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Differential Cross Sections for $np \rightarrow dX$ at 1.0 and 2.0 GeV

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Abstract

Inclusive deuteron spectra ($d^2\sigma/d\Omega dp$) have been measured for the reaction $np \rightarrow dX$ at neutron energies of 1.0 and 2.0 GeV. A quasi-monochromatic neutron beam was used, along with a liquid hydrogen target. Recoil deuterons at laboratory angles from 3° to 15° were tracked in wire chambers surrounding a 1.5 T·m dipole magnetic field. Particle identification was achieved using time-of-flight and momentum measurements. The deuteron data are compared with the predictions of a one-nucleon-exchange model with σ meson production. At 2 GeV the missing mass spectra suggest the large role played by both the η and ρ mesons in deuteron production.

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I. INTRODUCTION

Much of the data on neutron-proton interactions at energies of a few GeV is derived from bubble chamber results from Dubna and elsewhere [1,2]. In many of these experiments neutron beams with a very broad energy spread were used, making it difficult to obtain the detailed information required to test models of the reaction dynamics. In contrast to this situation, a program of n-p reaction studies was carried out at Saturne using a quasi-monochromatic beam of neutrons with good resolution magnetic analysis of outgoing protons and deuterons [3–6]. These experiments were, however, limited to maximum neutron energies near 1.2 GeV. At this highest energy the data for inclusive deuteron production show a striking enhancement at the threshold for two-pion production – the so-called ABC effect [7,8]. A recent reanalysis of these deuteron data also indicates the production of η mesons [9], although this effect is difficult to quantify since only a small component of the beam extended above the η production threshold.

Theoretical models of deuteron production near 1 GeV have considered intermediate $\Delta\Delta$ excitations [10], two-nucleon-exchange mechanism [11], as well as the production of σ mesons through a one-nucleon-exchange mechanism [12]. In the last case, the deuteron yield near the two-pion threshold is related to both the strength of the σNN coupling and to the s-wave $\pi\pi$ scattering phase shift. Information on the energy dependence of the ABC effect can be used to refine the parameters of this model. In a similar way, deuterons can be accompanied by the production of η and ρ mesons, with threshold energies of 1.25 and 1.85 GeV. Although the signal for ρ , but not η , production is present in $pp \rightarrow dX$ data at a few GeV [13], the ρ has not been observed in previous $np \rightarrow dX$ results.

The present investigation extends the studies of proton and deuteron spectra in n-p interactions to neutron energies of 1 and 2 GeV using a narrow-band neutron beam and magnetic detection of the outgoing particles. In Sec. II of this paper we describe the experimental apparatus used for these measurements. Section III describes the methods of data analysis, and the results and interpretation of these data are presented in Sec. IV.

II. EXPERIMENTAL SETUP

A. Neutron Beam

The experiment was done at the 12 GeV proton synchrotron of the National Laboratory for High Energy Physics (KEK-PS) in Tsukuba, Japan. Nearly monoenergetic beams of neutrons were derived from deuterons accelerated to energies of 2 and 4 GeV and slow-extracted over 1.5 seconds during a 4 second spill time. Typically, 10^{11} deuterons were delivered to the experimental hall during each spill.

A neutron beam production area was designed and built specifically for this experiment in the P1 hall, as shown in Fig. 1. This facility is described in more detail in Ref. [14]. The deuteron beam was incident on a 6 cm beryllium target where deuteron breakup occurred with high probability [6]. The incident deuteron flux was continuously monitored with a secondary emission chamber [15]. Charged particles were swept out of the resulting neutral beam with a dipole magnet located just downstream of the Be target, and the neutrons entered a 5 m long lead and iron collimator of square cross section. Neutrons in the collimated beam were geometrically limited to the $50 \mu\text{sr}$ solid angle centered around a 0° production angle. At the location of the liquid hydrogen scattering target, 9.85 m from the Be target, the neutron beam profile was a sharply defined square, 70 mm on a side, with negligible halo as indicated in Fig. 2. The FWHM momentum resolution was designed to be 7.2% at the neutron beam centroid energy (T_n) of 1 GeV, taking into account the effect of the Fermi momentum of the neutron in the deuteron beam. At $T_n = 2$ GeV, the resolution was slightly better.

