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UPPER LIMITS FOR BOUND STATES AND RESONANCE BEHAVIOR
IN THE TRINEUTRON SYSTEM

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Abstract: The trineutron mass spectrum was observed in the stopped pion radiative capture reaction ${}^3\text{H}(\pi^-, \gamma)3n$ by measuring the photon energy with a high resolution spectrometer. The present experiment improves upon an earlier experiment by a factor of 27 in statistics and 2.2 in resolution. An improved upper limit (95% confidence level) on the branching ratio (bound state)/(total radiative capture rate) is found to be 4×10^{-3} . No resonant structure is observed beyond that predicted by the pairwise interaction of the outgoing nucleons. The upper limit on the branching ratio to resonances with $\Gamma \lesssim 5$ MeV is 2×10^{-2} .

1. Introduction

It is well established that two-body scattering data is insufficient to determine completely the many-body and off-shell properties of the nucleon-nucleon force. The simplest case to handle theoretically is the three neutron system, and an extensive literature exists speculating on bound states and resonances.¹

In particular Okamoto² has shown that by considering the systematics of the binding of the last neutron in nuclei consisting of three neutrons and Z protons, and extrapolating to 0 protons, the 3 neutron system is unbound by 12 MeV. This extrapolation is in approximate agreement with the author's more detailed variational calculation and other work indicating the absence of bound states.³ However, Mitra

and Bhasin⁴ pointed out that although the experimental evidence indicates the four neutron system is probably unbound, this does not exclude a 3-neutron bound state. The trineutron would be dominated by the P-wave nucleon-nucleon force, whereas the S-wave force would be the most important for the 4-neutron case. A calculation by these authors using the separable potential approximation with the Faddeev equations supported the possibility of a bound 3-neutron state arising from the 3P force in the separable approximation. This conclusion was later disputed by Delves and Phillips⁵, who claimed that the calculation must contain a numerical error since the calculated energy was lower than the Hall-Post⁶ lower bound for the potential used. A more recent calculation⁷ contended that their disagreement with the variational results arose from the differences in the potential used. Currently efforts are being made to use more realistic potentials in the Faddeev approach. It was found in a recent calculation by Offermann and Glöckle⁸ using the Reid potential that in order to bind the most favorable case ($J^P = 3/2^-, {}^3P_2 - {}^3F_2$ force) a factor of four enhancement in the nucleon-nucleon force was necessary. They concluded therefore that a low energy resonance or bound state was very unlikely.

In the absence of experimental answers to these questions, one has traditionally turned to the $T = 1/2$ ground states of ^3He and ^3H , which provide the most thorough testing ground for three-body effects. There has been moderate success in calculating charge form factors, magnetic

moments, binding energies, and β -decay rates, although small discrepancies persist between theory and experiment owing to the inability of distinguishing off-shell, meson exchange, and three-body force effects and incorporating the Δ -resonance. Even here, calculations utilizing realistic Reid potentials do not agree very well in their predictions of the triton binding energy.⁹ Beyond the ground states, there appears to be little structure. There is some evidence for an excited state of ${}^3\text{He}$ at 12.4 MeV, but the analogues of this state have not been found.^{1a}

The properties of the $T = 3/2$ states are even less understood. Experimentally accessible reactions involve ${}^3\text{He}$ and ${}^3\text{H}$ targets, for which the $T = 1/2$ contribution is usually overwhelming. In the case of radiative pion capture on ${}^3\text{He}$, for example, the $T = 3/2$ contribution to the radiative capture spectrum is only about 21%.³ A notable exception is the reaction ${}^3\text{H}(\gamma, 2n)p$, where 90% of the contribution is expected to be from $T = 3/2$. A recent measurement¹⁰ of this reaction shows disagreement with existing calculations, but Faddeev calculations have not yet been done.

