EVIDENCE FOR BROAD RESONANCES IN THE THREE-NUCLEON SYSTEM

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Evidence for broad resonances in ^{3}He and the three-proton system has been observed in the continuum neutron spectra from the reactions ^{3}H(p,n) and ^{3}He(p,n) at 30 and 50 MeV. The positions and widths of possible resonances in the three-nucleon system have been calculated using a variational method. A comparison is made with data from photonuclear reactions.

Many experiments have been performed to search for excited states in the three-nucleon system by means of a variety of nuclear reactions.[1] None of the recent experiments has provided any definite evidence for excited states, although Olsen et al.[1] do claim weak evidence for a 1- to 1.5-MeV unbound trineutron from a study of the reaction ^{3}H(^{3}H, ^{3}He)$3n$. In the present work we have observed evidence for broad continuum resonances in (p,n) reactions on targets of ^{3}H and ^{3}He at incident energies of 30 and 50 MeV.

The gas targets, 95% enriched and at normal temperatures, were contained in stainless-steel cells at pressures of 3 to 4 atm. Background subtraction was made using an identical cell filled with normal hydrogen. Beams of 30- and 50-MeV protons were obtained from the Rutherford Laboratory proton linear accelerator. Neutrons were detected over the angular range of 2°-60° with the exception of the reaction ^{3}He(p,n) at 30 MeV for which the range was 10°-30°. The neutron energy spectrum was measured to an accuracy of ±0.2 MeV by means of a time-of-flight spectrometer with a 10-m flight path.[2] The energy resolution was ≤1.2 MeV (full width at half-maximum) at a neutron energy of 30 MeV.

For 50-MeV incident energy and neutron angles of 50° and 60°, the shape of the neutron spectra could be adequately reproduced from reaction threshold down to $E_n \simeq 6$ MeV by a simple phase-space calculation; four-body phase space for the reaction ^{3}He$(p,n)3p$ and a mixture of three- and four-body phase space for the reaction ^{3}H(p,n). An example for the reaction ^{3}He$(p,n)3p$ is shown in Fig. 1(a); the incident energy was 48.8 MeV and the neutron angle was 60°. The calculated four-body phase space (4PS) normalized to this spectrum is indicated by the dashed line. A three-body phase space (3PS) distribution is also shown in Fig. 1. It is seen that the shape of the observed spectrum is fitted very well by the 4PS

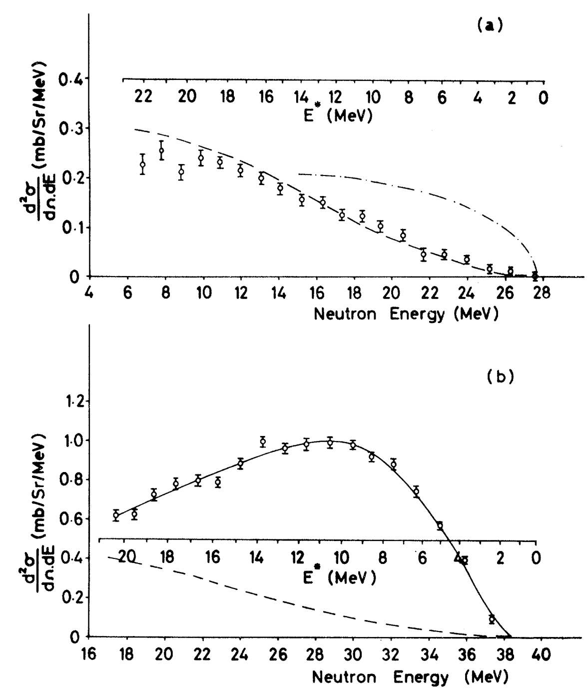

FIG. 1. Neutron spectra observed for the reaction ^{3}He$(p,n)3p$. The incident energy was 48.8 MeV and the neutron angles were (a) 60°, (b) 20°. The dashed curve is the calculated four-body phase-space distribution normalized to the spectrum measured in (a). The dash-dot curve gives the results of a three-body phase-space calculation.

but not by the 3PS calculation. Once having determined the normalization constant by fitting the data at wide angles it was then kept constant throughout the remainder of the phase-space calculation. The considerable departure from a 4PS distribution calculated using the same normalization constant at the more forward angles is shown in Fig. 1(b).

