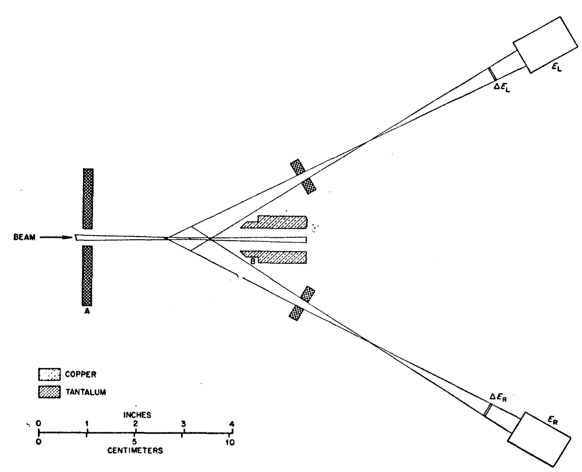

FIG. 1. Scale drawing of the scattering geometry as seen from above. The beam outline represents the region of half-maximum intensity of the first run.

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[2] B. Gottschalk, W. J. Shlaer, and K. H. Wang, Nucl. Phys. **75**, 549 (1965).

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

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TABLE I. Dimensions in inches of the detectors and angular acceptance of the telescopes.

Energy (MeV)	Front slits Width	Front slits Distance from center	ΔE Detectors Width	ΔE Detectors Height	ΔE Detectors Distance from center	E Detectors Width	E Detectors Height	E Detectors Distance from center	Limits of angular acceptance Polar	Limits of angular acceptance Azimuthal
47.1	0.178	2.69	0.30	0.30	7.22	0.75	0.75	7.91	27.0°, 33.0°	±2.4°
47.4	0.178	2.69	0.30	0.30	7.22	0.75	0.75	7.91	27.0°, 33.0°	+4.2°, −0.5

azimuthal acceptance was not symmetric about 0°, as indicated in Table I.

All detectors were made of plastic scintillator. The ΔE counters were 0.030-in. thick and were viewed edge-on by type-6199 photomultipliers. The E counters, viewed by type-6342A photomultipliers, were thick enough (1.0 in.) to stop 47-MeV protons.

Slit A prevented protons scattered by the entrance foil from illuminating the front slits of the telescopes. The baffles B were installed to eliminate a type of background that is particularly difficult to distinguish from genuine events. This background comes from proton-proton elastic scattering occurring about 1 in. beyond the center of the chamber with both particles coming off at about 45°, both protons penetrating the edges of the front slits, and then being rescattered into the telescopes with reduced energies. Within the kinematically allowed PPB region, such events cannot be distinguished from genuine events since they are in prompt coincidence. The baffles B eliminates these events by shielding the front slits against the 45° protons.

The energy response of both telescopes was measured by moving them to various pairs of angles appropriate for registering elastic proton-proton coincidences. In the first run the E counters were found to be somewhat nonlinear. The cause was later revealed to be saturation in the last stages of the photomultipliers. The problem was corrected before the second run by changing the voltage divider networks. For each run the appropriate measured response curves were used to analyze the data.

The electronic circuitry used to record the data was as described in Ref. 5. In brief, the two E pulses were accepted by the two-parameter analyzer only if a coincidence occurred between the ΔE counters within one beam burst. The thresholds for the ΔE signals were carefully adjusted to discriminate against the elastically scattered protons (35 MeV) which gave smaller ΔE pulses than the bremsstrahlung protons (11–19 MeV). By this means approximately 97% of the particles entering each telescope were prevented from triggering the coincidence circuit. Random coincidences were recorded concurrently in another portion of the analyzer memory by use of a duplicate coincidence circuit with one ΔE signal delayed by one cyclotron rf period.

As mentioned earlier, the detectors were made to subtend only a small range of azimuthal angles so as to minimize the acceptance of noncoplanar events. This made the experiment considerably more difficult than in our previous work with large apertures[5] for two reasons. (a) For each PPB event detected, the number of elastic protons that entered each telescope was 16×10^6, about five times larger than before. Thus accidental coincidences between elastic protons unrejected by the ΔE discrimination were more frequent relative to the true events. (b) To get a reasonable PPB yield ($\sim$2 counts per h) the beam current was increased by a factor of 5 to 10. This increased the number of accidental coincidences from slit scattering and neutron background.

To check the apparatus, the chamber was filled with a mixture of methane and hydrogen and the cross section for $^{12}C(p, 2p)$ was measured. Within the experimental error of $\sim$25% (due mainly to poor counting statistics) the result agreed with the 50-MeV measurement of Pugh *et al.*[6]

Table II gives details of the two runs, including the number of events from which the cross sections were calculated.

