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Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Measurement of the neutron-neutron scattering length at the CERN n_TOF facility

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Abstract: We propose to exploit the interaction of the two neutrons in the final state of the neutron-induced deuteron breakup reaction ^{2}H(n,p)nn for determining the neutron-neutron scattering length in a wide energy range (namely between 10 and 100 MeV) in a single experiment. By taking advantage of the unique features of the updated n_TOF facility, the measurement can be carried out at EAR2. The experiment is based on the detection of the three outgoing particles in kinematic coincidence, leading to a full three-body kinematic reconstruction. The feasibility of this challenging experiment requires a preliminary experimental activity in order to investigate the possibility of using an active target, based on liquid scintillation detector, highly enriched in deuterium.

Requested protons for the test: 5×10^{17} protons on target
Experimental Area: EAR2

Important insight into properties of hadrons and nuclei can be gained by ignoring the often-small effects created by electric charge. E.g., the proton and neutron have nearly identical masses and can be considered as two different states of a single particle, the nucleon. This leads to the expectation that the forces between nucleons should not depend on charge, once electromagnetic effects are removed [1]. This charge independence of nuclear forces is also manifested in nuclear properties.

Charge independence states that strong interaction forces do not distinguish between the neutron and proton. Overall, taking into account up and down quark mass difference and electromagnetic interactions, the general Hamiltonian does not commute with the isospin operator. So, isospin invariance and charge independence are only approximate symmetries. In quantum chromodynamics (QCD), charge-symmetry breaking (CSB) originates from the mass difference between up and down quarks and electromagnetic energy differences caused by their different electric charges and magnetic moments [2].

The $^1S_0$ scattering length is directly related to the strength of the nucleon-nucleon (NN) interaction, and it is very sensitive to small variations of the nuclear potential. Low energy NN scattering is characterized by the scattering length a and effective range r through an effective-range expansion of the S-wave phase shift $\delta(p)$ as [3]:

$$p\,\cot\delta(p) \;=\; -\frac{1}{a} + \frac{1}{2}\,r\,p^2 + \mathcal{O}(p^4) \quad , \tag{1}$$

where p denotes the momentum of the nucleon in the NN center-of-mass (CM) frame. So, the value of the scattering length is an ideal tool for determining the magnitude of CSB [4]. This was the motivation for the early attempts to obtain information on the magnitude of the proton-proton pp scattering length a_{pp}, the neutron-proton np scattering length a_{np}, and the neutron-neutron nn scattering length a_{nn}.

For the nuclear $^1S_0$ pp scattering length one obtains $a_{pp} = -17.3 \pm 0.3$ fm [5], where most of the uncertainty is associated with the model-dependent subtraction of the electromagnetic part of the pp interaction. The np scattering length is the most accurate value among the previous measurements cited, due to the absence of electromagnetic interaction and the easiness to perform the experimental setup, and one obtains $a_{np} = -23.7153 \pm 0.0043$ fm [6].

The experimental determination of a_{nn} scattering length is considerably more difficult because of the lack of a sufficiently dense free neutron target. From the 1970's, first attempts to obtain experimental information on a_{nn} were performed by kinematically incomplete neutron-deuteron (nd) breakup experiments. In these experiments the detection was restricted to the energy spectrum of the outgoing proton. These type of experiments yielded a wide range of values of a_{nn} related to unavoidable experimental difficulties and approximate theoretical methods used in data analysis. Recent attempts to obtain more accurate values for a_{nn} focused on kinematically complete nd breakup experiments and on the negative pion-deuteron ($\pi^- d$) capture reaction with three and two nucleons, respectively, in the final state. The most important measurements of a_{nn} performed in the last decades are reported in Tab. 1.

Focusing on the complete kinematically nd breakup experiments, that is the experimental method implemented by the present letter of intent, the two outgoing neutrons with nearly zero or small relative momentum are detected and the cross section in such a final-state

Year	Energy (MeV)	Process	Detected	a_{nn} (fm)	Reference
1967	$E_n = 14.4$	$d(n,p)nn$	p	$-21.5 + 3 - 1$	[15]
1967	$E_d = 32.5$	^{3}H(d,^{3}He)nn	^{3}He	-16.1 ± 1.0	"
1968	$E_n = 14.4$	$d(n,p)nn$	p	-17 ± 2	[16]
1972	$E_d = 18.4$	$d(n,p)nn$	nn	-14.5 ± 0.8	[17]
1972	$E_n = 49.6$	$d(n,p)nn$	p	-21.7 ± 1.2	[18]
1977	$E_n = 11$	$d(n,p)nn$	p	-16.6 ± 0.4	[19]
1977	$E_n = 13.98$	$d(n,p)nn$	p	-16.6 ± 0.5	[20]
1979	$E_n = 27$	$d(n,p)nn$	p	-16.9 ± 0.6	[21]
1987	$E_{\pi^-} = 220$	$d(\pi^-,\gamma)nn$	$nn\gamma$	-18.7 ± 0.6	[22]
1998	$E_{\pi^-} = 220$	$d(\pi^-,\gamma)nn$	$n\gamma$	-18.6 ± 0.4	[23]
1999	$E_n = 13$	$d(n,p)nn$	nn	-18.7 ± 0.6	[24]
2000	$E_n = 16.6$	$d(n,p)nn$	nnp	-16.2 ± 0.3	[25]
2000	$E_n = 25.3$	$d(n,p)nn$	nnp	-16.3 ± 0.4	"
2006	$E_n = 13$	$d(n,p)nn$	nnp	-18.6 ± 0.7	[26]
2008	$E_{\pi^-} = 48$	$d(\pi^-,\gamma)nn$	$nn\gamma$	$-18.63 \pm 0.10 \pm 0.44$	[27]

