Evidence for a $T=\frac{1}{2}$ Resonance in the ^{3}He System*

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Evidence for a broad resonance in the ^{3}He system has been found in the excitation function for the radiative capture of deuterons by protons. Supporting evidence is provided by the behavior of the angular distributions. The resonance is centered at (19.5 ± 0.5)-MeV excitation, has a width of about 2 MeV, and is most likely characterized by $(L^\pi, S, T) = (1^-, \frac{1}{2}, \frac{1}{2})$.

The existence of resonances in the three-nucleon system has been the subject of many investigations.[1] The simplest reactions that might show such effects are nucleon-deuteron scattering,[2] inelastic electron scattering from ^{3}He,[3] and either the photodisintegration of ^{3}He or the radiative capture of protons by deuterons. These reactions involve only three strongly interacting particles. No definite evidence for a resonance in the three-nucleon system has been found thus far from any of these reactions. Some indication of broad resonances in the three-nucleon system from reactions involving four strongly interacting particles has recently been published. Most notable are the reactions[4] ^{3}He$(p,n)3p$ and ^{3}H$(p,n)^3$He*, and the reaction[5] ^{3}He$(\pi^-,\pi^+)3n$ although for the last case it has been shown that the data can be interpreted by taking into account final-state interactions between two neutrons only.[6]

We present here evidence for a resonance in the ^{3}He system from measurements of the excitation function and angular distributions of the radiative capture of deuterons by protons. This work was stimulated by the results of an experiment by Berman, Fultz, and Yergin[7] in which they found structure in the excitation function for photodisintegration of ^{3}He into three nucleons.

The experimental method was very similar to one recently described.[8] The deuteron beam from the Oak Ridge isochronous cyclotron was focused on a polystyrene target (CH) of about 100 μg/cm^2. The beam energy was varied in steps of about 1 MeV from 20.0 to 45.2 MeV, the maximum energy available. That part of the ^{3}He spectrum corresponding to emission of γ rays in a 28° interval centered approximately at 90° in the c.m. system was measured with a position-sensitive silicon detector in the focal plane of a broad-range magnetic spectrograph. The spectrograph was positioned at 0° to the deuteron beam. The beam was collected in a Faraday cup placed in the high-momentum part of the focal plane.

The angular distribution for emission of a γ ray can be parametrized by[8]

$$d\sigma/d\Omega = a + b\sin^2\theta(1+\beta\cos\theta+\gamma\cos^2\theta), \qquad (1)$$

where θ is the c.m. angle between the deuteron and the γ ray. In the energy interval of interest b is mainly due to $E1$ transitions, β to interference between $E1$ and $E2$ transitions, and γ to $E2$ and higher-order transitions.

Most calculations of the magnitude of the photodisintegration cross section have been made under the assumption of electric-dipole transitions from the S states of the bound system, which leads to $d\sigma/d\Omega = b\sin^2\theta$.[9,10] To compare our yield measurements with such calculations, we deduced a value of b from our data. For this we required the angular distribution coefficients a/b, β, and γ at each energy. To supplement our previous measurements[8] at 19.8 and 29.6 MeV, we measured complete angular distributions at deuteron energies of 41.1 and 45.2 MeV. The angular-distribution parameters for intermediate energies were then determined by interpolation. Since the yield measurements correspond to γ emission near 90°, the contribution of the terms involving $\cos\theta$ is very small. Moreover, $a/b \ll 1$, so that the uncertainty in the deduced value of b due to an uncertainty in the parameters of the angular distribution is small.

At several energies peaks due to the $(d, {}^3\text{He})$ reaction on ^{12}C, ^{13}C, or target impurities, particularly ^{16}O, obscured part of the ^{3}He-capture continuum. Each spectrum was carefully examined for such peaks, and in case there was evidence for any contribution from such a reaction, that

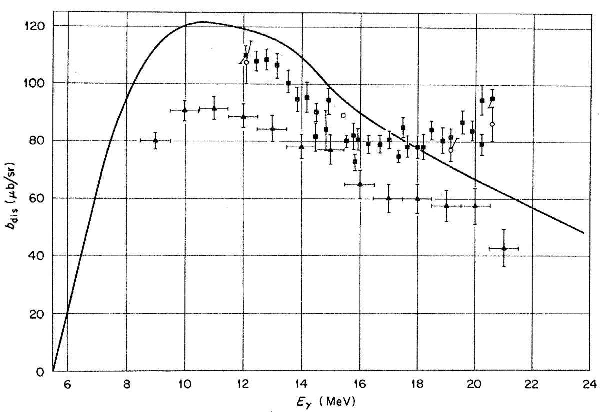

FIG. 1. Variation of b with excitation energy. Our results (closed square, open circle, open square) are given in terms of the two-body photodisintegration. The energy spread associated with each of these points is ±0.015 MeV, while the uncertainty of the abscissa is about ±0.03 MeV. The photodisintegration data of Ref. 11 are shown by closed triangles. The curve is a theoretical calculation from Ref. 10.

part of the spectrum was omitted.