The intensity of the neutron beam was initially calibrated, and the beam profile was continuously monitored, with a 3-plane array of segmented plastic scintillators. This neutron beam monitor (NBM) is shown near the neutron beam dump in Fig. 3, and is described in more detail in Ref. [16]. The first plane of the NBM, of 2 mm thickness, was used as a veto for incident charged particles, while the 10 mm thick second layer sampled the neutron

component. The third plane was oriented at right angles to the scintillator strips of plane 2. Planes 2 and 3 then provided an x-y profile of the neutron beam with a bin size of 10 mm.

The neutron detection efficiency of the 3-plane system was modeled with the GEANT code [17] using several hadronic interaction packages. The measured neutron yield was then compared with the yield calculated with the Monte Carlo detection efficiency, the measured deuteron flux, the known deuteron disassociation cross section, and the collimator solid angle acceptance. At each of several beam energies, this comparison showed agreement at the level of about 20%. With this confirmation, the neutron yield per deuteron was calculated and is shown in Table I. Neutron fluxes for subsequent production runs were determined from these conversion probabilities and the measured incident deuteron fluxes, as determined by the secondary emission chamber data.

B. Hydrogen Target

The scattering target consisted of a vertical cylinder of liquid hydrogen with diameter and height 120 mm and 150 mm, respectively. The wall of the hydrogen cell was constructed of stainless steel with a thickness of 0.1 mm. The vacuum vessel consisted of a vertical stainless steel cylinder of 3 mm thickness which was reduced to 0.15 mm in the direction of the charged particle spectrometer arm.

The hydrogen temperature and pressure were continuously monitored to maintain a constant target density. Averaged over the known neutron beam spot at the target location, the hydrogen thickness was calculated to be 0.815 g/cm^2 . The estimated accuracy of this result is about 5%. Target-full and target-empty data were sequentially collected at each beam energy to allow a subtraction of the backgrounds from materials other than hydrogen in the target.

C. Recoil Spectrometer

Charged particles from the target were detected and tracked in a set of segmented scintillators (RS1, 2, 3, and 4), multiwire proportional chambers (PC1 and 2), and drift chambers (DC1 and 2), configured around a 1.5 T·m large-gap dipole magnetic field, as shown in Fig. 3. (The detector arms shown to the right of the beam line in Fig. 3 were used to detect high energy gamma rays in coincidence with charged particle recoils. The results of that separate experiment will be reported at a later time.) Field maps of the magnet were collected both in the interior gap region as well as in the region of the fringing field. These data were collected at several magnet excitations. A stationary NMR probe was used during mapping and data collection to insure field reproducibility and stability.

Recoil particle time-of-flight (TOF) data were collected from pairs of recoil scintillators, RS1/RS2 and RS1/RS3, over a flight path of about 5 m. RS1 was composed of six vertical bars, each of 65 mm width and 220 mm height, with a thickness of 3 mm. Several elements of the RS1 array were located in the neutron beam. Both RS2 and RS3 were composed of 15 vertical bars of 200 mm width, 1200 mm height and 30 mm thickness. Photomultiplier tubes on both the top and bottom of each bar allowed the vertical hit position as well as the mean TOF to be determined. The overall meantime resolution between RS1 and RS2 was about 450 psec.

PC1 and PC2 were each 3-plane high-rate proportional chambers operated in the neutron beam directly downstream of the hydrogen target. Table II lists the geometry of these chambers and the wire spacings. Hit pattern data were collected from PC1 from coupled pairs of adjacent wires, and data readout was through a SPIDER system, designed and constructed at KEK. While the 2 GeV data were collected with both PC1 and PC2 operational, only PC1 was available for the 1 GeV run.

The drift chambers, DC1 and DC2, were each composed of four 128-wire planes with 9 mm sense wire spacing. Each chamber provided x, x', y, and y' readout, with alternate planes laterally staggered by 4.5 mm. Each wire was instrumented with an individual time-

to-digital converter; the RMS position resolution of each plane was about $320\text{ }\mu\text{m}$. The close proximity of DC1 and DC2 in a region of nearly straight particle trajectories enabled measurements of the horizontal and vertical profiles of track efficiency for each of the eight drift chamber planes. This was accomplished through a comparison of the actual hit position in each plane with the position predicted by hits in the three other similar planes.