RESULTS AND DISCUSSION

Figure 2 shows the net (prompt minus delayed) distributions of coincident events as a function of channel number from the first run, at 47.1 MeV. The curve is the kinematic locus for (30°, 30°) coplanar events, corrected for energy loss in the ΔE counters and the pulse-height response of the E counters. The efficiency of the ΔE pulse-height discrimination may be judged from the small number of events in which one of the pulses appears at about channel 80, where the elastic

TABLE II. Operating conditions and results for the two experimental runs. The correction factor was based on the assumption that the Φ distribution follows the Drechsel-Maximon distribution.[a] The error estimates correspond to one standard deviation.

Laboratory energy (MeV)	Beam current (nA)	Duration (h)	Counts in PPB region Prompt	Delayed	Net	Cross section (μb/sr^2) Uncorrected	Corrected
47.1±0.1	500	21	115	53	62±13	1.37±0.29	1.37±0.29
47.4±0.1	400	32	124	86	38±14	0.91±0.35	0.95±0.36

[a] Reference 7.

[6] H. G. Pugh, D. L. Hendrie, M. Chabre, E. Boschitz, and I. E. McCarthy, Phys. Rev. 155, 1054 (1967).

TABLE III. Summary of experimental (30°, 30°) cross sections. The symbol $\Delta\Phi$ represents the azimuthal acceptance corresponding to the half-height of the counters. The largest angle of noncoplanarity allowed by kinematics is denoted by Φ_m. The correction factors listed are based on the predicted Φ distributions from Drechsel and Maximon.[a]

E (MeV)	$\Delta\Phi/\Phi_m$	Correction for noncoplanarity	Cross sections (μb/sr^2) Uncorrected	Corrected	Reference
3.2				$0.15^{b}{+0.17 \atop -0.15}$	c
10				$<0.4^{b}$	d
10.5			<1.3		e
33.5	1.21	0.56	2.0 ± 0.6	3.6 ± 1.1	4
46	0.37	0.99	3.5 ± 1.1	3.5 ± 1.1	4
46	0.39	0.98	3.6 ± 1.1	3.7 ± 1.1	4
46	1.02	0.64	2.7 ± 0.8	4.2 ± 1.3	4
47.1	0.23	1.00	1.37 ± 0.29	1.37 ± 0.29	f
47.4	$\sim$0.4[illegible]	0.96	0.91 ± 0.35	0.95 ± 0.36	f
48	1.10	0.60	1.60 ± 0.27	2.68 ± 0.45	3
61.7	0.24	0.98	2.22 ± 0.72	2.27 ± 0.73	5
61.7	1.02	0.62	$1.27+0.15$	2.04 ± 0.24	5
65.0	0.81	0.72	1.68 ± 0.27	2.34 ± 0.38	g
157	0.11	1.00	10.6 ± 2.1	10.6 ± 2.1	
157.8	0.20	0.99	7.8 ± 1.6	7.9 ± 1.6	h
204				13.0 ± 2.4^{b}	11

[a] Reference 7.
[b] Authors give result including noncoplanarity correction
[c] E. A. Silverstein and K. G. Kibler, Phys. Rev. Letters **21**, 922 (1968).
[d] C. Joseph, A. Niiler, V. Valkovic, R. Spiger, S. T. Emerson, T. Canada, J. Sandler, and G. C. Phillips, Bull. Am. Phys. Soc. **13**, 567 (1968).
[e] G. M. Crawley, D. L. Powell, and B. V. Narasimha Rao, Phys. Letters **26B**, 576 (1968).
[f] This experiment.
[g] D. L. Mason, M. L. Halbert, A. van der Woude, and L. C. Northcliffe (to be published).
[h] B. Gottschalk, W. J. Shlaer, and K. H. Wang, Nucl. Phys. **A94**, 491 (1967).

protons were expected. Pairs of protons from the breakup of deuterium in the target gas would appear well above the PPB region. Three points in Fig. 2 are in the correct energy region for this process. About 10 would be expected if none were rejected by the ΔE discrimination. Since the thresholds were probably high enough to cut out a portion of these events, the observed number is reasonable.

The cross section corresponding to the net number of events in the PPB region is the uncorrected cross section in the first line of Table II. This number is an average of two semi-independent results obtained (a) from measurement of the integrated beam current, target density, and known geometry, and (b) from the number of counts relative to the elastic counting rate and the accurately known proton-proton elastic cross section. The two methods of calculation are described in detail in Ref. 5. The two results were in satisfactory agreement.

