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$d+d\rightarrow {}^4He+\gamma$ cross section measurement at 376 MeV

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Differential cross sections for $d+d\rightarrow {}^4He+\gamma$ have been measured at $\theta_\gamma(\mathrm{c.m.})=73°$ and $91°$ for $T_d=376$ MeV. Our results are a factor of 60 smaller than the cross section measured at $T_d=404$ MeV by Akimov *et al.* The ratios of our results to those of Arends *et al.* for the inverse reaction, $\gamma\,{}^4He\rightarrow dd$, are 2.0±0.9 at 73° and 1.7±0.9 at 91°. Considering the large uncertainties in both data sets, these ratios are consistent with time-reversal invariance in this isoscalar electromagnetic interaction of hadrons. Our data corroborate the reported deviation from the $\sin^2 2\theta$ angular distribution expected of this reaction.

[NUCLEAR REACTIONS ${}^2H(d,\gamma){}^4He$, $T_d=376$ MeV; measured $\sigma(\theta)$, $\theta(\mathrm{c.m.})=73°,91°$.]

I. INTRODUCTION

A measurement of the differential cross section for the reaction $dd\rightarrow {}^4He\gamma$ at intermediate energy is of interest for several reasons:

(1) There is a large discrepancy between the published results for the $dd\rightarrow {}^4He\gamma$ (Refs. 1 and 2) and $\gamma\,{}^4He\rightarrow dd$ (Refs. 3 and 4) reactions at intermediate energy. Since these reactions are related by detailed balance, this discrepancy, if taken at face value, implies a large and surprising violation of time-reversal invariance in the electromagnetic interaction of hadrons.[5]

(2) The shape of the angular distribution sheds light on the reaction mechanism, which at lower energies is completely dominated by an electric quadrupole transition.

(3) The measurement of the $dd\rightarrow {}^4He\gamma$ cross section may be a useful guide in evaluating the limits on the validity of charge symmetry[6] derived from searches for the related reaction $dd\rightarrow {}^4He\pi^0$.

In the intermediate energy region ($T_d=200-600$ MeV), two measurements of $dd\rightarrow {}^4He\gamma$ have been reported; both were made in searches for the reaction $dd\rightarrow {}^4He\pi^0$. Akimov *et al.*[1] at the Joint Institute for Nuclear Research quote $d\sigma/d\Omega=1.6\pm0.6$ nb/sr for $\theta_\gamma(\mathrm{c.m.})=42°$ at $T_d=404$ MeV, while Poirier and Pripstein[2] at Lawrence Berkeley Laboratory report an upper limit of 0.23±0.06 nb/sr for $\theta_\gamma(\mathrm{c.m.})=90°$ at 460 MeV. There are two measurements of the inverse reaction, $\gamma\,{}^4He\rightarrow dd$. Two cross section values have been obtained at Purdue by Asbury and Loeffler,[3] based on eight events observed at $E_\gamma=221$ MeV and two events observed at $E_\gamma=265$ MeV. Twelve data points were measured for $E_\gamma=213$, 258, and 330 MeV at Bonn by Arends *et al.*[4] The experimental data for $dd\leftrightarrow\gamma\,{}^4He$ at intermediate energies prior to our measurements are shown in Fig. 1. The $\gamma\,{}^4He\rightarrow dd$ data of Arends *et al.* are in disagreement by a factor of 200 with the measurement of the inverse reaction reported by Akimov *et al.* [Fig. 1(a)], in apparent violation of detailed balance. The data of Arends *et al.* also lie considerably below the upper limit of Poirier and Pripstein [Fig. 1(b)]. Even the less precise data of Asbury and Loeffler for $\gamma\,{}^4He\rightarrow dd$, while more than an order of magnitude larger than those of Arends *et al.*, fail to agree with the cross sections measured for $dd\rightarrow {}^4He\gamma$. Because the time-reversal operator is antiunitary, the sensitivity of a given type of reaction to possible violations of time-reversal invariance cannot be estimated theoretically without the use of a detailed model; consequently, time-reversal invariance must be investigated in many different reactions. It is therefore important that large discrepancies in cross section between reactions which are related by detailed balance be resolved experimentally.