D. Trigger and data acquisition

During the data acquisition, two different triggers were collected from alternate beam spills. The recoil arm singles trigger was a prescaled sample of events with at least one hit in each of the scintillator arrays, $\text{RS1} \cdot \text{RS2} \cdot \text{RS3} \cdot \text{RS4}$.

A second trigger sampled neutral events in the neutron beam monitor. These data were used to monitor the intensity and profile of the neutron beam.

Data were collected with a hybrid CAMAC and TKO [18] system, interfaced to a VAX 3500 computer. The dead time of the acquisition system was monitored and the measured yields were corrected for dead time losses.

III. ANALYSIS OF THE DATA

A. Tracking of charged particles

Particle momenta were determined from the measured hit coordinates in the wire chambers using a tracking algorithm based upon a Runge-Kutta method [19]. The hit pattern in all planes of each chamber was combined to yield one x and one y position. Thus the tracking at 1 GeV was done with three x and y coordinates; at 2 GeV four coordinates were used. At the lower beam energy the average hit multiplicity in each drift chamber plane was a little over 1, whereas at 2 GeV it was slightly less than 3. The tracking algorithm was applied to all combinations of hits, and the track with the minimum χ^2 that passed through

the target volume and had a corresponding hit in the projected element of the RS2 array was selected.

Monte Carlo calculations indicate the momentum resolution of this spectrometer to be about 3%. The measured spectra are consistent with this value.

B. Particle identification

The momentum determined from the track fitting procedure was combined with the particle velocity as derived from the TOF measurement in the recoil scintillators to calculate the particle mass. Only proton and deuteron tracks were observed since the spectrometer had no acceptance for low momentum pions. At 2 GeV an additional particle selection was made on the basis of energy loss in the RS2 scintillators.

The mass distributions at 1 and 2 GeV resulting from a subtraction of target-full and target-empty runs are shown in Fig. 4. While the mass peaks for both protons and deuterons are sharp and well-defined, there remains a tail of the proton peak due to accidental hits on the RS1/RS2 hodoscopes. The proton and deuteron yields have been determined by fitting an exponential curve to these spectra for each of several momentum regions and by subtracting the background yield from the region of the deuteron peaks. The correction to the proton yields due to the tail of the deuteron peak is negligible, as indicated by the spectra.

C. Differential cross sections and errors

The double-differential cross sections have been deduced from the usual expression,

$$\frac{d^2\sigma}{d\Omega dp} = \frac{Y}{\tau I P \eta_a \eta_c L \Delta\Omega \Delta p},$$

where τ is the hydrogen target thickness, I is the number of incident neutrons, P is the trigger prescale fraction for data acquisition, η_a is the efficiency of the tracking and analysis procedure, η_c is the efficiency of the tracking chambers, L is the live time fraction of the

acquisition computer and electronics, and $\Delta\Omega$ and Δp are the bin sizes for the solid angle and momentum.

Extensive Monte Carlo studies were done to determine the solid angle acceptance of the spectrometer as a function of both particle momentum and production angle (Fig. 5). These GEANT simulations considered the geometrical limitations imposed by the magnet as well as by each of the detector elements.

The analysis efficiency was similarly modeled with a Monte Carlo code which simulated the hardware trigger conditions and subjected events passing this requirement to the same analysis package used to track and analyze the actual data. The measured position-dependent efficiency for each plane of the wire chambers was used as input to this simulation. The observed fraction of simulated hardware triggers which subsequently passed all tracking conditions determined the analysis efficiency.

The largest systematic uncertainty of any of the parameters used to determine the cross sections was that due to the beam flux calculation. This uncertainty is estimated to be about 20% at both 1 and 2 GeV. When combined in quadrature with the considerably smaller estimated uncertainties of each of the other parameters, we find an overall systematic uncertainty in the measured cross sections of about 30%.