The second run was made at 47.4 MeV. As shown in Table II, there were more delayed and fewer net events in the PPB region. The resulting cross section confirms the result of the 47.1-MeV run, although its fractional error is almost twice that of the 47.1-MeV measurement.

Table II also presents the cross sections corrected for acceptance of noncoplanar events. For this purpose

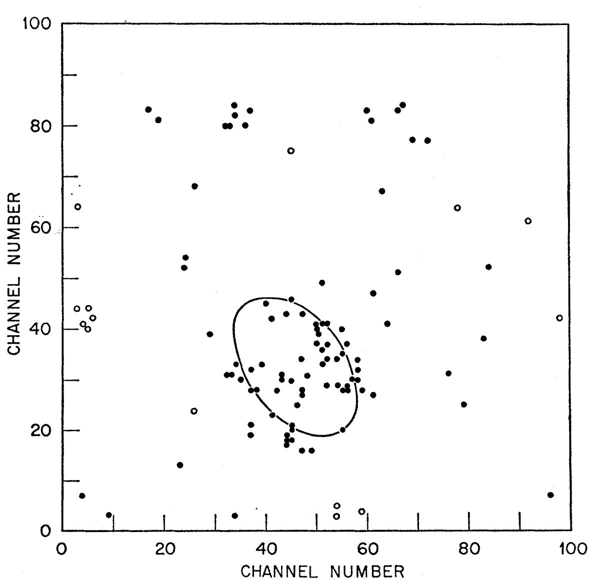

FIG. 2. Net distribution of coincidences for the run at 47.1 MeV. The pulse height in one E counter is plotted against the pulse height in the other. The curve is the expected kinematic locus for coplanar (30°, 30°) events.

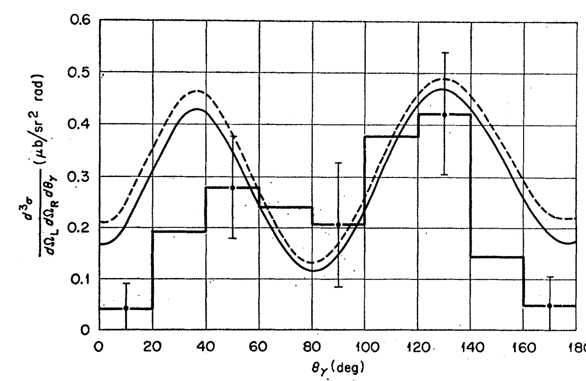

FIG. 3. Cross section as a function of γ-ray angle for the data of Fig. 2. The full and dashed curves are the predictions of Ref. 8 for the Bryan-Scott and the Hamada-Johnston potentials, respectively, for coplanar events.