The results of our measurements for b were converted to photodisintegration data by using the principle of detailed balance and are shown in Fig. 1. The 90° measurements, shown as closed squares, are given relative to the value at $E_{exc} = 15.3$ MeV (open square) at which energy we previously measured the absolute value of $b = 1.14 \pm 0.08$ μb/sr.[8] The three open circles represent additional absolute values of b from the complete angular distributions measured at $E_{exc} = 12.1$, 19.1, and 20.6 MeV; these are independent of the normalization point at 15.3 MeV.

The curve is from the calculation of Barbour and Phillips.[10] The shape of our experimental excitation function up to $E_{exc} \approx 17$ MeV is in good agreement with the calculated curve. The discrepancy in the absolute value is only 5-10% which is satisfactory in view of the uncertainty of the 15.3-MeV normalization. Above this energy, the experimental results start to deviate drastically from the predicted curve. Also shown are the results of the photodisintegration experiment of Berman, Koester, and Smith,[11] which agree with a similar measurement by Stewart, Morrison, and O'Connell.[12] The shapes of the two experimental excitation functions shown in Fig. 1 are in good agreement. In particular, there appears to be a plateau from about 17 to 20 MeV in the data of Ref. 11. These data also suggest that the cross section will decrease just above the highest deuteron energy available to us.

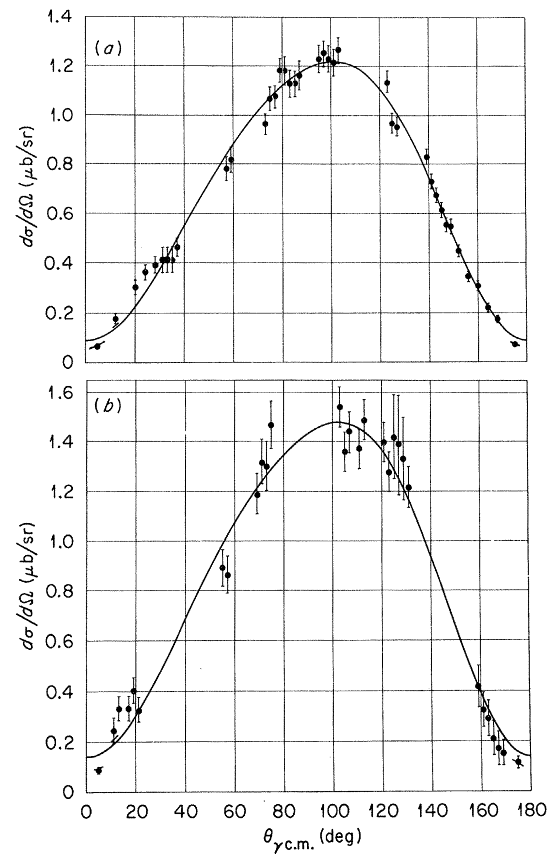

FIG. 2. Center-of-mass cross sections for $H(d, {}^3He)\gamma$ as a function of the c.m. angle between the γ ray and the deuteron. The deuteron bombarding energies were 41.1 MeV for (a) and 45.2 MeV for (b), corresponding to excitation energies of 19.2 and 20.6 MeV, respectively. The errors shown do not include the uncertainty (±8%) in the absolute cross section. The curves were calculated from Eq. (1) with the parameters of Table I. The effect of the finite bin size and energy resolution is shown near 0° and 180° by the short line segments.

The angular distributions for an excitation energy of 19.2 and 20.6 MeV are shown in Fig. 2. The experimental data are averaged over either 2° or 4° bins except for the end points which are averaged over 10° bins (see Ref. 8 for more details). Each curve is a least-squares fit of Eq. (1) to the data. The relevant parameters are summarized in Table I, together with the previously measured ones[8] at 12.1- and 15.3-MeV excitation.

The behavior of β, the coefficient of the interference term between $E1$ and higher-order transitions, differs markedly from what is expected. On the basis of simplified models[13] one predicts that $|\beta|$ slowly rises as a function of E_{exc} in this

Table I. Results of the angular-distribution measurements for $d+p \to {}^3\text{He}+\gamma$.