After subtraction of the phase-space distribution, broad peaks are observed which have consistent Q values and widths over the kinematic range of the experiment. These values are summarized in Table I. Both reactions are seen to exhibit a broad peak at about 16-MeV excitation with respect to the ground state of ^{3}He. Only the reaction ^{3}H(p,n) gives rise to an additional peak located at about 9.6-MeV excitation. This would imply isospin values of $\frac{3}{2}$ and $\frac{1}{2}$, respectively, for the two resonances. Characteristically double-peaked ^{3}H(p,n) spectra are shown in Figs. 2(a) and 2(b) for an incident energy of 30.2 MeV.

Tombrello and Slobodrian[3] have also observed a marked departure from a four-body phase-space distribution in the reaction ^{3}He(^{3}He, ^{3}H)3p, which they attributed to Coulomb distortion of phase space. In the present work we find the Q values for the observed peaks to be independent of angle of observation of the neutron and the energy of the incident proton, suggesting that they

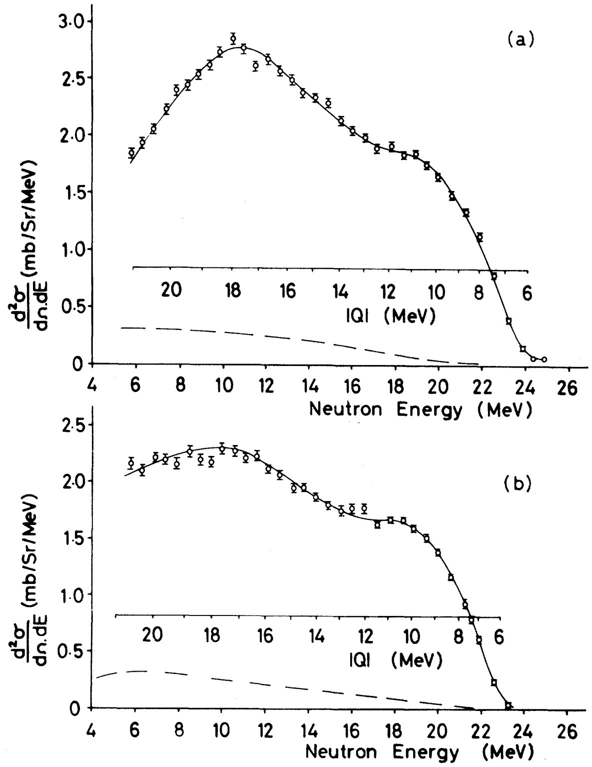

FIG. 2. Neutron spectra observed for the reaction ^{3}H(p,n). In (a) and (b) the incident energy was 30 MeV and the neutrons detected at (a) 2° and (b) 20°. The dashed curves are the predictions from a sum of 3- and 4-body phase-space calculations (see text).

Table I. Comparison between calculated and observed positions and widths of possible resonances in the three-nucleon system.

