about half as large as the shift between ^{120}Sn-^{122}Sn) it would certainly stimulate lively interest and discussion in its theoretical interpretation.

In general, the results of the three techniques of isotope shifts (i.e., muonic, optical, and electronic) are in fair agreement. However, when the conditions are favorable, the muonic x-ray method has the advantage that it yields, besides the changes of the rms radius, detailed information on the changes of more than one parameter of the nuclear charge distribution.

ACKNOWLEDGMENTS

The authors wish to express their profound appreciation to Dr. G. L. Rogosa of the U. S. Atomic Energy Commission for his continued interest and efforts, and to Dr. K. Runge for his invaluable help in the early stages of the experiment. We particularly wish to take this opportunity to thank Dr. M. Y. Chen and Dr. L. Wilets for many enlightening discussions, and also to acknowledge our indebtedness to D. N. Stacey, J. E. Hansen, A. Steudel, H. Walther, and R. A. Sorensen for communicating their results to us prior to publication. We are indebted to William Hunt and the cyclotron crew for their efforts in operating the accelerator, and to A. M. Rushton for his help in running the experiment. We also wish to thank J. Ostrowsky and K. Ng for their assistance in the preparation of the targets.

PHYSICAL REVIEW C VOLUME 1, NUMBER 4 APRIL 1970

Neutron-Proton Coincidence Measurement from the Neutron-Induced Breakup of the Deuteron

V. Valković, M. Furić, D. Miljanić, and P. Tomaš
Institute "Ruder Bošković," Zagreb, Yugoslavia
(Received 12 November 1969)

A method for measuring neutron–charged-particle coincidences from the 14.4-MeV neutron-induced reaction has been developed. The $n+d\rightarrow p+n+n$ reaction has been studied by the coincidence detection of the outgoing proton and neutron. The cross section has been measured as a function of five independent kinematic variables. A contribution of neutron-proton quasifree scattering has been observed. The cross section for $\Theta_n=\Theta_p=30°$ is found to be $\sigma=37.5\pm5.8$ mb/sr^2. This result is in fair agreement with the data for proton-proton quasifree scattering from the $p+d\rightarrow p+p+n$ reaction. The possibility of obtaining a proper a_{nn} value is discussed.

I. INTRODUCTION

Nuclear reactions with three particles in the final state have been studied with increasing interest in recent years. Special attention has been paid to reactions with three nucleons in the final state: (1) $n+d\rightarrow p+n+n$ and (2) $p+d\rightarrow p+p+n$. Since free neutron targets are not yet available, reaction (1) is the simplest one, giving hope to obtain information on the neutron-neutron force.

In spite of considerable experimental difficulties involved in the investigation of neutron-induced reactions, reaction (1) has been studied by many groups.[1–6] However, only the one-particle energy spectra and angular distributions have been measured. The peaks in the energy spectra have been interpreted as a consequence of the neutron-neutron and the neutron-proton final-state interaction. In order to extract the neutron-neutron scattering length, the measured single counter energy spectra have been analyzed using the Watson-type[7] theories, impulse approximation,[8] Amado approach,[9] and the graph-summation method.[10]

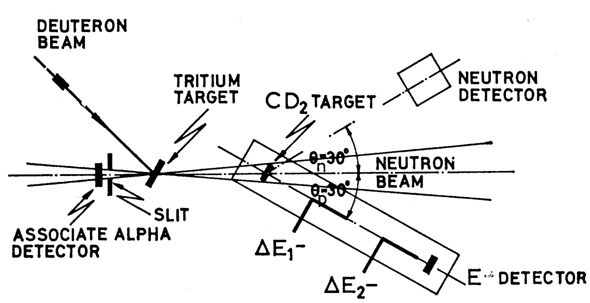

FIG. 1. Positions of the proton detector (counter telescope) and the neutron detector with respect to the neutron beam. The neutron beam was defined by a slit in front of the associated α-particle detector.

