it departs from the value obtained from the reaction $H^2(n,p)2n$, and is closer to −17 F, the mean value obtained from the reaction $H^2(\pi^-, \gamma)2n$. The theoretical prediction for a_{nn}, assuming exact charge symmetry, lies between −16.6 and −16.9 F.[18]

---

[1] R. P. Haddock, R. Salter, M. Zeller, J. B. Czirr, D. R. Nygren, and T. Maung, Bull. Am. Phys. Soc. 9, 443 (1963).

[2] J. W. Ryan, Phys. Rev. Letters 12, 564 (1964). See also K. M. Watson, Phys. Rev. 88, 1163 (1952).

[3] K. Ilakovac, L. G. Kuo, M. Petravić, and I. Šlaus, Phys. Rev. 124, 1923 (1961).

[4] M. Cerineo, K. Ilakovac, I. Šlaus, P. Tomaš, and V. Valković, Phys. Rev. 133, B948 (1964).

[5] V. K. Voitovetskii, I. L. Korsunskii, and Y. F. Pazkin, Phys. Letters 10, 109 (1964).

[6] M. Bander, Phys. Rev. 134, B1052 (1964).

[7] R. H. Dalitz, Ann. Rev. Nucl. Sci. 13, 339 (1963).

[8] E.g., K. Ilakovac, L. G. Kuo, M. Petravić, I. Šlaus, and P. Tomaš, Nucl. Phys. 43, 254 (1963).

[9] R. J. N. Phillips, Nucl. Phys. 31, 643 (1962).

[10] B. Lalović and V. Ajdačić, Proceedings of the Symposium on Nuclear Electronics, Paris, 1963 (unpublished).

[11] M. Konrad and V. Radeka, to be published.

[12] For a detailed description see, e.g., reference 4.

[13] In this way pulses corresponding to the particles produced in the E counter were rejected, while the number of those corresponding to the particles produced in the ΔE_1 counter and to random coincidences was appreciably reduced.

[14] G. Paić, I. Šlaus, and P. Tomaš, to be published.

[15] J. H. Coon, C. K. Bockelman, and H. H. Barshall, Phys. Rev. 81, 33 (1951).

[16] J. D. Seagrave, Phys. Rev. 97, 757 (1955).

[17] M. Cerineo, G. Paić, and I. Šlaus, to be published.

[18] L. Heller, P. Signell, and N. R. Yoder, Phys. Rev. Letters 13, 575 (1964); illuminating discussions with H. P. Noyes and P. S. Signell are acknowledged.

REACTIONS $H^3(n,p)3n$ AND $H^3(n,H^4)\gamma$ AT $E_n = 14.4$ MeV

V. Ajdačić, M. Cerineo, B. Lalović, G. Paić, I. Šlaus, and P. Tomaš
Institute "R. Bošković," Zagreb, Yugoslavia, and Institute "B. Kidrič," Belgrade, Yugoslavia

(Received 10 February 1965)

The proton spectra from the reaction $n + H^3$ at $E_n = 14.4$ MeV were measured with a semiconductor counter telescope[1] in conjunction with multidimensional analyzers.[2] The results of several independent measurements are summarized in Figs. 1 and 2. They reveal the following features:

(1) The cross section for the reaction $H^3(n,p)3n$, integrated from 3.8 to 5.1 MeV at 0°, is 12 mb/sr. This is smaller than the cross section for the breakup $H^3(n,d)2n$,[3] but is larger than predicted by Gammel and MacKellar.[4]

(2) The simultaneous breakup into three neutrons and a proton would give a proton energy spectrum of the form[5] $E_p^{1/2}(E_{\max}-E_p)^3$, with $E_{\max} = 5.1$ MeV. The failure to reproduce the experimental data can be interpreted as an indication of strong final interactions and gives hope[6] that the study of the reactions $H^3(n,p)3n$ and $He^3(p,n)3p$ might give some information about possible three-body forces.

(3) A group of protons extends from 5.9 to 6.9 MeV. Its width at half maximum is about 600 keV, comparable with the over-all resolution of the experimental arrangement. The total number of counts in this group is 892 ± 160.