Symmetry considerations play an important role in determining possible reaction channels for $dd\rightarrow {}^4He\gamma$. The two-deuteron initial state requires the reaction to obey Bose-Einstein statistics and the cross section to be symmetric about 90°. This severely restricts the number of allowed spin-parity states and thus the possible electromagnetic transitions to the ${}^4He$ final state. To the extent that the assumptions of charge symmetry and a central nuclear force are valid, the $E1$, $M1$, and $M2$ transitions are forbidden.[7] The first allowed multipole transition is the ${}^1D_2$-${}^1S_0$ electric quadrupole. It is thus expected that the angular distribution will have a $\sin^2 2\theta$ shape. At low energies ($T_d<32$ MeV) this is indeed the case.[8,9] However, the $\gamma\,{}^4He\rightarrow dd$ angular distributions of Arends *et al.* at energies corresponding to $T_d=350-600$ MeV show a marked deviation from this shape. Rather than a zero cross section at 90°, a maximum is observed and the data are consistent with a $\sin^2\theta$ angular distribution. It is difficult to reconcile this with a simple reaction mechanism involving only low-order multipoles. The alternative could be a two-step process involving meson and/or nucleon exchange; this is discussed in Sec. III.

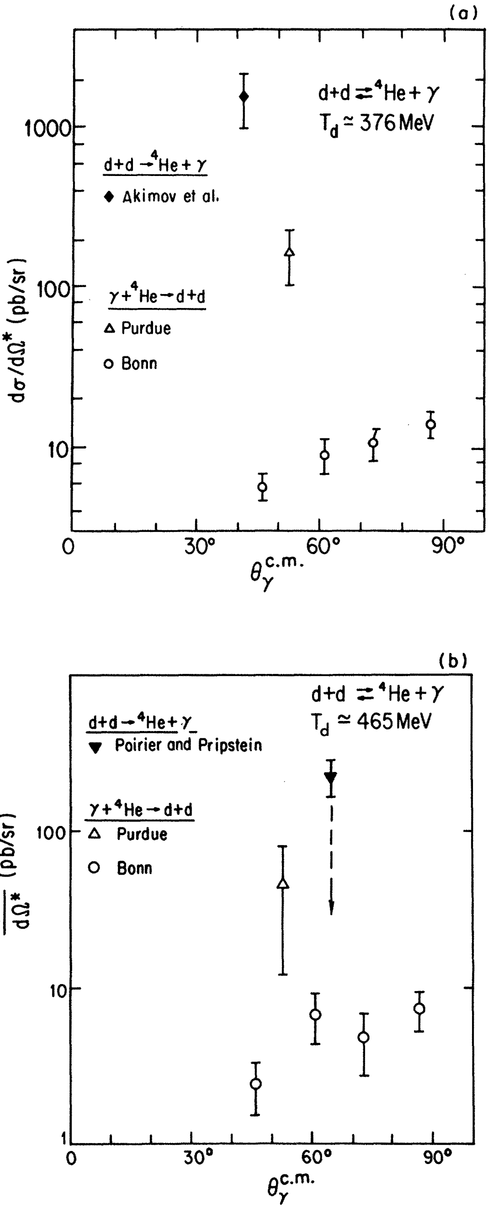

FIG. 1. (a) World data for dd→^{4}Heγ and the inverse reaction near 376 MeV. The dd→^{4}Heγ measurements are those of Akimov *et al.* (Ref. 1, diamond). The $\gamma\,^4$He→dd data of Arends *et al.* (Ref. 4, circles) and of Asbury and Loeffler (Ref. 3, triangle) have been divided by the appropriate detailed balance factors (38.9 for Ref. 4). No correction for energy dependence has been made for the data of Akimov *et al.* ($T_d = 404$ MeV) or of Asbury and Loeffler (equivalent $T_d = 391$ MeV). (b) Same as (a) for deuteron energies near 465 MeV. The dd→^{4}Heγ measurement is that of Poirier and Pripstein (Ref. 2, inverted triangle) at 460 MeV. The equivalent deuteron energy of the Asbury and Loeffler measurement is 479 MeV.