Table 1: A brief summary of the latest determination of the $^1S_0$ nn scattering length parameters. The table reports the energy involved and the reaction channels used in the measurements.

interaction (FSI) configuration is measured. The cross section shows a characteristic enhancement around zero relative momentum of the two neutrons. This enhancement is due to the associated strong nn interaction in the $^1S_0$ state and its sensitivity is a powerful method for obtaining experimental information on a_{nn}. On the other hand, solving a problem, where three nucleons in the final state are acting, is quite complex because of the presence of the interaction of the three-nucleon forces (3NF) involved in the nd breakup reaction. For instance, these considerations could also explain a possible dependence of the measured a_{nn} values as a function of the kinetic energy of the incoming neutron, as presented in Fig. 1. In addition, the average a_{nn} values obtained by the nd breakup reaction are different with respect to the values from the π^-d two-body capture reaction.

Recently, it has been concluded that the only way to reconcile these discrepancies would be to use the three-nucleon ($3N$) Faddeev equations [7] with modern NN interactions [8, 9, 10, 11] and including 3NFs [12, 13, 14] as well. With these new powerful theoretical tools at hand, it would be possible to perform experiment-specific theoretical analyses on nd breakup data which take into account all the details of the experimental setup and simultaneously incorporate state-of-the-art $3N$ dynamics.

So far, experiments have determined the neutron-neutron scattering length at a fixed incoming-particle energy and/or at limited angular coverage of the outgoing particles. We aim, for the first time, at systematically studying a_{nn} in a wide range of neutron energies (between 10 and 100 MeV) by using the time-of-flight technique in combination with a detection setup covering a large solid angle. This measurement would go beyond the present knowledge on the topic by studying the trend of nn scattering length as a function of energy.

The experiment is based on the neutron-induced deuteron breakup reaction to be studied

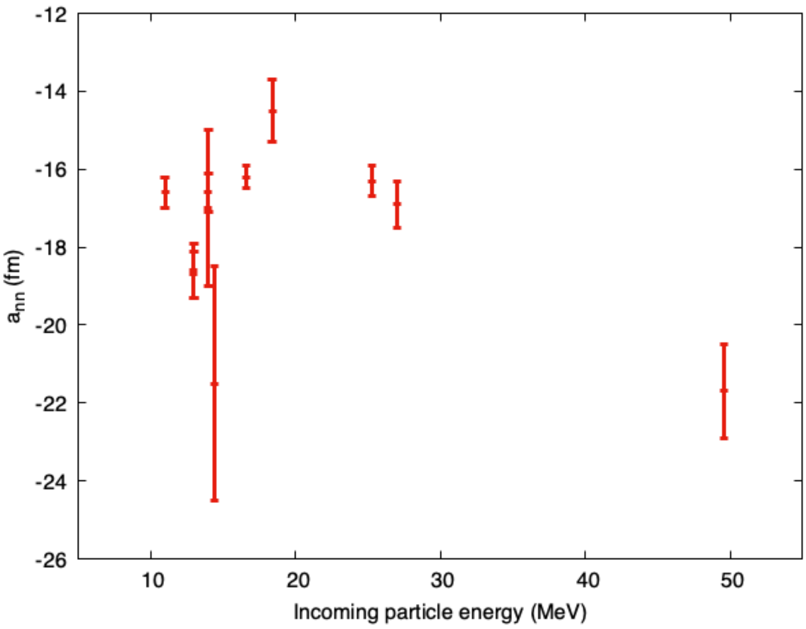

Figure 1: Neutron-neutron scattering length a_{nn} values reported in the literature as a function of the kinetic energy of the incoming neutron in nd breakup reactions.

at the EAR2 measurement station of the n_TOF facility. Thanks to its very wide neutron energy spectrum and high neutron flux obtained by the in-progress facility upgrades, n_TOF offers the unique opportunity to perform such a study with a good accuracy and excellent neutron-energy resolution.