E_d (MeV)	E_{exc} (MeV)	a/b	β	γ	b (μb/sr)	σ_{capture} (μb)
19.8	12.1	0.013 ± 0.007	-0.49 ± 0.03	0.16 ± 0.05	1.27 ± 0.09	11.18 ± 0.77
29.6	15.3	0.008 ± 0.003	-0.59 ± 0.02	0.25 ± 0.04	1.14 ± 0.08	10.17 ± 0.67
41.1	19.2	0.08 ± 0.02	-0.27 ± 0.03	0.39 ± 0.06	1.10 ± 0.09	11.04 ± 0.80
45.2	20.6	0.11 ± 0.03	-0.30 ± 0.06	$0.44^{+0.4}_{-0.2}$	1.30 ± 0.11	13.55 ± 1.00

energy range, as is the case indeed for the interval between 12- and 15-MeV excitation energy. However, at 19.2 and 20.6 MeV, $|\beta|$ is much smaller than expected.

The parameter a/b shows an order-of-magnitude increase from 15.3 to 19.1 MeV. However, it is not known if this is unreasonable since no detailed predictions of the behavior of a/b are available for this energy region. The energy variation of γ may be reasonable since at higher energies the contributions from multipole transitions other than $E1$ increase.

A possible explanation for the anomalies in the excitation function and the angular distribution is that there exists a resonance in the ^{3}He system centered at (19.5 ± 0.5)-MeV excitation with a width of about 2 MeV. In this energy range the dominant contribution to the coefficient b is presumably due to $E1$ transitions without spin flip from the symmetric S component of the ^{3}He ground state. Since the $p+d$ system has $T=\frac{1}{2}$, the resonance would thus be characterized by the quantum numbers $(L^\pi, S, T) = (1^-, \frac{1}{2}, \frac{1}{2})$.

The resonance could be due to an $E1$ transition from the D component of the ^{3}He wave function. In this case the quantum numbers would be different. It is hard to see, though, how this component, with a probability[14] of 4-8%, can make such a large contribution to the cross section.

A resonance with $(L, S, T) = (1, \frac{1}{2}, \frac{1}{2})$ should show up in the ^{22}P phase shifts. Although a sufficiently detailed phase-shift analysis of experimental nucleon-deuteron scattering is not yet available,[2] it is amusing to note that by using dispersion relations to predict p-d scattering, Ebenhöh, Rinat-Reiner, and Avishai[15] found an indication of a broad resonance in the ^{22}P phase shift centered at 18 MeV with a width of about 8 MeV.

One might also look for such a resonance in inelastic electron scattering. Frosch *et al.*[3] performed an inelastic-electron-scattering experiment using a 200-MeV electron beam. They report no evidence for resonances up to $E_{\text{exc}} = 17$ MeV, which is consistent with our results.

We are aware of only one inelastic-scattering experiment which covers the range of excitation energies of interest here. Slobodrian *et al.*[16] studied the inelastic scattering of ^{3}He by ^{3}He up to about 25-MeV excitation. This process can lead to $T=\frac{1}{2}$ and $T=\frac{3}{2}$ states in the three-nucleon system. They found no evidence for an excited state of ^{3}He.

The 19.5-MeV $T=\frac{1}{2}$ resonance was not observed by Williams *et al.*[4] although they did find evidence for a broad peak at 16 ± 1 MeV, which they assigned as a $T=\frac{3}{2}$ resonance.

The excitation function for the three-body photodisintegration of ^{3}He also shows structure from about 18 to 21 MeV.[7] Moreover, the β parameter changes sign at about 21 MeV.[7] This structure does not resemble in detail that observed in our experiment, but this is not surprising since the $T=\frac{1}{2}$ component in the three-body photodisintegration is very small.[17]

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[1] *Three Body Problem in Nuclear and Particle Physics*, edited by J. S. C. McKee and P. M. Rolph (North-Holland, Amsterdam, 1970). See especially the review by I. Slaus, p. 355 ff.

[2] For a recent review, see J. D. Seagrave, Ref. 1, p. 41.

[3] R. F. Frosch, H. L. Crannell, J. S. McCarthy, R. E. Rand, R. S. Safrata, L. R. Suelzle, and M. R. Yearian, Phys. Lett. 24B, 54 (1967).

[4] L. E. Williams, C. J. Batty, B. E. Bonner, C. Tschalär, H. C. Benöhr, and A. S. Clough, Phys. Rev. Lett. 23, 1181 (1969).