[1] K. Ilakovac, L. G. Kuo, M. Petravić, I. Šlaus, and P. Tomaš, Phys. Rev. Letters **6**, 356 (1961).
[2] M. Cerineo, K. Ilakovac, I. Slaus, P. Tomaš, and V. Valković, Phys. Rev. **133**, B948 (1964).
[3] E. Bar-Avraham, R. Fox, J. Portath, G. Adam, and G. Frieder, Nucl. Phys. **B1**, 49 (1967).
[4] A. Bond, Nucl. Phys. **A120**, 183 (1968).
[5] S. Shirato and N. Koori, Nucl. Phys. **A120**, 387 (1968).
[6] H. Grössler and R. Honecker, Nucl. Phys. **A136**, 446 (1968), and references therein.
[7] K. M. Watson, Phys. Rev. **88**, 1163 (1952).
[8] G. F. Chew, Phys. Rev. **80**, 196 (1950); G. F. Chew and F. E. Low, *ibid.* **113**, 1640 (1959).
[9] R. Amado, Phys. Rev. **132**, 485 (1963); R. Aaron, R. Amado, and Y. Yam, *ibid.* **140**, B1291 (1965); R. Aaron and R. Amado, *ibid.* **150**, 857 (1966).
[10] V. V. Komarov and A. M. Popova, Nucl. Phys. **54**, 278 (1964).

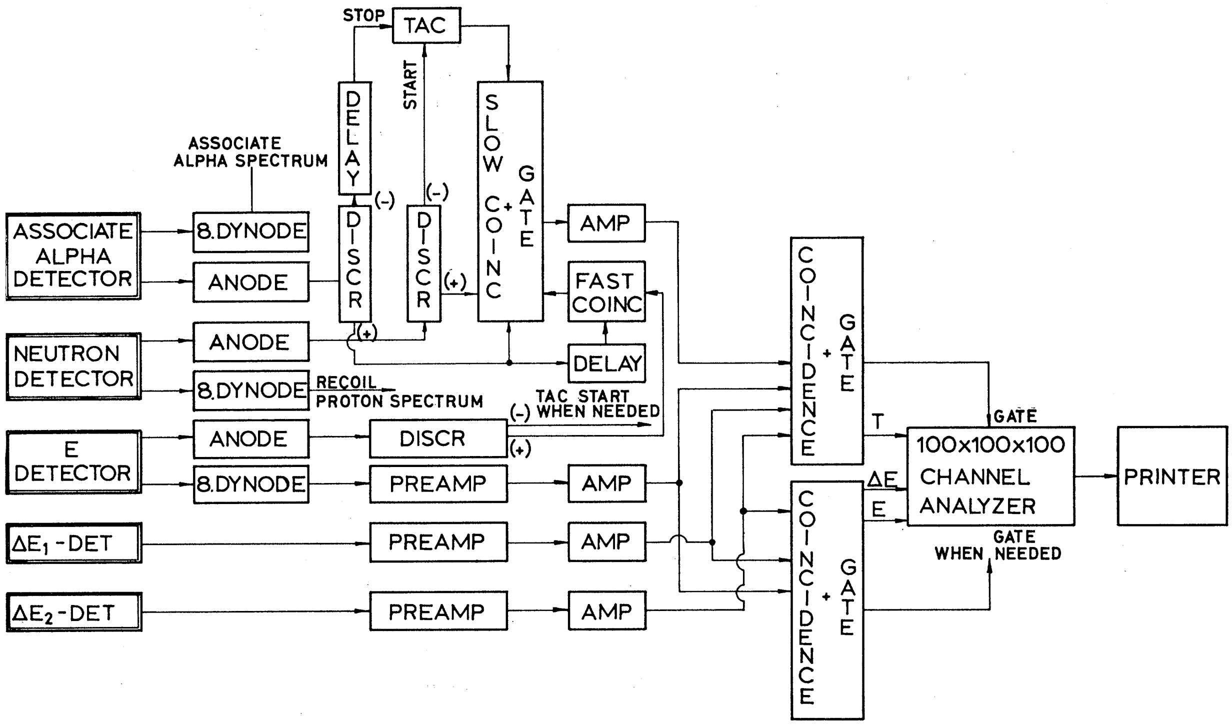

FIG. 2. Block diagram of the electronics used for the measurement of neutron-proton coincidences.

The spread in the extracted a_{nn} values cannot be considered only as a consequence of the inadequacies in the theories used. The cross section for reactions with three particles in the final state is a function of five independent kinematic variables. The measurement of the energy spectra at a given angle represents a kinematically "incomplete" measurement where a significant part of information is lost in the integration over the unmeasured variables. There is no procedure able to extract a trustworthy a_{nn} value from the incomplete measurement of three-particle final-state reactions. This fact was understood some time ago and coincidence measurements of the two outgoing neutrons from reaction (1) were performed.[11–13] Although the $(n, 2n)$ measurements encounter numerous experimental uncertainties and are time consuming, the advantage of the thick target could be used to overcome the low intensity of the incoming neutron beam. In all the measurements a peak corresponding to the neutron-neutron final-state interaction was observed.

