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# A Method for Unambiguous Detection of a Hypothetical Bound Two-Neutron System

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**Abstract** An experiment is proposed aiming at the unambiguous detection of mass  $A = 2$  neutral particles via elastic scattering and neutron exchange reactions on protons in a plastic scintillating fibre detector. Di-neutrons would be produced in ordinary  $\pi^-$  absorption at rest on  ${}^3\text{He}$  together with tagging protons. The basic advantages of the proposed process are the strict collinearity and opposite, and constant momenta of hypothetical di-neutrons and recoiling particles in the LAB reference frame. Moreover, the detection cross sections ( ${}^2n + p \rightarrow p + {}^2n$ ;  ${}^2n + p \rightarrow d + n$ ) are calculable with three-nucleon codes based on  ${}^1a_{nn}$  dependent  $nn$  interactions.

## 1 Introduction

A recent announcement of a discovery of bound di-neutrons existing in neutron halo nuclei [1] revived interest to these hypothetical, electrically neutral light nuclei. Certain level of excitement continues despite it became clear that the observed effect is, probably, due to emission of a correlated pair of neutrons originating from the virtual singlet spin state: the negative value of the scattering length  ${}^1a_{nn} = -18.7$  fm was used to interpret the measured data for the three-body decay. The phenomenon is very similar—if not identical—to the so called  $nn$  final state interaction ( $nn$ -FSI) peak observed frequently in many nuclear reactions in a specific kinematical configuration where the neutron pair with low relative momentum is emitted back-to-back with the recoiling system. Among them are neutron induced breakup reactions on deuterium and other light nuclei, radiative  $\mu^-$  capture on deuterium and ordinary  $\pi^-$  absorption on helium isotopes. The shape of the FSI peak has been astonishingly well modeled by Watson and Migdal already in 1952 [2,3] and is dependent on  $({}^1a_{nn})^2$ . The sign of  ${}^1a_{nn}$ , which is decisive for the existence or non-existence of a bound state, must be established from coherent neutron-neutron scattering. Since such an experiment has not been done yet, the negative sign of  ${}^1a_{nn}$  is motivated mainly by the lack of observation of bound multi-neutron systems, consistency in the description of the experimental data by the model nucleon-nucleon forces and isospin conservation in strong interactions. As all these arguments give only limited confidence (see e.g. [4]), the nonexistence of bound di-neutrons is still an open question.

On the frontier of the di-neutron research, the three-body decay of neutron-rich nuclei, the term “di-neutron” is used to describe a possible cluster existing in the nucleus (in the nuclear medium) before it decays. Such an object should not be confused with the bound di-neutron. Distinguishing between di-neutron clustering in nuclei and  $nn$ -FSI is not an easy task as the effective interactions in a model space consisting of halo neutrons and a core are complex and poorly known. This fact was pointed out in Ref. [5]. Moreover,

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In memory of Walter Glöckle.

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the reported observation [1] of a singlet neutron pair emitted from light nuclei at low excitation is not a new phenomenon. A similar effect has been observed already more than two decades ago [6]. Therein the emission of two correlated neutrons with low relative momentum from the excited  $^{10}\text{Be}$  nucleus was observed and satisfactorily described in an effective three-body model:  $^8\text{Be}_{gs} + n + n$ . The only differences with respect to Ref. [1] are the way of production ( $n + ^9\text{Be} \rightarrow n + n + ^8\text{Be}_{gs}$ ) and somewhat higher excitation energy ( $E_{ex} = 16$  MeV).

In the following, the terms “di-neutron”, “tri-neutron”, “tetra-neutron”, etc. are used exclusively to describe the bound states  $^2n, ^3n, ^4n$ , respectively. These objects must be stable in vacuum with respect to strong interactions and can decay only via weak interactions.