IV. RESULTS AND DISCUSSIONS

Proton emission at forward angles is dominated by the charge-exchange reaction and has been previously measured in a counter experiment at a maximum neutron energy of 1.2 GeV [3]. Earlier bubble chamber results near and above this energy [20] indicate that the forward-angle cross section multiplied by $p_{n,lab}^2$ is approximately independent of energy, although there may be systematic normalization differences between the counter and bubble chamber cross sections. At angles away from 0° the cross section $d\sigma/dt$ is found to depend only on the momentum transfer t , falling exponentially at increasing $|t|$.

Our measured proton momentum distribution at 1 GeV is shown in Fig. 6 for proton

lab angles extending from 3° to 5° . This, like all other spectra shown, is the result of a target-full and target-empty subtraction. Likewise, all of the errors shown in these spectra reflect only statistical uncertainties. The prominent peak near 1.7 GeV/c is identified as the charge-exchange contribution, while the broader peak centered near 1.3 GeV/c results from excitation of the Δ resonance. The combined resolution of the neutron beam and the spectrometer is exhibited by the charge-exchange peak in this spectrum. Charge-exchange cross sections derived from the proton data at 1 GeV, and the corresponding spectra at 2 GeV, have been compared with the previous results [3]. We find agreement at both energies at a level which is within the systematic errors quoted for our experiment.

Our measured deuteron momentum spectra at laboratory angles ranging from 4° to 12° are shown in Fig. 7 for an incident neutron energy of 1 GeV. The solid curves show the result of a calculation in the one-nucleon-exchange model with nucleon coupling to a σ meson (Fig. 8 (a)) [12]. The parameters of the calculation are those which were determined by fitting the 1.2 GeV data from Saturne [5] and the 0.8 GeV data from Los Alamos [21]. Especially at 4° and 6° , the bumps in these spectra near the kinematic threshold for two-pion production are the signature of the ABC effect. The significant difference between our results and this model calculation might be attributable to the contributions of other reaction mechanisms. For example, excitation of a $\Delta\Delta$ intermediate state (Fig. 8 (b)) was previously found to be important at 1.2 GeV [10,12].

The measured deuteron yield at momenta both above and below the kinematic limits for two-pion production is due to the reaction $np \rightarrow d\pi^0$. The isospin-related process $pp \rightarrow d\pi^+$ has previously been measured at this energy [22]. Our new np results are found to be consistent with the pp data.

This interpretation of the 1 GeV deuteron data is confirmed by the missing-mass spectrum shown in Fig. 9. Events with deuteron lab angles from 3° to 13° were included in this distribution. Single-pion production produces a rather broad peak around 140 MeV, whereas in the region of the two-pion threshold the yield is observed to be rapidly increasing. It has been previously suggested that the shape of this distribution can be used to determine

the $\pi\pi$ phase shift through a comparison with the σ production model [12]. Clearly, a quantitative comparison would require a more extensive model treatment of inclusive deuteron production at this energy through a variety of possible channels.

The measured deuteron momentum spectra at 2 GeV are presented in Fig. 10 for angles from 4° to 14° . The solid curves show the predicted distributions in the one-nucleon-exchange model with only σ production included [12]. The measured distributions are seen to be qualitatively different from the 1 GeV results, signaling the presence of additional reaction mechanisms at this higher energy. In particular, at angles less than 12° there is an observed suppression of the yield near the two-pion production peaks relative to an enhanced deuteron yield near 2 GeV/c. At these angles the one-nucleon-exchange model compares poorly with the data. As in the case at 1 GeV, the deuteron yield at the highest and lowest momenta measured – in the kinematic region below two-pion threshold – are found to compare favorably with previous single-pion production data in pp scattering near this energy [23].

The sources of the additional structure around the center of the measured momentum distribution (i.e. in the region of large missing mass) are evident in the missing-mass spectrum shown in Fig. 11. These results have been generated from deuteron events emitted in the angular range from 3° to 9° . Dominating this distribution are two broad peaks centered at the η and ρ masses. While the beam energy is well above the threshold for η production, the full width of the ρ peak is not observed, and has been cut off in this figure. The solid and dashed lines show the results of a Monte Carlo calculation, arbitrarily normalized, of the expected reconstructed ρ and η missing mass distributions, considering the neutron beam resolution and the momentum resolution of the spectrometer. In addition, a broad, non-resonant contribution from multi-pion emission should underlay these resonant peaks, although it is clear that np data at higher energy and with improved statistical accuracy would be very helpful in developing a quantitative model of deuteron formation at these energies. Data extending to 3 GeV neutron energy have been collected by this collaboration, and will be reported at a later time.