Since scattering experiments give accurate information on the n-p and p-p interaction, the correlated proton-proton and neutron-proton spectra from the $p+d\rightarrow p+p+n$ reaction have been studied mainly in order to understand the mechanisms of the reactions with three nucleons in the final state. It has been found that the observed enhancement in the cross section could be attributed to the final-state interaction between the pair of nucleons (FSI) and the quasifree scattering with the minimum momentum transfer to one of the nucleons in the target (QFS). A recent investigation[14] of the relative contributions of these two processes at bombarding energies around 10 MeV resulted in a surprising predominance of the QFS process. It was also pointed out that by a careful choice of kinematic variables the contributions of the QFS and the FSI could be isolated. In such a way the value for a_{np} was extracted from the FSI contribution, which is in perfect agreement with the value obtained from the neutron-proton elastic-scattering measurement.

The purpose of this work was to develop an experimental technique for the coincidence measurement of the outgoing proton and neutron from the $n+d\rightarrow p+n+n$ reaction. The observation of proton-neutron quasifree scattering and its agreement with the measured proton-proton scattering on the same target and at a similar bombarding energy would then suggest a prescription for the extraction of a trustworthy a_{nn} value.

II. EXPERIMENTAL TECHNIQUE

The measurements of neutron-proton coincidences from the $n+d\rightarrow n+n+p$ reaction were performed by

[11] R. Honecker and H. Grössler, Nucl. Phys. **A107**, 81 (1968).
[12] B. Zeitnitz, R. Maschun, and P. Suhr, Phys. Letters **28B**, 420 (1969).
[13] C. Perrin, J. C. Gondrand, S. Desreaumaux, P. Perrin, and R. Bouchez, contribution to International Conference on the Three-Body Problem in Nuclear and Particle Physics, Birmingham, 1969 (unpublished).

[14] A. Niiler, C. Joseph, V. Valković, W. von Witsch, and G. C. Phillips, Phys. Rev. **182**, 1083 (1969).