## 2 Neutral Nuclei—Hints from Theory?

In general, theory is reluctant to accept the existence of bound, electrically neutral nuclei. A collection of various arguments can be found e.g. in Ref. [7]. Nevertheless, there exist a number of inconsistencies and uncertainties in that discouraging picture. (i) For instance, all the model  $nn$  potentials are tuned at low energy such that they are compatible with the current experimental evidence of the nonexistence of the  $^2n$  bound state. Clearly, such potentials are biased. (ii) Another bias can be traced back to the nuclear structure calculations of neutron-rich nuclei. The model space must be truncated there for technical reasons. (iii) In the Faddeev calculations of the three-nucleon system in the continuum there exist persistent discrepancies in the description of the  $nnp$  observables at low energy. Three-nucleon forces cannot account for these discrepancies. Increasing the binding of the (standard)  $nn$  potential partly improves the situation but the results are inconclusive yet [4]. (iv) An interesting hint for the stronger than commonly accepted  $nn$  binding comes from lattice QCD calculations [8]. Unfortunately, these calculations were performed with a yet unrealistic pion mass of 0.51 GeV. It may happen that the strong  $nn$  binding will disappear when the QCD calculations converge at the pion mass of about 0.14 GeV. The question is still open.

Attention to the  $^2n$  bound state comes also from astrophysics and cosmology. It has been checked (Ref. [9]) that such states would affect the big bang nucleosynthesis only, if the binding energy were greater than 3 MeV. However, such strong binding is hardly expected given the current empirical evidence.

Finally, one should mention an unresolved, yet partial contradiction in the calculation of the dependence of nuclear binding on the hadronic mass (Refs. [10] and [11]). This aspect of hadronic interactions is important as it could explain why e.g. di-neutrons are not observed now but they existed in the early universe.

Concluding this brief and selective review one can say that theory analyzes and predictions are not encouraging but sufficiently incomplete and inconsistent to leave enough room for serious empirical searches of bound multi-neutron systems.

## 3 Experimental Searches for Bound Multi-neutrons

This paper does not intend to make an extensive overview of experiments searching for bound multi-neutrons. Instead, two experiments will be mentioned belonging to two distinct and characteristic classes. Both of these experiments, in a different way, try to prepare the neutron configuration such that a bound system can be formed. They differ also in the detection of a multi-neutron bound state. The strategy of the first experiment [12] is to produce a highly (charge) depleted system in the double pion exchange reaction (DPE) on helium:  $^4\text{He}(\pi^-, \pi^+)^4n$  and looking for possible structures in the spectrum of the recoiling pion. The second experiment [13] tries to produce bound tetra-neutrons by breaking up neutron rich, loosely bound  $^{14}\text{Be}$  nuclei in the Coulomb field and subsequently detecting neutral particles in a liquid organic scintillator.

No evidence for bound neutron clusters has been found in the DPE reaction and an upper limit for the production cross section was estimated to be less than 13 nb at 90% confidence level. Contrary to that the second experiment reported evidence for 6 events which could be interpreted as due to  $^4n$  particles. Unfortunately, this evidence was later discarded (Ref. [14]). It turned out that the detection cross section for  $^4n$  was overestimated in Ref. [13] by at least two orders of magnitude.

Presently, there are no convincing evidences for bound multi-neutron systems. In order to improve the sensitivity, any new experiment should assess both the production cross section and detection probability much better than achieved previously. In the proposed experiment, both these ingredients will be available from *ab initio* calculations where the model  $nn$  potential can be varied. At the same time, the evidence for directly detecting neutral particle with mass  $A = 2, 3, 4, \dots$  will not rely on any model calculation.

**Table 1**  $\pi^-$  capture at rest on  $^3\text{He}$ 

Final state	Kinetic energy (MeV)	Branching ratio (from [15])
$d + n$	$E_d = 45.3, E_n = 87.5$	$0.130 \pm 0.015$
$p + n + n$	$E_{p+n+n} = 130.6$	$0.552 \pm 0.065$
$nn$ -FSI	$E_p \approx 85.0, E_{(nn)} \approx 46.0$	$0.020 \pm 0.004 \pm 0.001$
$^2n + p$	$E_p = 85.8, E_{2n} = 44.8^a$	–

<sup>a</sup> Di-neutron binding energy of 200 keV was assumed

#### 4 $\pi^-$ Absorption at Rest on $^3\text{He}$

Charged pions slow down when passing through matter and, finally, form excited pionic atoms. The excitation energy is released by emission of X-rays and/or Auger electrons while the pion cascades down to the ground state. From there the pion can either disappear in beta decay or gets captured by the nucleus. Such a process is characterized by practically zero total momentum (capture at rest) and momentum transfer comparable with the pion mass.