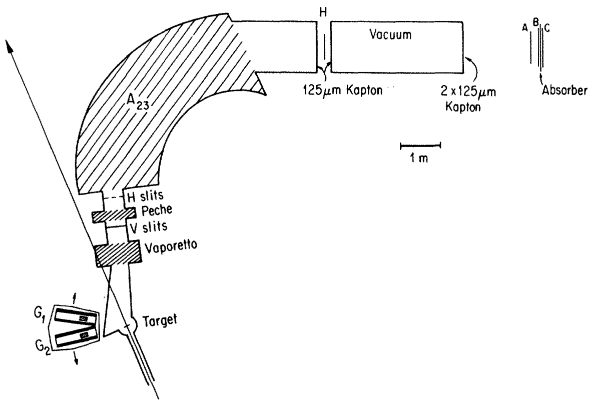

FIG. 2. The detection system used in this experiment. Gammas were detected in the lead glass Cherenkov counters G_1 and G_2. VAPORETTO is a quadrupole magnet used for focusing in the vertical plane; PECHE is a sextupole magnet not used in this experiment. The H and V slits determine the horizontal and vertical acceptance of the spectrometer. A_{23} is the main dipole magnet of the SPES I spectrometer. Alphas were detected by the scintillator hodoscopes H, A, and B with the hodoscope C used in anticoincidence to veto lighter particles.

II. EXPERIMENT

We have measured the differential cross section for dd→^{4}Heγ at θ_γ(c.m.)$=73°$ and $91°$ for $T_d = 376$ MeV; this energy matches the total center-of-mass (c.m.) energy of the $\gamma\,^4$He→dd measurement of Arends *et al.* at $E_\gamma = 213$ MeV. The experiment was performed at the Laboratoire National Saturne at Saclay. The Saturne II synchrotron provided a deuteron beam of about 2×10^{11} deuterons/sec. The beam was incident on a liquid deuterium target 15.6 mm (254 mg/cm^2) thick, with 0.025 mm titanium windows. The beam intensity was monitored by a secondary emission chamber, which was normalized using measurements of the induced radioactivity from the reaction $^{\text{nat}}$C(d,X)^{11}C.[10]

The laboratory cross sections expected for dd→^{4}Heγ based on the results of Ref. 4 are of the order of 20 pb/sr. It is therefore important to overconstrain the event signal by detecting the ^{4}He and γ in coincidence. The detection system (Fig. 2) was similar to that used in an earlier measurement of pd→^{3}Heγ (Ref. 11); experimental details may be found in Ref. 12. The ^{4}He's were momentum analyzed and detected in the SPES I spectrometer[13] which consisted of a bending magnet (A_{23} in Fig. 2) followed by four scintillator hodoscopes (H, A, B, and C in Fig. 2). These hodoscopes furnished time-of-flight (TOF) measurements

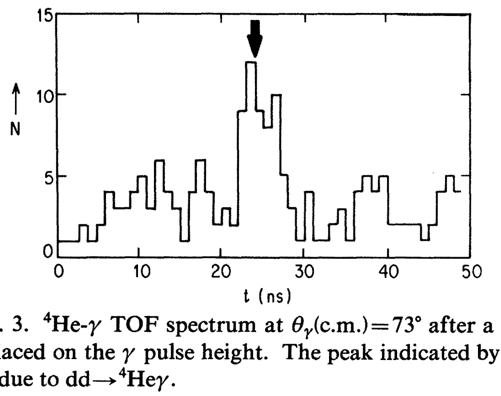

FIG. 3. ^{4}He-γ TOF spectrum at θ_γ(c.m.)$=73°$ after a cut has been placed on the γ pulse height. The peak indicated by the arrow is due to dd→^{4}Heγ.