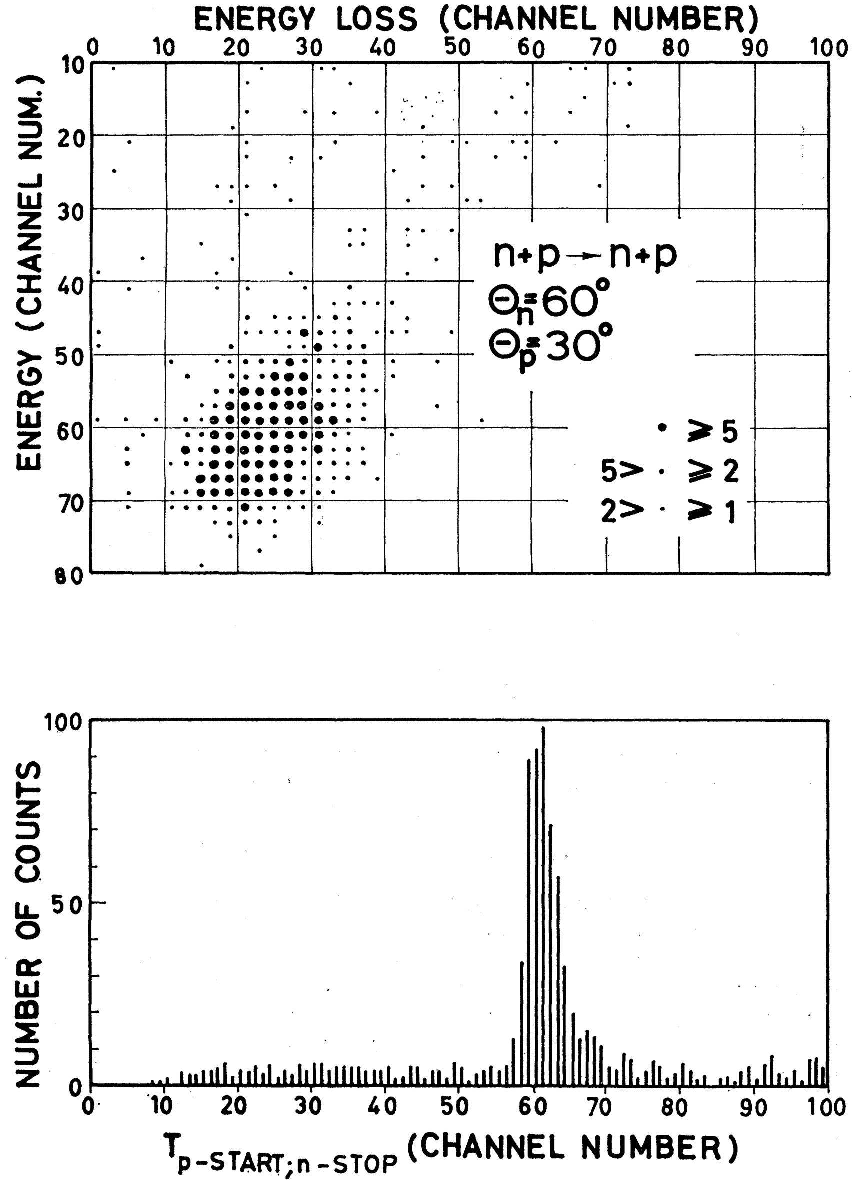

FIG. 3. Distribution of the events from neutron-proton elastic scattering for $\Theta_p=30°$ and $\Theta_n=60°$. The T axis is the time-to-amplitude converter output with the proton as a start pulse and the neutron as a stop pulse.

the method described below. Neutrons were produced by the $H^3(d, n)He^4$ reaction using a 150-keV deuteron beam from a Cockcroft-Walton accelerator. The maximum yield of neutrons during the measurements was 5×10^8 neutrons/sec in 4π. The associated α-particle detector was used to "collimate" the neutron beam in such a way that the other detectors were outside the beam (see Fig. 1). This was achieved by fast coincidences between the E and α detectors and the neutron and α detectors. Charged particles were detected by a counter telescope consisting of three proportional gas counters followed by a scintillation CsI(Tl) counter. The particle identification was achieved by measuring the energy E and the energy loss ΔE. The deuterium target was heavy polyethylene, 10 mg/cm^2 thick and 2.2 cm in diam. Neutrons were detected by an NE 218 liquid scintillator, 7.6 cm long and 7.6 cm in diam. The time difference between proton and neutron pulses, T, was measured by a time-to-amplitude converter. The block diagram of the electronics used is shown in Fig. 2, while the details of the setup are described in Ref. 15. The data were analyzed by a $100\times100\times100$ channel analyzer and recorded by a printer in three-parameter format (E, ΔE, T). Since the CD_2 target-neutron detector distance was only 30 cm, the measurement of the neutron-proton time difference could not be used to determine the neutron energy. However, such a measurement is still complete since the cross section is

[15] V. Valković, D. Miljanić, P. Tomaš, B. Antolković, and M. Furić, Nucl. Instr. Methods **76**, 29 (1969).