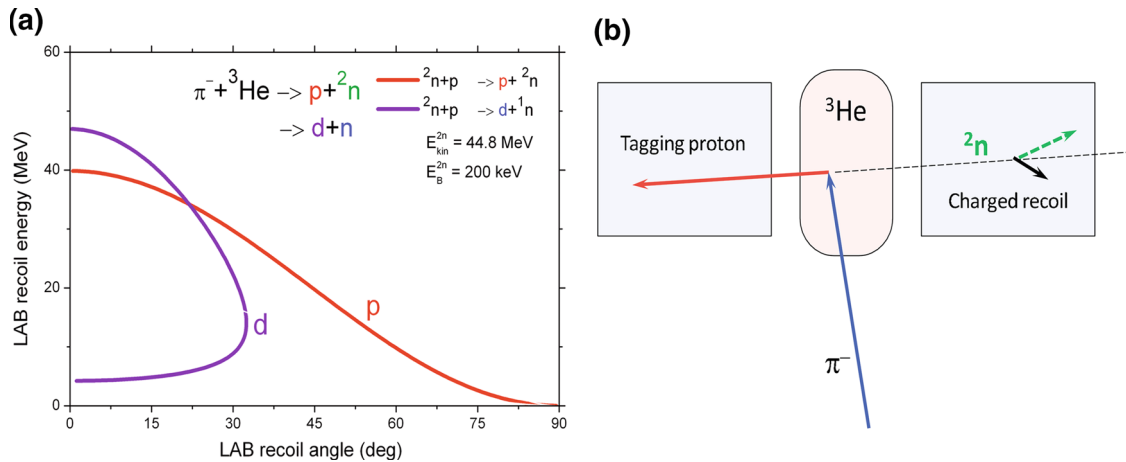
Ordinary (non-radiative) negative pion absorption on  $^3\text{He}$  leads to two- and three-body final states as summarized in Table 1. These processes were extensively studied in the past and detailed information can be found in Ref. [15]. If di-neutrons exist, they can be produced in  $\pi^-$  absorption at rest on  $^3\text{He}$ , leading to the two-body final state with zero total momentum in the LAB system. The question arises whether such a process is probable, given the large momentum transferred to one of the final neutrons? A positive answer can be deduced from the experimental data showing that as much as 2% of the stopped  $\pi^-$  result in the final state where a singlet neutron pair with very low relative momentum ( $nn$ -FSI) is emitted back-to-back with the recoiling proton as shown in Table IV of Ref. [15]. Among them there could be bound di-neutrons as well, which are not registered in the experiment of Ref. [15] since the applied detecting system was not designed for that purpose. The advantage of this reaction is that the production cross section can be reliably calculated using a set of compatible potentials ( $\pi N$ ,  $2N$  and  $3N$ ) where the  $nn$ -interaction is varied to allow for different binding properties [16].

#### 5 Principle of the Experiment

The proposed experiment exploits the fact that in the  $\pi^-$  capture at rest on  $^3\text{He}$  hypothetical di-neutrons are produced with fixed kinetic energy of  $E_{2n} = 44.8$  MeV in the LAB system together with a fixed energy proton ( $E_p = 85.8$  MeV) emitted collinearly in the opposite direction. This is an ideal situation for efficient tagging of di-neutrons with monoenergetic protons. The detecting system should be capable to detect a neutral, mass  $A = 2$ , strongly interacting particle of fixed kinetic energy. The key feature of this proposal is to utilize the nuclear interaction of di-neutrons with protons at rest. In such a three-nucleon system, two-body final states (elastic scattering, neutron pick-up) and di-neutron breakup (three-body final state) will take place. The corresponding cross sections can be calculated with percent precision using the same set of potentials as in the case of pion absorption. The advanced Faddeev codes can be modified accordingly such that the usual triplet (deuteron) in the initial state is replaced with a singlet appropriate for the involved di-neutron [16].

The fixed kinetic energy of impinging di-neutron forces the recoiling protons and deuterons (in elastic scattering and neutron pick-up channels) to follow the two-body kinematics as shown in Fig. 1a. If the applied detector is capable to reconstruct momenta of detected charged particles with sufficient precision, the events corresponding to the detection of monoenergetic di-neutrons will populate a narrow band along the kinematical curves. In order to maximize the detection efficiency, the recoil detector should have the lowest possible energy threshold in order to exploit the angular range with large cross section in both  $^2n + p \rightarrow p + ^2n$  and  $^2n + p \rightarrow d + n$  channels.