The possible origin of this group was carefully examined. Separate measurements performed to this end showed that as much as 2% of hydrogen contamination of the targets could contribute no more than 0.3 mb/sr to this group. The reaction $N^{14}(n,p)C^{14}$ could give several groups of protons with energies above 7.5 MeV and one at 6.7 MeV. However, no protons with energies higher than 7 MeV, nor deuterons[3] from $N^{14}(n,d)C^{13}$, were observed. The possibility that the 6.4-MeV group stems from the N^{14} contamination was definitely ruled out by a separate measurement[7] of the reaction $n + N^{14}$. Since the intensity of the 6.4-MeV proton group was independent of the amount of He^3 in the target, as is evident from Figs. 1 and 2, it could not be assigned to the $n + He^3$ interaction. Several measurements performed in different experimental conditions have excluded also the possibility that this group is due to an experimental error.

The remaining alternative is to assign the 6.4-MeV proton group to the $n + H^3$ interaction. If one accepts this, one is obliged to assume the existence of a bound state of three neutrons. Its binding energy would then be about 1 MeV and the cross section $\sigma(\varphi = 0°)_{H^3(n,p)n^3} = 3.8$ mb/sr.

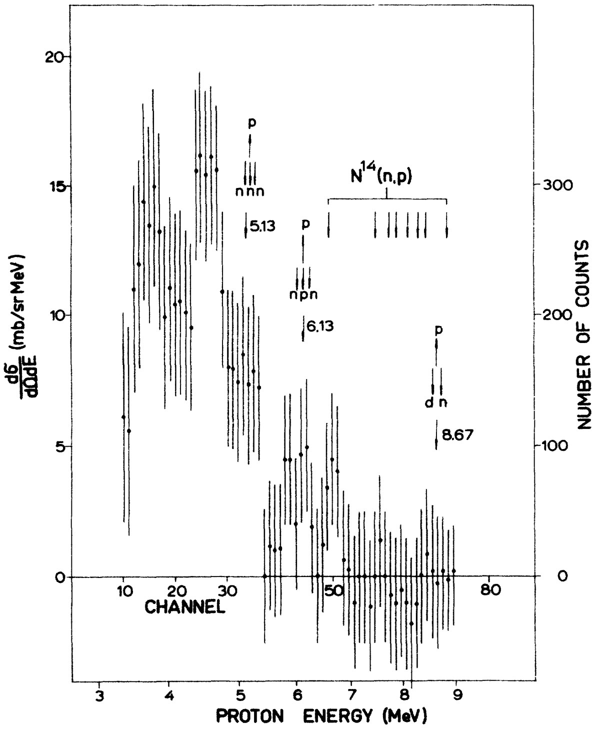

FIG. 1. The proton spectrum at 0° from the reaction $n+H^3$ obtained from a solid Cu-Ti-H^3 target with 0.3 mg of H^3 and a 0.1-mg gas-H^3 target, with the over-all He^3 content of about 8%. The arrows indicate the maximum proton energies for the breakup processes $H^3(n,p)3n$, $He^3(n,p)nnp$, and $He^3(n,p)nd$, and the energies of proton groups from the reaction $N^{14}(n,p)C^{14}$.

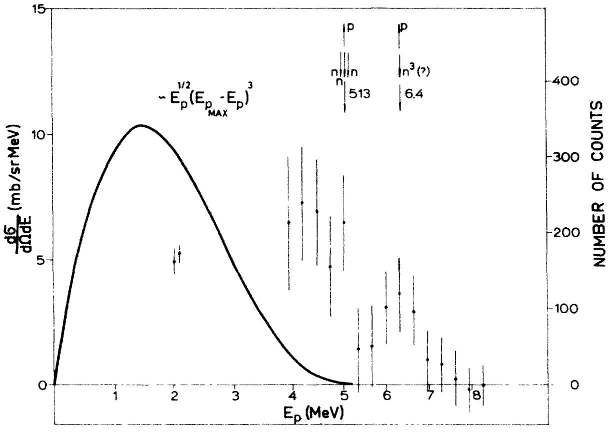

FIG. 2. The proton spectrum at 0° from the reaction $n+H^3$ obtained from a 1.3-mg H^3-gas target with He^3 content less than 0.4%. The data at about 2 MeV were obtained in a separate measurement with two thin detectors in coincidence followed by a thick detector in anticoincidence. The solid curve was calculated under the assumption of simultaneous breakup into three neutrons and a proton with relative angular momenta $L_{n_1n_2}=0$, $L_{n\,2n}=1$, and $L_{p\,3n}=0$.