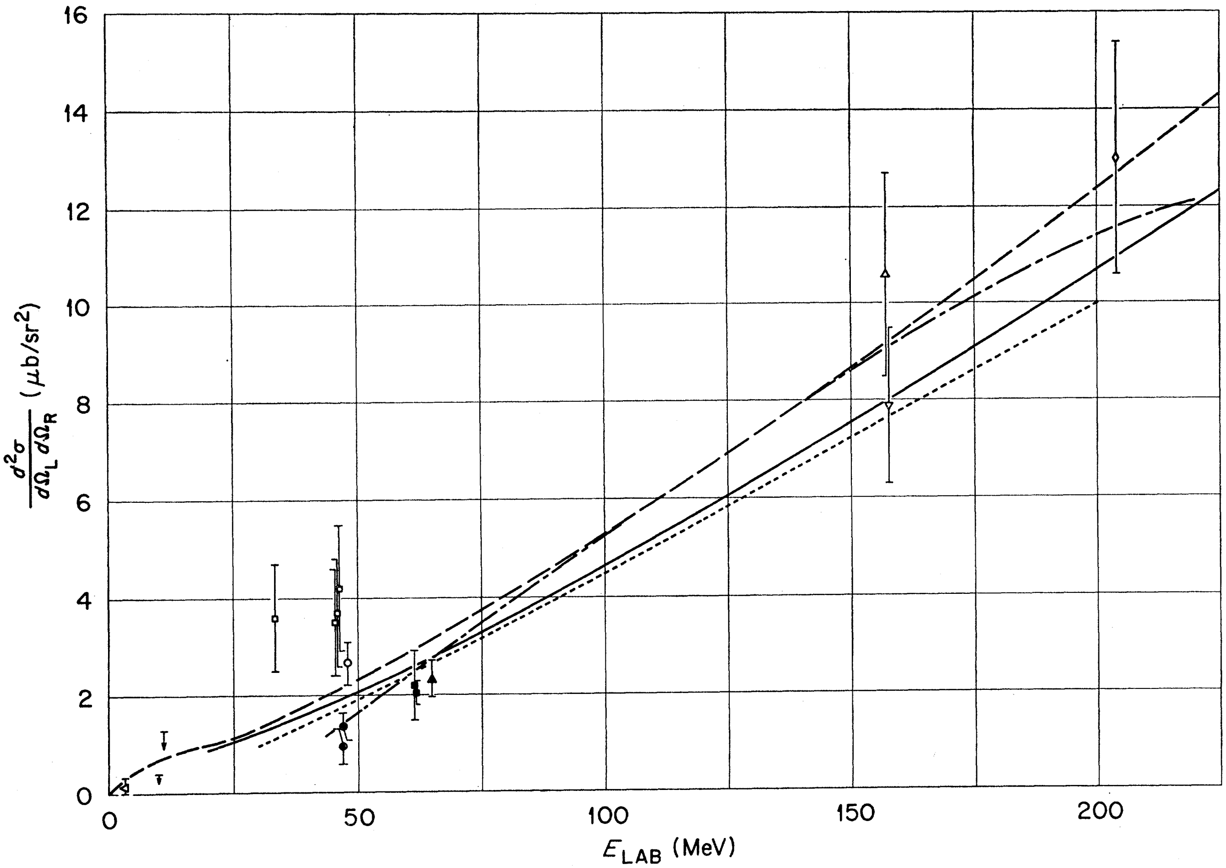

FIG. 4. Coplanar (30°, 30°) PPB cross sections as a function of bombarding energy. The points are corrected experimental results from Table III, as follows: ● present experiment; ■ Ref. 5; ▲ D. L. Mason, M. L. Halbert, A. van der Woude, and L. C. Northcliffe (to be published); △ E. A. Silverstein and K. G. Kibler, Phys. Rev. Letters **21**, 922 (1968); □ Ref. 4; ○ Ref. 3; △ Ref. 2; ▽ B. Gottschalk, W. J. Shlaer, and K. H. Wang, Nucl. Phys. **A94**, 491 (1967); ◇ Ref. 11. The upper limits shown at 10 and 10.5 MeV are from C. Joseph, A. Niiler, V. Valkovic, R. Spiger, S. T. Emerson, T. Canada, J. Sandler, and G. C. Phillips, Bull. Am. Phys. Soc. **13**, 567 (1968), and G. M. Crawley, D. L. Powell, and B. V. Narasimha Rao, Phys. Letters **26B**, 576 (1968), respectively. The theoretical curves are as follows: solid curve, Bryan-Scott potential (Ref. 8); long-dashed curve, Hamada-Johnston potential (Refs. 7, 8, and 13—the portion below 30 MeV is from Ref. 13 only); dot-dashed curve, Tabakin potential (Ref. 9); short-dashed curve, model-independent leading terms (Ref. 12).

the decrease of the cross section with Φ calculated at 48 MeV by Drechsel and Maximon[7] was adopted. (This calculation was made with the Hamada-Johnston potential, but predictions at 62 and 158 MeV for the Hamada-Johnston and Reid soft-core potentials showed that the variation with Φ does not depend on the choice of potential.) This distribution was numerically integrated over the range of Φ permitted by the height of the ΔE counters for each run. The uncorrected cross sections were then divided by the resulting correction factors. The correction factor was nearly unity for the first run. A small correction was needed for the second run because of the azimuthal asymmetry noted earlier.

The histogram in Fig. 3 is the distribution of events in Fig. 2 as a function of γ-ray polar angle. The area under the histogram is 0.685 μb/sr^2. The method used to extract this distribution from the data was analogous to that used in the 61.7-MeV work.[5] The full curve in Fig. 3 is a coplanar calculation by Brown[8] for the Bryan-Scott III potential. The prediction for the Hamada-Johnston potential (dashed curve) has the same shape but is about 10% larger. The data are in reasonable agreement with the prediction, allowing for the fact that the experimental distribution ought to be lower than the predictions near 0° and 180° for the following two reasons. (1) The finite energy resolution causes a net loss of events from these portions of the (E_L, E_R) diagram because the kinematics severely limits the area of the bins near 0° and 180° (see Ref. 5, especially Fig. 7). (2) Noncoplanar events cannot have γ-ray angles of 0° or 180°.