A generic layout of the experiment is shown in Fig. 1b. Low energy negative pions impinge onto a container filled with  $^3\text{He}$  gas cooled down to about 5 K in order to maximize the pion stop density in the target. The target assembly could be similar to that described in Ref. [15]. The target itself is viewed by two highly granulated plastic scintillator blocks placed on both sides of the beam axis. Such detectors could be constructed from plastic scintillating fibres allowing for momenta reconstruction of stopped charged particles. The data acquisition system should be triggered by the registration of a monoenergetic proton with energy of 85.8 MeV in the



**Fig. 1** (Color on-line) **a** Kinematics for  ${}^2n$  induced  $p$  and  $d$  recoils. **b** Generic layout of the experiment. Explanations in text

anticoincidence with charged particles detected in first few layers of the opposite detector. The data analysis should look for charged recoils beginning at the extrapolation line along the tagging proton momentum.

## 6 Summary and Outlook

An experimental approach is proposed aiming at the unambiguous detection of free bound di-neutrons assuming that they are produced in ordinary  $\pi^-$  capture at rest on  ${}^3\text{He}$ . The detection principle does not rely on any model calculations. Stringent selection constrains come solely from two-body reaction kinematics in two detection channels ( ${}^2n + p \rightarrow p + {}^2n$  and  ${}^2n + p \rightarrow d + n$ ) on protons contained in plastic scintillator material. The *ab initio* calculations of both production and detection processes with unique sets of  $\pi N$ ,  $2N$  and  $3N$  potentials will allow to impose stringent limits on the di-neutron production cross section in case the corresponding events are not found.

It is possible to extend the proposed scheme on searches for heavier neutral nuclei ( ${}^3n, {}^4n$ ) exploiting the  $\pi^-$  absorption at rest on  ${}^4\text{He}$  and, in further perspective, on lithium isotopes.

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## References

1. Spyrou, A., et al.: First observation of ground state dineutron decay:  ${}^{16}\text{Be}$ . *Phys. Rev. Lett.* **108**, 102501 (2012)
2. Watson, K.M.: The effect of final state interactions on reaction cross sections. *Phys. Rev.* **88**, 1163 (1952)
3. Migdal, A.B.: The theory of nuclear reactions with production of slow particles. *JETP (Sov. Phys.)* **1**, 2 (1955)
4. Witała, H., Glöckle, W.: Dineutron and the three-nucleon continuum observables. *Phys. Rev. C* **85**, 064003 (2012)
5. Marques, F.M., et al.: Comment on “First observation of ground state dineutron decay:  ${}^{16}\text{Be}$ ”. *Phys. Rev. Lett.* **109**, 239201 (2012)
6. Bodek, K., et al.: Neutron-neutron scattering length in the reaction  ${}^9\text{Be}(n, nn){}^8\text{Be}$  at 10.3 MeV. *Few-Body Syst.* **8**, 23–35 (1990)
7. Timofeyuk, N.K.: Do multineutrons exist? *J. Phys. G Nucl. Part Phys.* **29**, L9–L14 (2003)
8. Yamazaki, T., et al.: Helium nuclei, deuteron, and dineutron in 2+1 flavor lattice QCD. *Phys. Rev. D* **86**, 074514 (2012)
9. Kneller, J.P., McLaughlin, G.C.: Effect of bound dineutrons upon big bang nucleosynthesis. *Phys. Rev. D* **70**, 043512 (2004)
10. Flambaum, V.V., Wiringa, R.B.: Dependence of nuclear binding on hadronic mass variation. *Phys. Rev. C* **76**, 054002 (2007)
11. Beane, S.R., et al.: Nucleon-Nucleon scattering from fully dynamical lattice QCD. *Phys. Rev. Lett.* **97**, 012001 (2006)
12. Goringe, T.P., et al.: Search for the tetra-neutron using the reaction  ${}^4\text{He}(\pi^-, \pi^+){}^4n$ . *Phys. Rev. C* **40**, 2390 (1989)
13. Marques, F.M., et al.: Detection of neutron clusters. *Phys. Rev. C* **65**, 044006 (2002)
14. Sherrill, B.M., Bertulani, C.A.: Proton-tetra-neutron elastic scattering. *Phys. Rev. C* **6**, 027601 (2004)
15. Gotta, D., et al.: Negative pion absorption at rest in  ${}^3\text{He}$ . *Phys. Rev. C* **51**, 469 (1995)
16. Witała, H.: Private communication