TABLE I. Event yields for $dd\rightarrow{}^4\text{He}\gamma$ vs photon counter pulse height cut.

c.m. angle (deg)	Channel of pulse height cut	Total yield	Net yield	Correction factor	Corrected number of events
73	83	867	63±41	1.85±0.19	117±77
73	90	403	68±27	2.08±0.21	142±58
73	95	188	48±18	2.30±0.23	110±43
73	100	110	50±13	2.60±0.26	130±36
73	105	58	36± 9	2.97±0.30	107±29
73	110	40	28± 7	3.48±0.35	98±26
73	116	24	21± 5	4.65±0.47	98±25
73	122	17	14± 5	6.33±0.63	89±33
91	160	718	46±37	1.50±0.11	69±56
91	180	281	53±23	1.82±0.15	96±42
91	200	114	22±15	2.33±0.19	51±35
91	220	61	20±10	3.22±0.32	64±33
91	240	32	17± 7	4.85±0.58	82±35
91	260	16	10± 5	6.87±0.89	69±36

over a flight path of 5.23 m, as well as energy loss measurements, to provide unique particle identification of the ^{4}He. Gammas were detected in two lead glass Cherenkov counters,[14] each $10\times10\times15$ cm^3, located 103 cm from the target and heavily shielded. For each ^{4}He-γ coincidence event, we recorded the spectrometer data, the pulse height of the photon signal, and the TOF between the ^{4}He and the γ. The solid angle of the system was determined by the photon counters. For each γ angle, the spectrometer angle and momentum acceptance were set for the associated ^{4}He particle from $dd\rightarrow{}^4\text{He}\gamma$. We verified these settings using the reaction $dp\rightarrow{}^3\text{He}\gamma$, which has a cross section approximately 3000 times that of $dd\rightarrow{}^4\text{He}\gamma$.

The signal for the $dd\rightarrow{}^4\text{He}\gamma$ reaction was derived from the ^{4}He-γ TOF spectrum, which was gated by a cut on the pulse height in the photon counter. The background in the TOF spectrum, primarily due to ^{4}He production in the target walls in coincidence with accidental signals in the photon counters, is substantially reduced by means of this cut. The TOF spectrum at $\theta_\gamma(\text{c.m.})=73°$ is shown in Fig. 3; the peak indicated by the arrow is at the position expected in the TOF spectrum for the $dd\rightarrow{}^4\text{He}\gamma$ reaction. The remaining background under the peak was determined using a linear fit to the spectrum outside the region of the peak. The resulting net area of the peak in Fig. 3 is 36±9 counts. The probability that this peak is due to statistical fluctuations is less than 10^{-6}; for the peak observed at 91°, this probability is approximately 10^{-3}. It should be noted that the unlikely possibility of contamination of the $dd\rightarrow{}^4\text{He}\gamma$ signal by the isospin-forbidden reaction $dd\rightarrow{}^4\text{He}\pi^0$ is prevented by the kinematic separation of the two reactions.

The number of events in the TOF peak was corrected to account for the good events discarded by the cut on photon counter pulse height. This correction factor, determined by analysis of photon counter pulse height data obtained for $dp\rightarrow{}^3\text{He}\gamma$, is tabulated for several thresholds in Table I. Consistent results for the corrected numbers of events were obtained for a wide range of photon-counter pulse-height cuts, as can be seen in Table I; the degree of variation is reflected by the range of values, 1.5—6.9, obtained for the correction factor. Small ($\sim10\%$) corrections were made for losses due to insufficient momentum acceptance in the spectrometer, and for interaction of γ's before reaching the detectors. These corrections were based on Monte Carlo calculations incorporating the Stanford Electron-Gamma Shower (EGS) code[15] for the γ shower development. The gamma counter efficiency (0.78 or 0.80, depending on angle) was calculated using the EGS program along with measurements of the detection efficiency for incident electrons. The results agree well with

TABLE II. Measured cross sections for $dd\rightarrow{}^4\text{He}\gamma$ at 376 MeV. Also shown are the results of Arends *et al.* (Ref. 4) for the inverse reaction $\gamma\,{}^4\text{He}\rightarrow dd$ at 213 MeV after division by the detailed balance factor, and the ratio between the two experiments. A systematic uncertainty of 28% (see Table III) is included in the uncertainty quoted for the ratio. Other uncertainties are statistical only.