The prerequisite for this experiment is the possibility to use an active target, similar to the one used in [26], suitable for the peculiar conditions at a spallation source, i.e. presence of an intense γ-flash and a continuous neutron energy distribution. In the present case, the active target exploits the properties of a liquid or plastic scintillation detector highly enriched in deuterium, thus providing a clear signature of the occurrence of the $d(n,p)nn$ reaction in the target. It is worth mentioning that this experimental setup allows us to extract the a_{np} scattering length as well, thus benchmarking our results. In particular, at high neutron energies it is possible to determine a_{np} when a small relative momentum between neutron and proton is measured.

In this Letter of Intent we propose, as experimental starting point, to develop and test two different active targets made of NE-232 liquid scintillator and BC436 plastic scintillator, respectively, to study the active target response while irradiated with the n_TOF-EAR2 neutron beam. More in detail, the active volume is foreseen to be a cylinder, 6.0×4.0 cm in height and diameter so to cover the whole neutron beam spot. The scintillators will be contained in a vessel able to guide the light into a Photomultiplier or SiPM array. The results of the proposed test will provide:

- information on the response to the γ-flash and related determination of the highest neutron energy that can be reached;
- determination of the background rate induced by the neutron beam in the active

target.

The data analysis will be performed in combination with Monte Carlo simulations. It is worthwhile to mention that the proposed test will also validate the use of the active target method for future experiments at n_TOF.
According with the results of the proposed active target test (this technique was successfully exploited in [26]), the final experimental setup will be complemented by a neutron detector able to reconstruct the momentum of the two neutrons impinging on its active volume. Due to the constraints for large solid angle, angular coverage and angular resolution, the neutron detector geometry and structure requires substantial improvements with respect to actual state-of-the-art, thus a neutron-detector development has already started.
As a final remark for the INTC, we remind that in 2006 the n_TOF Collaboration already submitted a proposal (INTC-P-204) for a measurement of the neutron-neutron scattering length. Although the experiment was recommended for approval, the measurement was never carried out. In the original proposal, the installation of the detection systems along the horizontal beam-line, in front of EAR1, was foreseen in order to increase the counting rate. Accordingly, several modifications of the neutron beam line were required that finally hindered the realization of the experiment. Now, with the availability of EAR2 station and the neutron spallation source upgrade, the measurement can be performed in this new experimental area with a dramatic improvement in terms of neutron flux and TOF determination.
As already stated, we firmly believe that the physics case is relevant with respect to the measurements performed up to now (see Table 1) and the actual experimental conditions at n_TOF allow to perform a systematic study in a wide neutron energy range. As a matter of fact, the proposed measurement would go beyond the present knowledge on the topic by studying the trend of *nn* scattering length as a function of energy.
Summary of requested protons for the active target test: 5×10^{17} .

References

[1] W. Heisenberg, Über den Bau der Atomkerne. I, Zeitschrift fiir Physik 77, 1-11 (1932), Republished by Springer Berlin Heidelberg, 1989

[2] G. A. Miller, et al., Physics Reports **1** (1990) 1

[3] S. Weinberg, Lectures on Quantum Mechanics, Cambridge University Press 2015

[4] M. J. Moravcsik, Phys. Rev. **136** (1964) B624

[5] J. R. Bergervoet, et. al., Phys. Rev. C **38** (1988) 15

[6] R. W. Hackenburg, Phys. Rev. C **73** (2006) 044002

[7] H. Witaa, et al., Phys. Rev. C **39** (1989) 384

[8] R. B. Wiringa, et al., Phys. Rev. C **51** (1995) 38

[9] R. Machleidt, Phys. Rev. C **63** (2001) 024001

[10] J. J. de Swart, et al., Few Body Systems, Suppl.8 (1995) 438

[11] B. S. Pudliner, et al., Phys. Rev. C **56** (1997) 1720

[12] W. Glöckle, et al., Physics Reports **274** (1996) 107

[13] D. Hüber, et al., Few Body Systems **4** (1993) 1432

[14] S. A. Coon, and H. K. Han, Few-Body Systems **30** (2001) 131

[15] Ivo Šlaus, Rev. Mod. Phys. **39** (1967) 575

[16] E. Fuschini, et al., Nuclear Physics A **109** (1968) 465

[17] B. Zeitnitz, et al., Phys. Rev. Lett. **28** (1972) 1656

[18] A. Stricker, et al., Nuclear Physics A **190** (1972) 284

[19] V. Kulkarni, et al., Nuclear Physics A **367** (1981) 157

[20] R. C. Haight, et al., Phys. Rev. C **16** (1977) 97

[21] W. von Witsch, et al., Physics Letters B **80** (1979) 187

[22] O. Schori, et al., Phys. Rev. C **35** (1987) 2252

[23] W. Tornow, et al., Nuclear Physics A **631** (1998) 421

[24] D. E. González Trotter, et al., Phys. Rev. Lett. **83** (1999) 3788

[25] V. Huhn, et al., Phys. Rev. C **63** (2000) 014003

[26] D. E. González Trotter, et al., Phys. Rev. C **73** (2006) 034001

[27] Q. Chen, et al., Phys. Rev. C **77** (2008) 054002