The existence of neutron matter,[8] n^2,[9] n^4,[10] and n^6[11] has been the subject of extensive studies, but so far it has tacitly been assumed that there is no bound n^3. To the authors' knowledge the existing data do not rule out the possibility that a particle-stable n^3 exists. The most stringent condition on its binding energy is probably given by the controversial existence of He^7[12] and He^8[13]. Since three neutrons in these nuclei cannot be bound by less than 1 MeV, even if they exist the upper limit for the binding energy of n^3 would be ≳1 MeV.

The existence of n^3 with a binding energy of about 1 MeV implies the existence of $T=\frac{3}{2}$ excited states in H^3 and He^3 at about 7.5 MeV. There should be, therefore, a resonance in the n-d and p-d scattering at $E_n \approx 1.8$ MeV and $E_p \approx 2.8$ MeV, respectively. These resonances should be very narrow (≲1 keV) as the nucleon-deuteron system has $T=\frac{1}{2}$, and would presumably escape experimental observation. It is intriguing that there is a peak[14] in the p-d elastic scattering at about 2.6 MeV. The assumed $T=\frac{3}{2}$ level in He^3 being close to the $p+p+n$ threshold, an appreciable admixture of $T=\frac{3}{2}$ component in the p-d system might occur.

The existence of n^3 would also imply the existence of n^4. The evidences concerning n^4 are still controversial.[10] On the other hand, there is by now substantial evidence against the existence of H^4 and H^5.[15] In a separate measurement, using the same targets and with two thin detectors in coincidence followed by a thick counter in anticoincidence,[16] a direct detection of H^4 supposedly produced in the capture reaction $H^3(n,H^4)\gamma$ was attempted. The upper limit for the cross section for this reaction was found to be 0.2 mb/sr, while the cross sections for similar processes are $H^1(n,H^2)\gamma$, $\sigma = 36.4 \pm 2.9\ \mu b$[17]; $H^2(n,H^3)\gamma$, $\sigma = 29.4 \pm 5.8\ \mu b$[18]; $H^2(p,He^3)\gamma$, $\sigma \approx 26\ \mu b$.[19]

The very probable nonexistence of H^4 and H^5 might be interpreted as evidence that the existence of n^3 and n^4 is highly improbable. However, even being "less bound," n^4 could be particle stable, while H^4 decays into H^3+n. If it turns out that there is no n^4, then either there is also no n^3, or, if n^3 does exist, our concepts on nuclear forces should be revised.

The authors express their deep thanks to Professor M. Paić for his constant support and encouragement during this work and to the participants of the Few Nucleon Problems

Summer Meeting in Herceg-Novi, July 1964, for many stimulating discussions.

---

[1] B. Lalović and V. Ajdačić, Proceedings of the Symposium on Nuclear Electronics, Paris, 1963 (unpublished).

[2] M. Konrad and V. Radeka, to be published.

[3] V. Ajdačić, M. Cerineo, B. Lalović, G. Paić, I. Šlaus, and P. Tomaš, preceding Letter [Phys. Rev. Letters 14, 442 (1964)].

[4] J. L. Gammel and D. MacKellar, Phys. Rev. 133, B1434 (1964).

[5] L. M. Delves, Nucl. Phys. 20, 275 (1960).

[6] I. Šlaus, Lectures on Nuclear Interactions, edited by B. Lalović (The Federal Nuclear Energy Commission of Yugoslavia, Belgrade, Yugoslavia, 1962), Vol. I, p. 51.

[7] G. Paić, D. Rendić, and P. Tomaš, to be published.

[8] K. Brueckner, J. L. Gammel, and J. Kubis, Phys. Rev. 118, 1095 (1960); Ya. B. Zeldovich, Zh. Eksperim. i Teor. Fiz. 38, 1123 (1960) [translation: Soviet Phys.–JETP 11, 812 (1960)]; A. I. Baz, V. I. Goldanskii, and Ya. B. Zeldovich, Usp. Fiz. Nauk 72, 211 (1960) [translation: Soviet Phys.–Usp. 3, 729 (1961)].