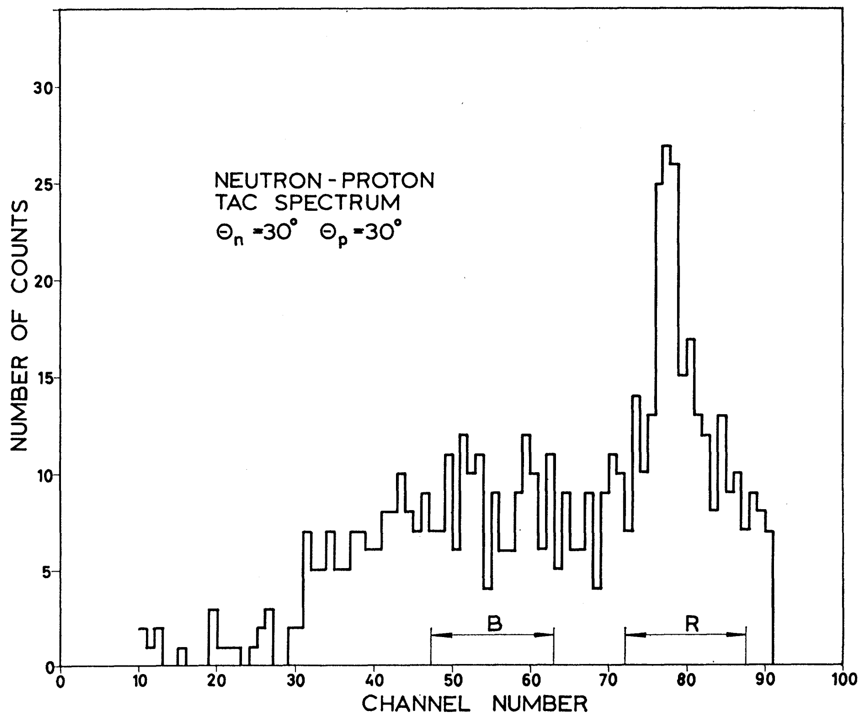

FIG. 4. Protons from the neutron-induced deuteron breakup were identified by the $dE/dx-E$ measurement. The projection of the events from the proton hyperbola on the T axis is shown. The intervals of T taken into account to obtain the foreground and background coincidence proton spectra are indicated.

measured as a function of five independent kinematic variables (directions of two momenta and the absolute value of one of them).

III. RESULTS AND DISCUSSION

The setup was checked by measuring neutron-proton elastic scattering from a CH_2 target. The particle separation was done by the E-ΔE measurement, while the additional background reduction was performed taking into account the distribution of the events along the T axis. Protons scattered by neutrons directly from the tritium target were concentrated in the sharp peak ($\Delta T=8$ nsec), whereas those scattered by neutrons degraded in energy or in momentum were distributed monotonously along the whole T axis (range 200 nsec). The data obtained from the measurement of neutron-proton elastic scattering ($\theta_p=30°$, $\theta_n=60°$) are shown in Fig. 3. The distribution in the E-ΔE plane is shown together with the projection on the T axis. The T value is given only for the events from the proton hyperbola. Elastic neutron-proton scattering was studied at several angles to determine the efficiency of the neutron detector and to normalize the measured cross section from the deuteron breakup (see Ref. 15).

In order to measure the contribution of neutron-proton quasielastic scattering in the neutron-induced breakup of the deuteron, the proton and neutron detectors were fixed at $\Theta_p=\Theta_n=30°$. The angular openings of the detectors were $\Delta\Omega_p=3.5\times10^{-2}$ sr and $\Delta\Omega_n=5\times10^{-2}$ sr. The data distributed in the E-ΔE plane were carefully examined, and only the data from the proton hyperbola were taken for further consideration. The distribution in the E-T plane was made only for protons, and the projection on the T axis is shown in Fig. 4. The time peak in the 77th channel corresponds to true coincidences between neutrons and protons. The foreground spectrum of protons detected in coincidence with neutrons was obtained from the events in the proton hyperbola with the T in the peak. The background spectrum contained protons with T outside the peak in the interval of the same width. Both spectra are projected on the E axis, and the difference between the foreground and the background spectra is shown at the bottom of Fig. 5.

On the top of Fig. 5, the relative energies in the neutron-proton and neutron-neutron subsystems are shown together with the energies of the outgoing neutrons as functions of the detected proton energy. The observed broad peak corresponds to neutron-proton quasifree scattering with the neutron from the deuteron as a spectator particle ($E_{\min}=0.19$ MeV). The peak cannot be attributed to any final-state interaction since the relative energies of all the subsystems are rather high. The shape of the spectrum is reasonably well reproduced by the simple-impulse-approximation-type calculation.[16] The theoretical curve was normalized to the experimental data. The cross section integrated over the observed peak is found to be $d\sigma/d\Omega_1 d\Omega_2=(37.5\pm5.8)$ mb/sr^2, which is smaller by a factor of approximately 4 than predicted by the spectator model calculation.

When the differences in the neutron-proton and pro-

[16] A. F. Kuckes, R. Wilson, and P. F. Cooper, Ann. Phys. (N.Y.) **15**, 193 (1961).