[5] J. Sperinde, D. Fredrickson, R. Hinkins, V. Perez-Mendez, and B. Smith, Phys. Lett. 32B, 185 (1970).

[6] A. C. Phillips, Phys. Lett. 33B, 260 (1970).

[7] B. L. Berman, S. C. Fultz, and P. F. Yergin, Phys. Rev. Lett. 24, 1494 (1970).

[8] B. D. Belt, C. R. Bingham, M. L. Halbert, and

A. van der Woude, Phys. Rev. Lett. 24, 1120 (1970); B. D. Belt, thesis, University of Tennessee, 1970 (unpublished).

[9]J. M. Knight, J. S. O'Connell, and F. Prats, Phys. Rev. 164, 1354 (1967).

[10]I. M. Barbour and A. C. Phillips, Phys. Rev. C 1, 165 (1970).

[11]B. L. Berman, L. J. Koester, and J. H. Smith, Phys. Rev. 133, B117 (1964).

[12]J. R. Stewart, R. C. Morrison, and J. S. O'Connell, Phys. Rev. 138, B372 (1965).

[13]See, for example, G. M. Bailey, G. M. Griffiths, and T. W. Donnelly, Nucl. Phys. A94, 502 (1967).

[14]L. M. Delves and J. M. Blatt, Nucl. Phys. A98, 503 (1967); R. A. Malfliet and J. A. Tjon, Phys. Lett. 30B, 293 (1969).

[15]W. Ebenhöh, A. S. Rinat-Reiner, and Y. Avishai, Phys. Lett. 29B, 638 (1969).

[16]R. J. Slobodrian, J. S. C. McKee, D. J. Clark, W. F. Tivol, and T. A. Tombrello, Nucl. Phys. A101, 109 (1967).

[17]G. Barton, Nucl. Phys. A104, 289 (1967).

Search for Microwave Pulses Associated with Gravitational Radiation*

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A microwave radiometer has been used to search for pulses of radio waves from the the direction of the galactic center. The results were compared with data from Weber's gravitational-wave experiment. No strong evidence was found associating microwave pulses with pulses of gravitational radiation.

In a series of Letters,[1-3] Weber has reported evidence for the detection of pulses of gravitational radiation. In this Letter, we present the preliminary results of an experiment to search for pulses of microwave emission accompanying the gravitational radiation events he observes.

Weber reports that the gravitational radiation arrives in bursts lasting less than 20 sec.[2,4] The characteristic energy flux for a detectable event[1] is 10^4 erg/cm^2 sec in his bandwidth of 0.03 Hz, or

$$E_g \sim 3\times10^5 \text{ erg/cm}^2 \text{ sec Hz}.$$

Events of this magnitude or greater are detected about twice a day. An important feature of his experiment is the directional sensitivity of the apparatus (roughly 70° full width at half-maximum in the main beam[3]) which permits him to search for individual sources. He finds one which he indentifies tentatively with the galactic center.[3] It produces a sidereal time anisotropy which is a six-standard-deviation effect and argues strongly for a nonterrestrial origin for his events—otherwise one would expect the anisotropy in solar time rather than sidereal. His observations imply that very large energy fluxes are involved. If the source of his events is at the galactic center ($d \sim 3\times10^{22}$ cm), the total emitted energy for a detectable event is 3×10^{51} erg/sec Hz.

Weber's results are clearly important and need to be checked. To duplicate his experiment is likely to take several years. Last winter, Martin Rees and Remo Ruffini pointed out to me another conceivable check: Look for possible bursts of *electromagnetic* radiation associated with the gravitational-wave events. From several possible sources of gravitational waves, such as catastrophic stellar collapse or rotating neutron stars, one might also expect the emission of some electromagnetic radiation.[5] The collapse of a star with a magnetic field is certain to produce electromagnetic radiation of some sort. The amount and the spectrum of radiation emitted are, of course, open (and important) questions. Nevertheless, the threshold sensitivity of electromagnetic detectors is so much better than that of Weber's detector that we considered a search for electromagnetic emission worthwhile.

In the past year, two experiments to search for pulsed electromagnetic radiation have been carried out, both at radio wavelengths where there is little obscuration of the galactic center. Charman *et al.*,[6] using five spaced receivers at 150 MHz, searched for pulsed radiation arriving in coincidence at two or more receivers. Their receivers were not directional, and they were unable to correlate their results with those of Weber. In addition, the galactic center was above their horizon only for a few hours for most of their runs. They report no indication of signals with a definite extraterrestrial origin.

Experimental details.—The present experiment was planned along quite different lines. The re-