This experiment		Arends *et al.*		Ratio
θ_γ (c.m.) (deg)	$\frac{d\sigma}{d\Omega}$ ($dd\rightarrow{}^4\text{He}\gamma$) (pb/sr)	θ_γ (c.m.) (deg)	$\frac{d\sigma}{d\Omega}$ ($\gamma\,{}^4\text{He}\rightarrow dd$) (pb/sr)	This experiment / Arends *et al.*
73°	21±5	73°	10.5±2.3	2.0±0.9
91°	23±10	87°	13.9±2.6	1.7±0.9

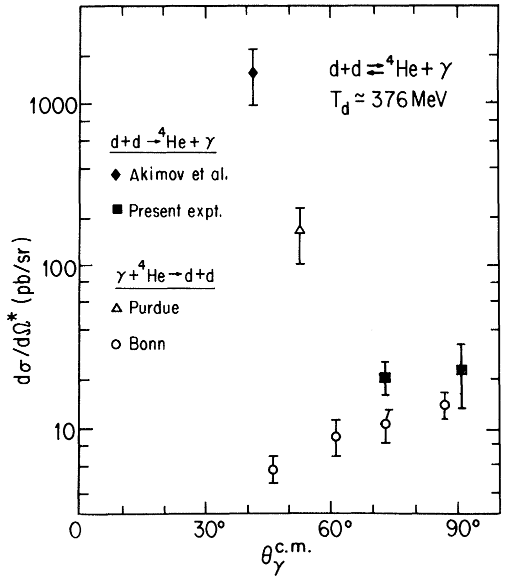

FIG. 4. Results for dd→^{4}Heγ at 376 MeV from this experiment (filled squares). Also shown are the previously-reported results for dd→^{4}Heγ and the inverse reaction near 376 MeV. The dd→^{4}Heγ measurement is that of Akimov *et al.* (Ref. 1, diamond). The γ ^{4}He→dd data of Arends *et al.* (Ref. 4, circles) and of Asbury and Loeffler (Ref. 3, triangle) have been divided by the appropriate detailed balance factors. No correction for energy dependence has been made for the measurement of Akimov *et al.* ($T_d = 404$ MeV) or of Asbury and Loeffler (equivalent $T_d = 391$ MeV). Systematic uncertainties (28% for the present experiment) are not shown.

those of a "self-terminating" Monte Carlo calculation discussed in a previous calibration report.[14]

III. RESULTS AND DISCUSSION

Our measured cross sections for dd→^{4}Heγ at 376 MeV are given in Table II and are shown in Fig. 4. The error bars indicate the uncertainties due to counting statistics and to the correction procedure described above; not included is an overall systematic uncertainty of 28%, due to the uncertainties listed in Table III. The angular acceptance for γ's was approximately ±3°.

Our results at $T_d = 376$ MeV are a factor of 60 lower than the measurement of Akimov *et al.* at $T_d = 404$ MeV. If one assumes the $\sin^2\theta$ angular dependence suggested in Ref. 4, the disagreement becomes a factor of 130. The possibility that this disagreement is due to a strong dependence of the cross section on energy is not supported by the measurements of the inverse reaction by Arends *et al.* The primary difference in technique between the present measurement and that of Akimov *et al.* is that the latter was a single-arm experiment in which only the ^{4}He was detected. The ratios of our results to those measured by Arends *et al.*[4] for the inverse reaction, γ ^{4}He→dd, are 2.0±0.9 at 91° and 1.7±0.9 at 73°. (The uncertainties reflect the combined statistical and systematic uncertainties in the two measurements.) The large uncertainties limit us to the conclusion that detailed balance is satisfied to within a factor of 2 in this system.