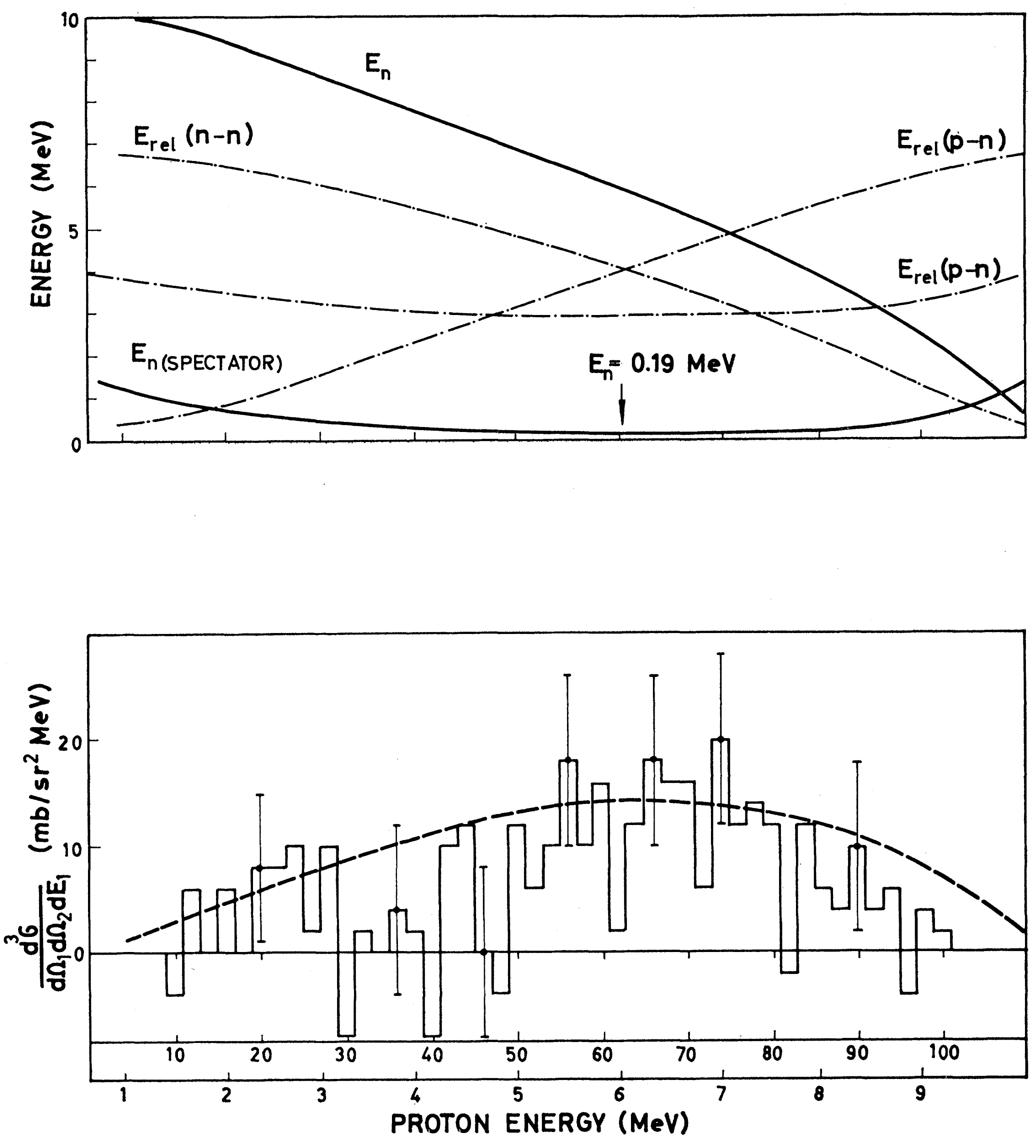

FIG. 5. Dashed curves on the top correspond to the relative energies in n-n and n-p systems. The solid curves are the kinetic energy of the two outgoing neutrons. At the bottom are shown coincidence proton spectra for $\Theta_p = 30°$ and $\Theta_n = 30°$ as a projection on the proton energy axis. The solid curve is the calculated spectator model contribution normalized to the experimental data.

ton-proton elastic-scattering cross section were taken into account, the measured cross section was found to be in fair agreement with the data for proton-proton quasifree scattering at 11 MeV obtained by the Rice group.[14] The comparison with the results from Ref. 13 shows that the neutron-proton QFS process is predominant over the neutron-neutron and neutron-proton FSI.

These facts give the encouragement that a trustworthy a_{nn} value could be obtained by measuring neutron-proton coincidences from the $n+d \rightarrow n+n+p$ reaction. The prescription should be as follows: The isolated contribution of the neutron-proton FSI should be measured, and a_{np} should be extracted using a reasonably sophisticated FSI theory. If the agreement with the a_{np} value from neutron-proton elastic scattering were obtained, the same analysis should be performed on the isolated neutron-neutron FSI contribution. This contribution could be measured by the technique described.

ACKNOWLEDGMENT

The help of Dr. B. Antolković at different stages of the experiment is gratefully acknowledged.