Neutron-induced deuteron breakup cross section at 10.3 MeV

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The absolute cross section of $n+d \rightarrow n+n+p$ at 10.3 MeV incident neutron energy has been measured in the so called "space-star" configuration. The results are compared with three-nucleon calculations based on the Paris potential and the new Bonn potential. The agreement within the experimental uncertainties of 8% puts an upper limit to the combined corrections due to relativistic effects, on-shell two-nucleon uncertainties, and the three-nucleon force.

I. INTRODUCTION

Nuclear dynamics traditionally is described by the (nonrelativistic) Schrödinger equation employing nucleon-nucleon (NN) potentials. Subnucleonic degrees of freedom are ignored. Several potentials have been constructed in order to reproduce the experimental NN data for the bound states and the scattering states from zero energy up to several hundred MeV.

Among these, the Paris potential[1] played the role of an almost standard reference during the last decade. It reproduces the existing experimental data to a large extent. Another potential which is frequently referenced is the Bonn potential, the latest version of which was published only recently.[2] Both these potentials are based on meson theory, i.e., on the assumption of virtual meson exchanges between the nucleons as being responsible for their mutual strong interaction. There is good reason to believe that meson theory (in its historical sense) is the appropriate concept for the NN interaction in the domain of nuclear physics in general.[2]

Beyond reproducing the NN data, the important question arises regarding how well these potentials describe the next, more complicated, case of three interacting nucleons. The answer is *a priori* open. The trinucleon systems offer a fertile field for testing the pair forces, and new points of view come into play: There are now bound states as well as rearrangement and breakup channels simultaneously. The trinucleon systems

(i) (implicitly) contain the full off-shell information of the NN force (2NF) which, in principle, does not enter the NN systems;

(ii) three-nucleon forces (3NF's) may occur which cannot arise in the NN systems.

Faddeev, in his pioneering work,[3] showed that a system of three coupled integral equations yields a complete and unique set of solutions for any three-body system interacting via short-range forces. For reasons of convenience, the equivalent system of Alt, Grassberger, and Sandhas (AGS) equations[4] is frequently preferred.

II. TWO-NUCLEON AND THREE-NUCLEON FORCES; STATE OF THE ART

It is not a trivial task to disentangle the NN off-shell and the 3NF effects. In particular, it is impossible to deduce the 2NF (including its off-shell behavior) and the 3NF when starting from experimental data only.[5] The opposite way to assume a 2NF and a 3NF and to compare the corresponding numerical results with experimental data also leaves too many ambiguities. There are several reasons:

1. To solve the Faddeev (or AGS) equations is an ambitious task, and the degree of sophistication of the 2NF for which this was possible has always been a direct function of the available computing power. Progress has been slow, and for more than a decade it has been difficult to correlate the physical input to these calculations with their numerical output. In most cases, one- or few-term separable potentials were employed, yet these are nonrealistic since they are nonlocal. There have been also other approaches, but all these attempts suffered from several deficiencies of the potentials, which also were not realistic. Uncertainties remained of the order of 10% due to these inadequacies.

2. The 3NF effects on the 3N observables are not large. If present, they introduce at most small corrections of the order of some 10^{-2} and thus are quite comparable to, e.g., relativistic corrections and, in particular, to the above-mentioned uncertainties. Additionally, to calculate 3N observables employing realistic 2NF's and 3NF's is a tremendous task—apart from lacking knowledge of the realistic 3NF's. Up until now only one pilot study has been published for breakup using, however, model forces: Malfliet-Tjon potentials I and III in a unitary-pole approximation and the Tucson-Melbourne 2π-exchange 3NF averaged over the totally antisymmetric spin-isospin state of the three nucleons.[6] In reality, 2N tensor forces and the various coupling mechanisms between orbital motion and spin degrees-of-freedom in the 2π-exchange 3NF are important. Conse-

quently, the full, i.e., nonaveraged effect of that 3NF and its interplay with the realistic 2NF are still unknown.

Only very recently has the solution of the three-body problem for the full realistic NN interaction become feasible. This marks a breakthrough in the calculational techniques which may be decisive for the future understanding of 3N systems (and the nuclear forces acting therein). The bound state problem has recently been solved by several groups. These rigorous calculations by various schemes[7] show that present-day 2NF's fall short in yielding the correct triton binding energy[8] (except the Bonn potential). The missing energy of ≈ 1 MeV is likely to originate from relativistic and/or 3NF effects. Experience with the 2π-exchange 3NF's clearly demonstrates[9] that the additional binding energy can be provided for. These calculations are impaired, however, by a wrong πN off-shell amplitude for not too soft pions and by a strong cutoff dependence of the πNN form factor.