Table III lists all presently available (30°, 30°) experimental results. Many of these measurements were made with large azimuthal acceptance and require appreciable corrections for the detection of noncoplanar events. The cross sections given in Refs. 3 and 4 include

[7] D. Drechsel and L. C. Maximon, Phys. Letters **26B**, 477 (1968); and private communication.

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corrections based on the assumption that the Φ dependence of the cross section was due to phase space only. However, the measurements of Gottschalk, Shlaer, and Wang[2] at 158 MeV and the theoretical calculations of Drechsel and Maximon[7] at 48, 62, and 158 MeV show a very different dependence on Φ. The azimuthal dependence predicted by Pearce, Gale, and Duck,[9] though different near $\Phi=\Phi_m$, is in general agreement with the Drechsel-Maximon distribution. Therefore, the noncoplanarity correction factors listed in Table III differ from those used by the authors of Refs. 3 and 4. They were obtained by numerical integration of the Drechsel-Maximon distribution over the azimuthal acceptance angle of each counter system. Since the theoretical distribution varies only slowly with energy, the 48-MeV theoretical curve was used to obtain correction factors for the data at 33.5, 46, 47.1, 47.4, and 48 MeV, the 62-MeV curve for the data at 61.7 and 65.0 MeV, and the 158-MeV curve for the data at 157 and 157.8 MeV. (The corrected cross section for 48 MeV was actually taken from Ref. 10. The same Φ distribution was used; our result was essentially identical.) The cross section at 204 MeV[11] was obtained for a nearly coplanar geometry and already includes a correction based on measurements of the noncoplanarity. Likewise, the results quoted for 3.2 and 10 MeV include corrections for noncoplanarity.

The tabulated 61.7-MeV result differs from the originally published value[5] because the Drechsel-Maximon Φ distribution is slightly different from the parabola assumed in Ref. 5; this leads to a 15% smaller correction. The error estimate is also smaller in Table III. The original estimate[5] was set at the 90% confidence level. To conform with the prevailing custom of quoting a standard deviation, we have reduced our original estimate of error by a factor of 1.65.

Figure 4 shows the coplanar cross sections (integrated over γ-ray angle) for (30°, 30°) as a function of bombarding energy. The curves are theoretical predictions, identified in the caption, while the plotted points show the corrected experimental results listed in Table III. It is evident from Fig. 4 that our five measurements (solid points) are lower than the others at similar energies. It is possible that the type of prompt background eliminated in our work by the baffles B have could caused an excess of counts in the other work.

Our results at 47 MeV fall significantly below the calculation by Nyman[12] of the model-independent leading terms of the integrated cross section. The reason for this is not understood at present.

Of the calculations based on various potential models of the nucleon-nucleon interaction, our data agree best with the calculation of Ref. 9 based on the Tabakin potential (dash-dot curve), although more refined calculations with this potential give larger cross sections.[13] Our points are generally consistent with a prediction based on the Bryan-Scott potential (solid curve). The Hamada-Johnston predictions (dashed curve) tend to be above our results. Recent estimates by Marker and Signell[14] show that Coulomb effects reduce the Hamada-Johnston predictions by about 5% at 62 MeV and 6% at 47 MeV. Although one cannot at this time make any firm statements about the best choice of nucleon-nucleon potential, it does appear from the present results that a momentum-dependent potential is preferable to a hard-core potential.

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[10] D. Drechsel, L. C. Maximon, and R. E. Warner (private communication).
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[13] P. S. Signell, *Advances in Nuclear Physics 2* (Plenum Press, Inc., New York, 1968).
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Search for States in the Three-Neutron and Triton Systems*

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^{3}He spectra from the bombardment of tritium and of ^{3}He targets with 22.25-MeV tritons are presented. No clear evidence for new states in either residual nucleus is obtained; however, the $^3H(t,{}^3He)3n$ spectra provide weak evidence for the existence of a "trineutron" unbound by 1 to 1.5 MeV.

RECENTLY, there have been many searches for states in the three-nucleon system. Searches for a three-proton state have been made via the $^3He(p,n)3p$ [1,2] and $^3He(^3He,t)3p$ reactions,[3] and evidence for ^{3}He excited states has been sought from spectra of the $^3He(p,p')^3He$,[4–8] $^3He(^3He,^3He')^3He$,[9] $^3He(^4He,^4He')$-

* Work performed under the auspices of the U. S. Atomic Energy Commission.
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