		3p excitation relative to the 3p threshold (MeV)	excitation relative to the ground state (MeV) ^{3}He*	^{3}H*	3n excitation relative to the 3n threshold (MeV)
T=$\frac{1}{2}$	Expt.		E = 9.6 ± 0.7 Γ = 5 ± 1	...	
	Theory, both potentials; S=$\frac{3}{2}$, L=1		E = 9.0	E = 9.3	
T=$\frac{3}{2}$	Expt.	E = 9 ± 1 Γ = 10.5 ± 1	E = 16 ± 1 Γ = 9 ± 1	...	1.0 - 1.5 [c]
	AT-potential[a]; S=$\frac{1}{2}$, L=1	E = 5.5	E = 10.9	E = 10.6 Γ = 1.6	E = 2.1 Γ = 1.6
	EH-potential[b]; S=$\frac{1}{2}$, L=1	E = 7.3	E = 12.6	E = 12.0 Γ = 2.7	E = 3.5 Γ = 2.7

[a]I. R. Afnan and Y. C. Tang, Phys. Rev. 175, 1337 (1968).
[b]H. Eikemeier and H. H. Hackenbroich, Z. Physik 195, 412 (1966).
[c]Ref. 1.

are due to broad resonances in the three-nucleon system and not due to the distortion of phase space by kinematical or other effects.

The position of the 9.6-MeV peak in the $^3H(p,n)$ spectra corresponds to the region where the quartet p-wave phase shift in p-D scattering goes through a positive excursion.[4] Further contributions in the $T=\frac{1}{2}$ channel are to be expected from the fact that the doublet p-wave phase shift also goes positive between about 10 and 20 MeV. A simple isospin argument indicates that the ratio of the $T=\frac{3}{2}$ contribution to the cross section for the two reactions should be $\sigma_{p\text{-}^3H}(T=\frac{3}{2})/\sigma_{p\text{-}^3He}(T=\frac{3}{2})=\frac{1}{3}$. The fact that the cross sections are observed to be about equal may be explained by Coulomb effects and a very broad $T=\frac{1}{2}$ resonance contribution to the p-^3H reaction. The phase-space calculations using the normalization constant as determined above predict a total $^3He(p,n)$ cross section of 20 μb at a proton energy of 13.1 MeV, where Cookson[5] has measured it to be 5 μb (uncertainty 18 μb).

A theoretical investigation using a realistic soft-core nucleon-nucleon interaction[6,7] has been performed to find predictions of $L=1$ resonances for three nucleons with $(S,T)=(\frac{3}{2},\frac{1}{2})$, $(\frac{1}{2},\frac{1}{2})$, and $(\frac{1}{2},\frac{3}{2})$. By means of a variational technique[8] a resonancelike behavior was found in all three cases with a fairly well defined quasibound resonance structure.[9] For the $T=\frac{1}{2}$ states this evidence is supported by the experimental nucleon-deuteron phase shifts.[4]

In the energy region where the nucleon-deuteron phase shifts $^2\delta_1$ and $^4\delta_1$ have a positive slope one expects from general theoretical considerations broad $T=\frac{1}{2}$ resonances, which are centered around the energy of maximum slope. The present calculations result in a set of quasibound resonance structures in which the 1p nucleon moves in the extreme tail region of a slightly distorted deuteron. Consequently the rms radii of these states are large compared with the bound states of the three-nucleon system, e.g., about 6.5 F for the best $(\frac{3}{2},\frac{1}{2})$ structure. The energy expectation values are in general agreement with the positions of the resonances derived from the phase shifts of Ref. 4.

No independent evidence is available for the $T=\frac{3}{2}$ state. The potential of Ref. 6 and the potential $S1$ of Ref. 7 predict a three-neutron resonance which is centered at 3.5 and 2.1 MeV, respectively, above the three-neutron threshold and with a width of about 2.6 or 1.6 MeV, respectively. For the corresponding states in ^3He and in the three-proton system one has to include the Coulomb force.

For the three-proton state the Coulomb potential contributes about 25% to the total potential energy of the bound resonance structure. The level shift between the three-neutron state and the three-proton resonance cannot therefore be calculated in perturbation theory. Our calculations, which include the distortion of the wave function due to the Coulomb force, given considerably larger shifts (3-4 MeV). This may result from the fact that the Coulomb barrier provides a much better localization in space for the three-proton state, thus giving rise to an increase in internal kinetic energy which is much larger than the gain in potential energy. The results are summarized in Table I.