[9] D. E. Groce and R. E. Shamu, Congrès International de Physique Nucléaire, Paris, 1964 (to be published); H. B. Willard, J. K. Bair, and C. M. Jones, to be published, and references therein.

[10] P. E. Argan, G. Bendiscioli, A. Piazzoli, U. Bisi, M. J. Ferrero, and G. Piragino, Phys. Rev. Letters 9, 405 (1962); P. E. Argan and A. Piazzoli, Phys. Letters 4, 350 (1963); V. I. Goldanskii, Phys. Letters 9, 184 (1964); J. D. Schiffer and R. Vandenbosch, Phys. Letters 5, 292 (1963); E. Lohrmann, H. Meyer, and H. O. Wüster, Phys. Letters 6, 216 (1963); F. von Hippel and P. O. Divakaran, Phys. Rev. Letters 12, 128 (1964); A. Piazzoli, Proceedings of the Ninth Summer Meeting, Herceg-Novi, Yugoslavia, 1964 (to be published); R. E. P. Davis, A. Beretvas, N. E. Booth, C. Dolnick, R. J. Esterling, R. E. Hill, M. Raymund, and D. Sherden, Bull. Am. Phys. Soc. 9, 627 (1964); M. J. Beniston, B. Krishnamurthy, R. Levi-Setti, and M. Raymund, Phys. Rev. Letters 13, 553 (1964). See also reference 11.

[11] O. D. Brill, N. I. Velikov, A. A. Kurashov, A. A. Ogloblin, V. M. Pankratov, and V. P. Rudakov, to be published.

[12] V. V. Balashov, At. Energ. (USSR) 9, 48 (1960) [translation: Soviet J. At. Energy 9, 544 (1961)].

[13] O. V. Lozkhin and A. A. Rimski-Korsakov, Zh. Eksperim. i Teor. Fiz. 40, 1519 (1961) [translation: Soviet Phys.–JETP 13, 1064 (1961)]; B. M. K. Nefkens, Phys. Rev. Letters 10, 243 (1963).

[14] R. Sherr, J. M. Blair, H. R. Kratz, G. L. Bailey, and R. F. Taschek, Phys. Rev. 72, 662 (1947); repeated in 1964 by the Rice group, G. C. Phillips, private communication.

[15] A. Schwarzschild, A. M. Poskanzer, G. T. Emery, and M. Goldhaber, Phys. Rev. 133, B1 (1964); R. J. Cence and C. N. Waddell, Phys. Rev. 128, 1788 (1962); B. M. K. Nefkens and G. Moscati, Phys. Rev. 133, B17 (1964); W. L. Imhof, F. J. Vaughn, L. F. Chase, H. A. French, R. G. Johnson, and M. Walt, U. S. Air Force Special Weapons Center Report No. AFSWC-TDR-62-26, Air Forces Project No. 8802, March 1962 (unpublished); V. N. Andreev and S. M. Sirotkin, Zh. Eksperim. i Teor. Fiz. 19, 797 (1964) [translation: Soviet Phys.–JETP 46, 1178 (1964)]; P. C. Rogers and R. H. Stokes, Phys. Letters 8, 320 (1964); B. M. Spicer, Phys. Letters 6, 88 (1963); R. V. Popić, B. Z. Stepančić, and M. R. Aleksić, Phys. Letters 10, 79 (1964). A. Bernstein, Proceedings of the Ninth Summer Meeting, Herceg-Novi, Yugoslavia, 1964 (to be published); and references therein.

[16] The advantages of such arrangement were that the H^4 nuclei, independently of their binding energy, could be detected with $T = 0$, 1, and 2, provided only that their lifetime be longer than 6 nsec.

[17] J. G. Tudorić, I. Šlaus, and P. Tomaš, to be published.

[18] M. Cerineo, K. Ilakovac, I. Šlaus, and P. Tomaš, Phys. Rev. 124, 1947 (1961).

[19] C. Becchi, G. E. Manuzio, L. Meneghett, and S. Vitale, Phys. Letters 8, 322 (1964).