To isolate $T = 3/2$ states, one should look for three protons or neutrons in the final state. An early ${}^3\text{H}(n, p)3n$ experiment¹¹ claimed evidence for a trineutron state bound by 1 MeV, but this was not substantiated by later investigations¹² of the same reaction. Furthermore, calculations^{13,14} have shown the cross section for the (n, p) reaction

with production of a narrow 3n state to be somewhat below the experimental sensitivity. Data from the reaction ${}^3\text{He}(p,n)3p$ also failed to show structure.¹⁵ A study of the double charge exchange reaction ${}^3\text{He}(\pi^-, \pi^+)3n$ by Sperinde, et al¹⁶ was initially taken as evidence for a resonance at $E^*(3n) = 9 \pm 1$ MeV, but later reinterpretation of the same data by Phillips¹⁷ showed that the data could be explained by the 1S_0 pairwise attraction of the outgoing nucleons. A complete list of experiments can be found in ref. 1b. Two features occur in all the data: (a) there is no evidence of bound state behavior, and (b) there is a large enhancement in cross section for low 3-neutron kinetic energy. Although detailed calculations exist for only a few cases, the gross features of the low energy enhancements are explainable in terms of the 1S_0 two-body nucleon-nucleon force in the final state.¹⁷ There are two difficulties associated with accurate calculations: (a) the influence of other strongly interacting particles present in the final state on the shape of the 3-neutron spectrum is difficult to calculate, and (b) the transition operator is poorly understood. These complications led us to consider the ${}^3\text{H}(\pi^-, \gamma)$ reaction which for the following reasons is unusually favorable for the study of structure in the $3n$ system near threshold:

(a) The final state interaction of the photon can be neglected.

(b) The nuclear capture of the pion, which occurs predominantly from s atomic states, is well described by the Kroll-Ruderman term¹⁸ in the impulse approximation. For radiative capture on the closely

related ^3He nucleus, Phillips and Roig have shown that this approach correctly reproduces the Panofsky ratio (the ratio of the charge exchange rate to the radiative capture rate), and when the final state interaction was treated in the Amado model, the resulting curve shape agreed with the measured spectrum.¹⁹

(c) The ^3He data and calculation agreed that, for a given spin-isospin channel, the lowest threshold final state was preferentially populated. In the case of the breakup channel $^3\text{He}(\pi^-, \gamma)2n + p$, low relative kinetic energy among the outgoing nucleons was favored.

(d) A partial wave analysis²¹ of the $T = 3/2$ part of the reaction $^3\text{He}(\pi^-, \gamma)2n + p$ showed an expected population of 60% 2P and 40% 2S . The $L = 1$ states are cited in a number of calculations^{2,4,5,13,14} as being the most likely candidates for binding.

The conceptual advantages are to some extent offset by the experimental difficulties: A large target of liquid tritium (LT_2) in a thin windowed cryogenic dewar requires extensive safety precautions, only a few percent of the pions stopping in the target are absorbed radiatively, and high resolution spectroscopy (1-2%) at photon energies in the 100 MeV region is possible only at low efficiency. The experiment described in this paper was made possible by the availability of a reasonably sized tritium target with handling capabilities and a high flux pion beam at the Clinton P. Anderson Los Alamos Meson Physics Facility (LAMPF).

The first run at LAMPF in 1974²⁰ showed the feasibility of the experiment, but the final spectrum contained only a limited number of events (1000) recorded with resolution of 3.5 MeV FWHM at 129.4 MeV. The experiment was further troubled by substantial background arising from pions stopping in the target impurities and the cryogenic container. No evidence of a bound tri-neutron state was found with the upper limit of 6% branching ratio to such a state, but a suggestion of possible structure around 6 and 15 MeV excitation was present in the data. The shape of the spectrum was adequately fitted by a theoretical calculation^{3,21} (described in Section 3) which assumes no resonances.

We report here the results of a new experiment which improved upon the previous one in resolution, statistics and background by factors of 2.2, 27 and 2, respectively.