In summary, the double-differential cross sections ($d^2\sigma/d\Omega dp$) for the reaction $np \rightarrow dX$ have been measured at $T_n = 1$ and 2 GeV. At $T_n = 1$ GeV, the results are consistent with earlier measurements around this energy. The one-nucleon-exchange model underestimates the experimental results and it is indicated that further theoretical investigations including other mechanisms should be considered. At $T_n = 2$ GeV, striking enhancement around the highest missing mass regions has been observed. This phenomenon could be explained by the ρ and η production reactions.

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TABLES

TABLE I. Transformation efficiency from deuterons to neutrons.

T_d (GeV)	T_n (GeV)	transformation probability
2.0	1.0	$(1.16 \pm 0.31) \times 10^{-3}$
4.0	2.0	$(2.14 \pm 0.58) \times 10^{-3}$
4.7	2.35	$(2.46 \pm 0.67) \times 10^{-3}$
5.4	2.7	$(2.79 \pm 0.75) \times 10^{-3}$
6.0	3.0	$(3.07 \pm 0.84) \times 10^{-3}$

TABLE II. Configuration of the chambers.

	planes	effective area	wire spacing	read-out
PC1	x,u,v	319 mm $\times$ 155 mm	1 mm	2 mm
PC2	x,y,u	320 mm $\times$ 192 mm	2 mm	2 mm
DC1,2	x,x',y,y'	115 mm $\times$ 115 mm	9 mm

FIG. 1. The P1 beam line at the KEK-PS showing the Be production target (Be T), charged particle sweeping magnet (D2), neutron collimator(Pb Col.), and the P1 experimental cave.

X projectin of tracks onto target

Y projectin of tracks onto target

FIG. 2. Neutron beam profile at the liquid hydrogen target. Units are in mm. The horizontal distribution is more rounded than the vertical distribution, due to the shape of the hydrogen target.

Setup of E235 experiment

FIG. 3. The detector layout used for experiment E235. The neutron beam is incident from the left, and passes through the hydrogen target as well as the wire chambers PC1, PC2 and the scintillator RS1. The neutron beam monitor was located near the entrance to the beam dump during the production runs, but could be positioned at the location of the LH₂ target to measure the beam profile. The lead glass detectors were used to detect gamma rays in coincidence with recoil particles and are not used in the present analysis.

FIG. 4. Mass spectra (in arbitrary units) for $T_n = 1$ GeV (left) and $T_n = 2$ GeV (right).

FIG. 5. The solid angle of the spectrometer for $\theta_{lab} = 5^\circ$ (triangle), 10° (circle) and 15° (square).

The theta bin width of 2° in lab is used.

FIG. 6. The double-differential cross section for $np \rightarrow pX$ at 1 GeV for $\theta_{lab} = 4^\circ$.

FIG. 7. The double-differential cross section in the lab frame for $np \rightarrow dX$ at $T_n = 1$ GeV. The solid lines are the results of the theoretical calculation of the one-nucleon-exchange model, which also indicate the region where $\pi\pi$ production is kinematically allowed.

FIG. 8. Diagrams of the theoretical calculations. (a) one-nucleon-exchange model. (b) $\Delta\Delta$ model.

FIG. 9. Missing mass spectrum for the reaction $np \rightarrow dX$ at $T_n = 1$ GeV. Events of 3° to 13° in lab are plotted.

FIG. 10. The double-differential cross section in the lab frame for $np \rightarrow dX$ at $T_n = 2$ GeV. The solid lines are the results of the same theoretical calculation as Fig. 7.

FIG. 11. Missing mass spectrum for the reaction $np \rightarrow dX$ at $\theta_{lab} = 3-9^\circ$, $T_n = 2$ GeV. The solid line is a result of Monte Carlo simulation for the $np \rightarrow d\rho$ reaction, and the dashed line is for the $np \rightarrow d\eta$ reaction. Details are written in the text.