III. THREE-NUCLEON REACTIONS WITH NEUTRONS, AND EXPERIMENTAL SETUP

Compared with the bound state system, 3N reactions in the continuum provide another, and presumably more sensitive, test of nuclear dynamics in that the nuclear Hamiltonian is tested by continuum S-matrix elements. These are, in Born approximation, a direct measure of the potential energy. In breakup, different kinematical configurations are possible in which the nuclear forces are sensed in different ways. Therefore continuum measurements along with rigorous calculations are highly desirable. The first aim should be to establish the degree of agreement over as much of the phase space as possible and over a wide energy range before drawing any further conclusions (e.g., on the three-body force).

It is not yet possible to strictly include the Coulomb force in the calculations. The validity and the accuracy of approximations are generally questionable. We thus consider only $n+d \rightarrow n+n+p$ breakup. In this experiment, the kinematically complete definition of the breakup events is ensured by observing both outgoing neutrons in coincidence. Together with the necessity of providing a neutron "beam" for initiating the reaction, this poses severe experimental problems. We estimate that experimental uncertainties of less than 10% should be accessible at present

We performed measurements of the absolute cross section of $d(n,nn)p$ at 10.31 MeV and compared them with rigorous calculations based on realistic 2NF's (not including 3NF's). In this work we concentrate on a specific breakup configuration, the symmetric "space-star," where the end points of the c.m. momenta of the three nucleons form an equilateral triangle oriented perpendicular to the beam direction. In Ref. 10 it has been shown that the cross section in this configuration is largely insensitive to simple model 2NF's (purely s-wave test potentials without tensor forces). Consequently, if that holds true for the full interaction, possible effects of 3NF's are less disturbed by 2NF off-shell effects than in different configurations, and therefore this configuration is a good testing ground for 3NF effects. In Ref. 6 the cross section in the space-star configuration at 10 MeV has been estimated to be enhanced by 4% by 3NF's.

Beyond theoretical arguments, the symmetric space star has distinct experimental advantages in comparison with other configurations: The third particle (p) can easily be detected in the active target (almost constant energy, $E_p \approx 2.5$ MeV), and large solid angles are possible due to the stable kinematics.

The (kinematically complete) experiments have been carried out at the Bochum Dynamitron Tandem Laboratory. A pulsed beam of neutrons (pulse width 1.2 ns, repetition rate 5 MHz) with $E_n = 10.31$ MeV and with intensity $I_n = 8 \times 10^6\ \mathrm{s}^{-1}$ has been used.[11] The target consisted of a mixture of NE213 and deuterated NE232 scintillator liquids (deuteron to proton ratio 9:1) of thickness 1.4 cm designed as to limit multiple scattering of the outgoing neutrons to about $\frac{1}{3}$ of all events and to keep the associated systematic uncertainty small. Breakup events were identified by detecting two outgoing neutrons in the noncoplanar NE213 scintillators at $\theta_1 = \theta_2 = 48.9°$, $\Phi_{12} = 120°$ (18 cm i.d.$\times$7.5 cm, $\Delta\Omega_1 = 4.55$, and $\Delta\Omega_2 = 6.77$ msr), and the proton in the target scintillator for background reduction.

The energies of the neutrons were determined by their time-of-flight (TOF), and pulse-shape discrimination was employed for γ suppression. The master coincidences of the events were defined by requiring valid signals from the target scintillator and the two neutron detectors within the coincidence time (200 ns). For each breakup event a total of eight parameters was recorded on tape (target scintillator: pulse height, TOF; either detector: pulse height, TOF, pulse shape). Simultaneously, np elastic scattering was measured in one of the neutron detectors for absolute normalization via its known cross section.[12] The detector gains were controlled by a feedback system using stabilized light-emitting diode (LED) light pulses.[13] Dead time was checked by feeding LED pulses into all detectors.

In Fig. 1(a) the coincidence spectrum is shown as it directly built up during the measurement. In addition to the kinematical band of true coincidences in the central part of the curved band, there are three more contributions from accidentals. Two pronounced bands, parallel to the two TOF axes, originate from nd elastic events in either detector coinciding with a random neutron or γ event in the other. About six channels lower there are weaker second such bands from np elastic events. Besides, the plane is covered by an extended, fairly low, general background of accidental γ events.