2. Description of Experimental Arrangement

The experiment was carried out in the low energy pion beam (LEP) at LAMPF. Figure 1 shows the setup. As in the previous LT_2 experiment, a magnetic pair spectrometer was employed to measure the high energy photon spectrum. The spark chambers were replaced by multiwire proportional chambers (MWPC) with 3 planes of 512, 1024, and 512 wires at -60° , 0° , and $+60^\circ$ to the vertical, respectively, and 2 mm wire separation. High energy photons from the target entered the spectrometer through a collimator and struck a 0.0108 cm gold foil, converting

2% of the photons into an e^+e^- pair. These particles were momentum analyzed in the magnetic field of two parallel C-magnets with common pole tips (gap = $33 \times 41 \times 218 \text{ cm}^3$, $B = 0.8 \text{ T}$). The MWPC recorded the entrance and exit positions of the charged particles. The occurrence of a recorded event required that at least two pairs of AB scintillator trigger counters fire in coincidence with fast trigger signals directly from the MWPC planes. A scintillator π C covering the collimator opening rejected charged particles from the target and collimator. MWPC wire addresses were transferred to tape by a PDP-11/45 computer via a Berkeley-developed readout system using a microprogrammed branch driver in combination with a CAMAC interface system. The computer also provided preliminary analysis for on-line monitoring.

The acceptance of the pair spectrometer was calculated by Monte-Carlo methods to be 2.6×10^{-5} at 130 MeV. Acceptance as a function of energy is shown in Figure 2.

The target, consisting of 6 g of LT_2 (58 kCi) at 23K in a 25.4 mm dia X 28.6 mm stainless steel flask with a wall thickness of 0.076 mm, was surrounded by an outer vacuum jacket 33 mm x 50 mm dia. X 0.12 mm wall thickness. There was a 25% background contribution from the stainless steel containers; separate target empty runs were made to correct for this background.

The LT_2 target, together with an identical liquid hydrogen (LH_2) target ($T = 19K$), were mounted on a moveable rack allowing them to be interchanged. Runs of about 8 hours LT_2 were interspersed with 1 hour LH_2 runs for purposes of normalization, energy calibration, and determination of instrumental resolution. A typical hydrogen spectrum (Figure 2) indicates the resolution at 130 MeV to be about 1.8 MeV. The LT_2 and cryogenic system as well as extensive personnel safeguards were provided by LAMPF.

Contaminants in the tritium gas were 0.07% D, 0.29% H, and 1.25% 3He by atom. The deuterium background can be neglected. The strong 3He peak at 135.8 MeV was not observed, indicating that the solubility of 3He in LT_2 is negligible at these levels of observation. The H_2 line at 129.4 MeV was observed at $\sim 40\%$ of the intensity which would be predicted from a ratio of atoms in the sample, indicating some transfer of pions captured on H to T. The uncertainty in the hydrogen contribution to the spectrum slightly reduces the quality of the LT_2 spectrum in the vicinity of the LH_2 peak at 129.4 MeV; since the $3n$ threshold is at 126.96 MeV, this is not a serious background problem for the continuum or for the case of a bound state existing just below threshold.

Pion stopping rates in LT_2 averaged $5 \times 10^5/\text{sec}$ at a primary proton current of 150 μA , a momentum bite of $\Delta p/p \sim 2\%$, and a momentum before degrader of 200 MeV/c.

The raw data were scanned for patterns characteristic of an e^+e^- pair. A cut on the e^+e^- entrance coordinates was used to eliminate conversions before the gold foil when the πC counter test failed. This cut also eliminated electrons with unusually large multiple scattering angles, improving the energy resolution significantly.

A multiparameter polynomial of momentum as a function of the MWPC coordinates, based on idealized Monte Carlo generated events, was used to translate the trajectory data into photon energy spectra.

3. Results and Discussion

The final spectrum consisted of 27000 tritium events between 60 and 130 MeV with a resolution of 1.8 MeV at 130 MeV. The stainless steel background amounted to 25% of the total spectrum. The target empty signal was measured and showed no significant structure. There were ~ 90 counts due to H_2 contamination in the tritium, of which two-thirds were in the radiative exchange peak at 129.4 MeV. The raw data is shown in Figure 3.