As can be seen in Fig. 4, our data are consistent with the cross section maximum observed by Bonn near $\theta_\gamma(\text{c.m.}) = 90°$, in disagreement with the $\sin^2 2\theta$ angular distribution which is observed at lower energies.[8,9] The deviation from the $\sin^2 2\theta$ shape indicates a different reaction mechanism than the $^1D_2$-$^1S_0$ electric quadrupole transition which governs the data at lower energies. Effects of the noncentral part of the nuclear force, specifically of the *d*-wave part of the deuteron wave function, are not expected to be large and are not needed to explain the low energy data. It is not altogether surprising that the lowest allowed multipole transitions fail to describe the reaction at the energies considered here; the approximation represented by the use of only the low-order terms of a multipole expansion is valid only in cases in which the photon wavelength is large compared to the dimensions of the radiating system. In our case ($E_\gamma = 202$ MeV) the photon wavelength is approximately 1 fm, which is comparable to the size of the ^{4}He nucleus (rms charge radius $\simeq 1.6$ fm). At intermediate energies, we expect the reaction mechanism to include a strong contribution from nucleon and/or meson exchange, which in similar cases dominates the simple radiative term. For example, in the np→dγ reaction it is known[16] that production of the Δ(1232) resonance in the intermediate state contributes greatly to the cross section at intermediate energies. For the reaction pt→^{4}Heγ, which has the same final state as dd→^{4}Heγ, it is straightforward to construct Feynman diagrams which include the production of a Δ [Figs. 5(a) and (b)]. However, for dd→^{4}Heγ the possibilities are limited by symmetry requirements. For this reaction to occur with a Δ in the

TABLE III. Systematic uncertainties for this experiment.

Beam monitor:	4%	cross section of monitor reaction
	3%	consistency of measurements
Target thickness:	9%	
Solid angle:	1%	
^{4}He detection efficiency:	7%	
Photon detection efficiency:	7%	
Correction for:		
Spectrometer acceptance	10%	
Photon interaction	10%	
Photon pulse height cuts	20%	
Total	28%	

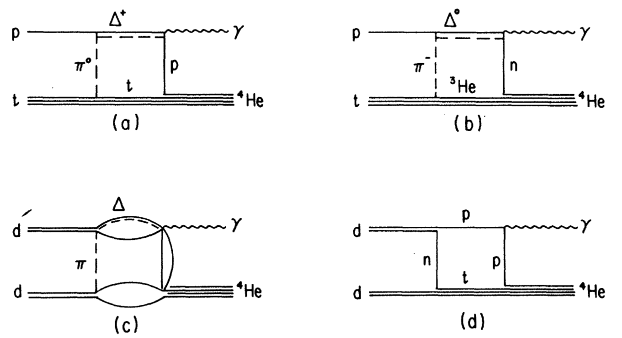

FIG. 5. (a) and (b) Possible Feynman diagrams for $pt\rightarrow{}^4He\gamma$ that include exchange of a pion and production of the Δ resonance. (c) Diagram for $dd\rightarrow{}^4He\gamma$ including pion exchange. The Δ resonance can be formed, but dissociation of the deuterons is required to conserve isospin. (d) Diagram for $dd\rightarrow{}^4He\gamma$ including nucleon exchange. The Δ resonance cannot be formed if isospin is to be conserved.

intermediate state requires dissociation of the deuterons and an unlikely vertex between four nucleons and the ^{4}He [Fig. 5(c)]. Exchange of a nucleon leads to an allowed two-step process [Fig. 5(d)], but one that does not include the Δ. In light of our results, some such exchange process appears necessary to explain the deviation from the $\sin^2 2\theta$ shape which fits the data at lower energies.

In conclusion, our data, when compared with those of Arends *et al.* for the inverse reaction, show no evidence for a large violation of detailed balance in the $dd\rightarrow{}^4He\gamma$ system. Our data are consistent with a large, unexplained deviation from the expected $E2$ reaction mechanism, as previously reported in Ref. 4.

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