The present theoretical results are self-consistent insofar as no level shift is introduced by coupling the bound structures to the three-particle decay modes. This self-consistency can only be obtained if the virtual deuteron is represented accurately enough in the wave function. Again very large radii for the resonance structures, 4 to 6 F, are found. The 1p nucleon now moves essentially in the tail of a virtual deuteron.

The potentials used so far contain no spin-orbit or p-wave components, and the effect of these interactions has to be studied more carefully. Nevertheless we believe that the general structure of the resonances which we have observed is very similar to the resonances which are generated by the potentials of Refs. 6 and 7. A more complete theoretical analysis will be published in due course.

The dominating states are the $(\frac{3}{2},\frac{1}{2})$ and the $(\frac{1}{2},\frac{3}{2})$ resonances, whereas the $(\frac{1}{2},\frac{1}{2})$ state is extremely broad and weak, as is already indicated by the $^2\delta_1$ phase shift of Ref. 4. In the reaction $^3H(p,n)$ one expects the $(\frac{1}{2},\frac{1}{2})$ maximum at roughly the same position as the $(\frac{1}{2},\frac{3}{2})$ resonance, and thus one can only observe one enhanced peak.

A comparison can also be made between the present results and data from photonuclear reactions. The $He^3(\gamma,n)$ excitation functions[10] exhibit a pair of broad maxima associated with the two- and three-body photodisintegration of ^3He. After division by a dipole $(E_\gamma{}^3)$ density-of-states factor the positions and widths of the maxima are found to agree within experimental error with those determined in the $^3H(p,n)$ experiment. The reaction $^3He(\gamma,n)2p$ gives a peak at 14 ± 1 MeV with width 8 ± 1 MeV to be compared with the values 16 ± 1 and 9 ± 1 MeV, respectively, obtained in the present experiment for a possible $T=\frac{3}{2}$ resonance. The ^{3}He$(\gamma, d)p$ data give a peak at 8.5 ± 1 MeV with width 6 ± 0.5 MeV to be compared with values of 9.6 ± 0.7 and 5 ± 1 MeV, respectively, observed for a possible $T=\frac{1}{2}$ resonance in this experiment. A similar equivalence between a broad ^{4}He(n,p) resonance and the α-particle photodisintegration data has been observed by Measday and Palmieri.[11]

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ESSENTIAL SINGULARITIES IN GENERAL RELATIVITY*

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Spherically symmetric initial solutions of the coupled gravitational–massless scalar field–"charged particle" system are exhibited. For a given set of coupling constants, there are generally either no or two nonsingular solutions. In the latter case, one of these has essential singularities in the scalar and gravitational constants at zero coupling. Other properties of the solutions are listed. The corresponding results in tensor-scalar gravitation are also outlined.

It is generally believed that, for a physically sensible source, the initial value problem in general relativity has one and only one solution, which reduces appropriately when either the gravitational constant κ or various matter parameters vanish. This is the case, for example,[1] for a spherically symmetric distribution of electric charge e, bare mass m_0, and (coordinate) radius ϵ. We consider here the apparently analogous system where e is replaced by a coupling f to a massless scalar field ψ. A recent purely exterior, static solution of this system had singular behavior in one of the integration parameters.[2] We show here that, while this solution actually corresponds to the special limit of an infinitely extended dilute source (and is really singularity free), there are complete initial solutions which behave even more strangely: For a given set (m_0, f, ϵ) there may be either no solutions, or one, or two different ones. In the latter case, one (otherwise nonsingular) branch has essential singularities in the limit of vanishing coupling constants κ or f. There is also a (nonzero) minimum allowed source extension. These radical departures from the electromagnetic results are presumably due to the absence of a conserved charge with unique "Coulomb" scalar self-field (since the latter may radiate even in a spherically symmetric configuration), to a peculiar degeneracy between the scalar and Newtonian metric