Phillips and Roig^{3,21} have predicted the shape of the curve in the approximation in which the initial state capture is described by the Kroll-Ruderman term in the impulse approximation and the final state interactions are treated in the Amado model, that is, using a separable s-wave nucleon-nucleon potential approximation to solve the Faddeev equations. They have assumed $a_{nn} = -20.34$ fm, $r_{nn} = 2.73$ fm, $P(S') = 1.8\%$, and $P(D) = 0.0\%$. Above 30 MeV excitation of the 3-neutron

system the calculation is considered unreliable due to the increasing importance of short range correlations and uncertainties in the off-shell pion-nucleon transition amplitude. No bound state or resonant behavior was obtained. Table 1 summarizes the results of this calculation.

Phillips and Roig³ found the γ spectrum of the main component (4P) of the $^3\text{He}(\pi^-, \gamma) \text{dn}$ reaction to be insensitive to the strength of the nd interaction. Unfortunately, calculations using different parameters have not been carried out for the present case of $T = 3/2$. The most recent experimental value of $a_{\text{nn}} = -18.3 \text{ fm}^{22}$ as well as a realistic adjustment of $P(S')$ to $\sim 1.2\%$ and $P(D)$ to $\sim 5\%$ should be explored. We hope that the data presented here will motivate such calculations.

In Figure 4, the calculated curves, obtained by drawing a smooth curve through the points in Table 1, and then folding with the instrumental acceptance and resolution, are superimposed on the LT_2 data corrected for background. The curves were normalized to the data between 95 and 125 MeV. The large effect of the final state interactions is made clear by comparing the predicted curve a) with the curve b) obtained for a plane wave $3n$ final state.

The agreement between curve a) and the data is surprisingly good in view of the severity of the separable approximation as well as the uncertainty due to the choice of parameters. Assuming the correctness

of the curve, the upper limit (95% confidence level) on the branching ratio to resonances with $\Gamma \leq 5$ MeV within 20 MeV of the $3n$ threshold is 2×10^{-2} . The upper limit on the existence of bound states when the total $3n$ energy is less than 3 MeV above threshold is 4×10^{-3} , except at 2.44 ± 0.9 MeV below threshold, where this limit is increased to 1×10^{-2} due to hydrogen contamination in the target.

Absolute normalization of the data, expressed in terms of the radiative branching ratio ${}^3\text{H}(\pi^-, \gamma)3n / ({}^3\text{H}(\pi^-, 3n) + {}^3\text{H}(\pi^-, \gamma)3n)$ was found to be $5.3 \pm 0.7\%$, in agreement with the earlier data ($4.8 \pm 0.8\%$) and the value $6.5 \pm 2.0\%$ predicted by Phillips and Roig.^{3,21}

In conclusion, we have performed an experiment expected to be highly sensitive to the presence of $3n$ structure near threshold and see no evidence for it, other than a very pronounced shift to low $3n$ energy which can be explained in terms of the simple s-wave pair-wise interaction between neutrons in the final state. In particular, there is no evidence for a $3n$ bound state or narrow resonance, and in view of the excellent agreement between the LT_2 spectrum and the curve of Phillips and Roig, the effect of 3-body forces, if they exist, is probably small; the properties of the 3-body states studied here are satisfactorily explained in terms of a 2-body potential calculation.

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TABLE 1

Relative amplitude of radiative capture on tritium as a function of energy.

Gamma energy (MeV)	1S_0 final state n-n interaction ^{a)}	No final state interaction ^{a)}
85.5	0.017	0.026
100.8	0.078	0.089
109.8	0.200	0.160
115.9	0.349	0.183
120.3	0.403	0.120
123.5	0.266	0.039
125.5	0.073	0.004

^{a)}Ref. 3 and 21.

FIGURE CAPTIONS

- Figure 1. Plan view of experimental set-up.
- Figure 2. Acceptance of spectrometer as a function of gamma energy from Monte Carlo calculations, checked by comparison with the observed Panofsky ratio in the hydrogen spectrum. Typical hydrogen spectrum used for calibration purposes is also shown.
- Figure 3. Raw tritium data and background spectrum.
- Figure 4. Measured tritium spectrum with background subtracted. Curve a), Amado model and curve b), plane wave for $3n$ final state, from ref. 3 and 21, folded with the experimental resolution and corrected for spectrometer acceptance.

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FIGURE 1

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FIGURE 2

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FIGURE 3

FIGURE 4

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