In the off-line data analysis the γ events which were not already rejected by the hardware were virtually eliminated. By setting an upper threshold in the target detector pulse-height spectrum well above 2.5 MeV, the np random elastic events were removed. The resulting spectrum is shown in Fig. 1(b), where the random nd elastic events can easily be separated from the true events. Background remaining under the true kinematical band ($\approx 4\%$) was removed by interpolation from both neighboring sides. The absolute efficiencies of the neutron detectors had been measured in a separate experiment for a set of energies by utilizing the associated-particle

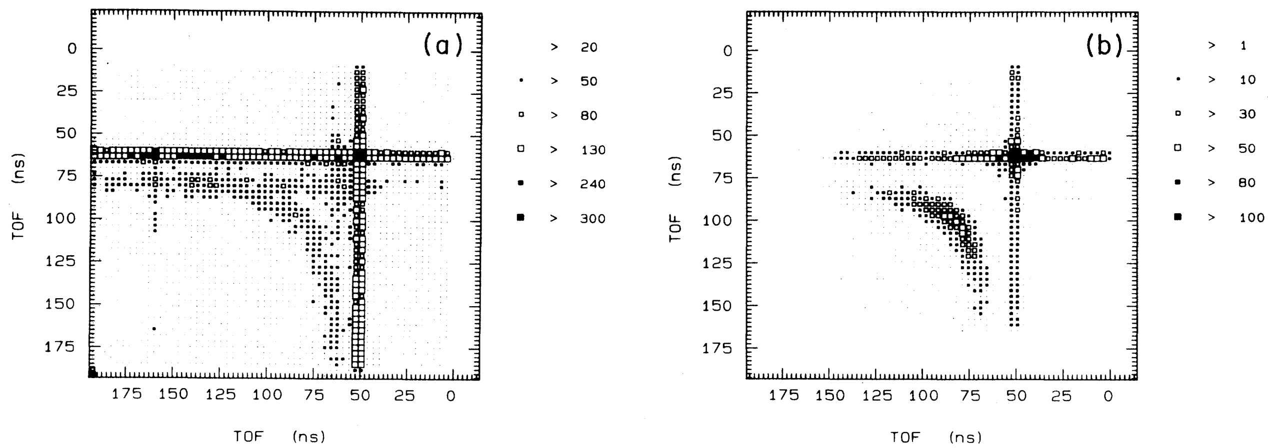

FIG. 1. TOF coincidence matrix of events (a) built up during measurement, (b) after off-line analysis.

method applied to $^3H(p,n)^3He$ and $^2H(d,n)^3He$. For interpolation to other energies the Monte Carlo code NEFF4 (Ref. 14) has been used.

The resulting absolute differential cross section is plotted in Fig. 2. It has been corrected for finite-geometry and multiple-scattering effects in the target by Monte Carlo simulation (the correction factor being 1.47–1.52 along the kinematical curve). Dead-time losses were identical for breakup and *np* elastic scattering (22%). The projection of the breakup events onto the mean arc has been performed by a Monte Carlo simulation. The error bars include the statistical as well as the estimated systematic uncertainties. At $E_1=2.73$ MeV, the space-star point, we have about 6% statistical uncertainty (the energy bin along the kinematical curve being 0.25 MeV), and the (absolute) detector efficiencies are known to within 3.5%. Correcting the breakup events for finite geometry and multiple scattering gives an uncertainty of 3%. The statistical uncertainty of *np* elastic scattering is 2%, to which background subtraction adds another 3% of systematic uncertainty. Altogether, we have an experimental uncertainty of $\approx 8\%$ at the space-star point, with $d^5\sigma/d\Omega_1/d\Omega_2 dS = 1.40 \pm 0.11$ mb/sr^2 MeV.

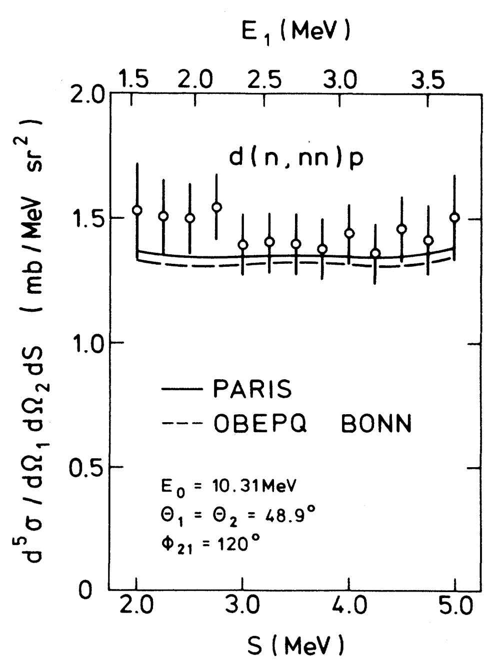

FIG. 2. Differential cross section, measured data, and full calculations.

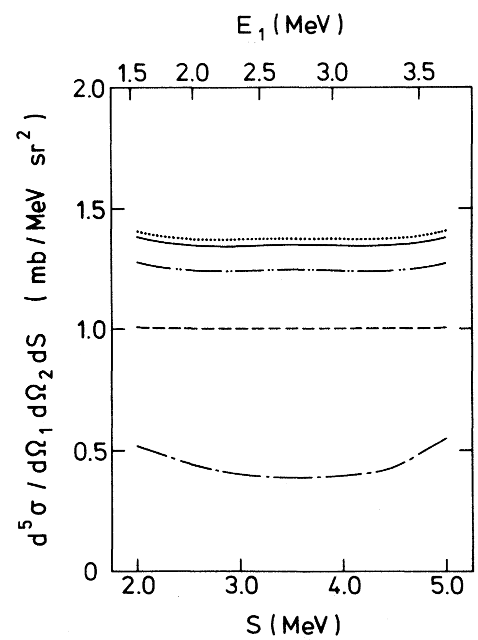

FIG. 3. Full calculation (Paris potential, solid line) and results for selected partial waves omitted. Dotted lines: without *p* and *d* waves (except $^3D_1$); dashed lines: without $^1S_0$; dashed-dotted lines: without $^3S_1$-$^3D_1$; dash-dot-dot lines: dynamical test, *T* built up by $^1S_0$ and $^3S_1$-$^3D_1$ exclusively. Compare with Fig. 2.

TABLE I. Different $^1S_0$ phase shifts $\delta(^1S_0)$ and $^3S_1$-$^3D_1$ mixing parameters ϵ_1.

	$\delta(^1S_0)$ (deg)				ϵ_1		
T_{lab} (MeV)	*np* (Ref. 18)	*pp* (Ref. 18)	Paris	OBEPQ	*np* (Ref. 18)	Paris	OBEPQ
25	51.83	48.49	48.35	50.88	0.69	1.69	1.57
50	41.60	38.96	38.07	40.24	0.92	1.89	1.57
100	26.68	24.59	23.83	25.57	1.15	2.14	1.31
150	16.36	14.66	13.33	14.83	3.54	2.59	1.11

IV. SCHEME OF THE NUMERICAL CALCULATIONS AND COMPARISON WITH THE EXPERIMENTAL DATA

Modified AGS equations[15] were solved without introducing finite-rank approximations of any kind. This is fully equivalent to solving the Schrödinger equation for those 2NF's. Compared with prior calculations, the only approximation for the 2NF's we introduced is to include only states with $j \leq 2$; this has been checked numerically to be sufficient at 10 MeV. The general method has been given elsewhere,[16] and first results for elastic scattering have been reported.[17]

Our rigorous three-nucleon calculations were based on the Paris (Ref. 1) potential and the new Bonn potential OBEPQ.[2] We solved modified AGS equations,[15]

$$T = tP + tPG_0T \qquad (1)$$

in a partial-wave projected momentum-space basis. Therein t is the two-body off-shell t operator, G_0 the free propagator, and P the operator for two cyclic permutations of three nucleons. The 2NF was assumed to act in the $^1S_0$, $^3S_1$-$^3D_1$, $^1P_1$, $^3P_0$, $^3P_1$, $^3P_2$-$^3F_2$, $^1D_2$, and $^3D_2$ states. Along with the experimental data the theoretical cross sections for both potentials are shown in Fig. 2, with the two curves coinciding within 4%. This is a remarkable result, since the $^1S_0$ phase shift and the $^3S_1$-$^3D_1$ mixing parameter ϵ_1 of the two potentials are quite different, as indicated in Table I. This supports the stability of that specific breakup cross section against the 2NF input as estimated previously.[10]

From Fig. 2 we find that the absolute cross section measurement and the parameter-free calculational results agree well within the experimental error bars quoted ($\approx 8\%$), and we conclude that the combined effect of relativity, the 2NF on-shell uncertainty, and the 3NF's (if present) is smaller.

In addition, we wanted to study which partial waves are important in the space-star configuration. The breakup amplitude $U_0 = (1+P)T$ is obtained in a partial-wave decomposition. Based on the full calculation (Paris potential only), we selectively dropped in U_0 all two-body subsystem p and d waves, and the $^1S_0$ and the $^3S_1$-$^3D_1$ contribution (in the two-body t operator the full interaction is maintained). The resulting cross sections are shown in Fig. 3. Clearly the waves with $^3S_1$-$^3D_1$ are dominant, followed by the $^1S_0$ contribution. The change in cross section by dropping the p and d waves (not $^3D_1$) is less than 2%. More interesting, however, is the dynamical test wherein in t, the two-body input for solving Eq. (1), the p and d forces are neglected from the beginning, and not only later in the partial wave decomposition of U_0 as above. The resulting cross section, also shown in Fig. 3, is about 8% lower than the full result. We therefore conclude that the p and d waves play an important role in building up T dynamically. Since the 2π-exchange 3NF has a remarkable effect on the p-wave components in the triton wave function, its effect on the breakup cross section, specifically in the space-star configuration, should be studied rigorously. The cross section in this configuration is largely insensitive to the 2N forces used. Therefore this experiment (and possibly future ones with higher accuracies) puts upper limits on the effects of relativity, 2NF uncertainties, and 3N forces.

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