Meson Production in $p+d$ Collisions and the $I=0$ π-π Interaction. III. Spin and Parity of the $I=0$ Anomaly*†

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In an auxiliary experiment an attempt was made to determine the spin and parity of the $I=0$ anomaly by detecting charged pions and gamma rays in coincidence with He^3. The results are consistent with the interpretation that the predominant mode of decay is into two pions with a charged-to-neutral ratio of 2/1, indicating a state of spin 0 and even parity.

I. INTRODUCTION

A COMPARISON of the momentum spectra of H^3 and of He^3 produced in $p+d$ collisions showed the anomaly to be an $I=0$ isotopic spin state.[1] Since the computed resolution functions were not as wide as the anomaly, we inferred that the anomaly has an extremely short lifetime and that the dominant mode of decay was into two pions. In other words, the anomaly is an enhancement in the double pion production for low energies of the two-pion (2π) system. Therefore it was felt to be important to have direct information on the decay products. The experiment consisted in measuring the relative number of γ rays and charged pions in coincidence with the He^3 of several different momenta.

Table I gives the decay characteristics for particles of mass less than $3m_\pi$ for the eight simplest sets of quantum numbers. If the anomaly is $J^{PG}=0^{++}$, then a strong decay into two pions is expected. In this case, apart from kinematical factors, the π and γ counting rates should be independent of He^3 momentum. Before the discovery[2] of the ω^0, there was some speculation[3] that the anomaly might be the 1^{--} particle postulated by Nambu.[4] For this assignment the anomaly decays primarily into $\pi^0+\gamma$, and one would expect an increase in the γ-He^3 coincidence rate in the region of the anomaly. For most of the other decay modes listed in Table I, there should also be a difference in the π-He^3 and γ-He^3 rates in the region of the anomaly.

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[1] See previous papers I and II; see N. E. Booth, A. Abashian, and K. M. Crowe, Phys. Rev. Letters **7**, 35 (1961); and A. Abashian, N. E. Booth, and K. M. Crowe, Phys. Rev. Letters **5**, 258 (1960).

[2] B. C. Maglić, L. W. Alvarez, A. H. Rosenfeld, and M. L. Stevenson, Phys. Rev. Letters **7**, 178 (1961).

[3] See for example R. G. Sachs and B. Sakita, Phys. Rev. Letters **6**, 306 (1961); see also, the discussion following N. E. Booth, A. Abashian, and K. M. Crowe, Rev. Mod. Phys. **33**, 393 (1961).

[4] Y. Nambu, Phys. Rev. **106**, 1366 (1957).

II. EXPERIMENT

The experiment was performed in a two-week period at the end of the second run at the 184-in. cyclotron.[5] For this auxiliary experiment the D_2 gas target was replaced by a modified version of the Y-shaped target used in the first run.[6] The modification consisted of a long thin stainless steel "bubble" wall 0.028 in. thick on the side of the target opposite the He^3 or H^3 momentum-selected beam.

For He^3 produced at a laboratory angle of 11.8 deg and with momenta corresponding to the peak of the anomaly, i.e., $w\approx 310$ MeV, the "w system", which we denote by w, is produced at a laboratory angle of 84 deg. At this angle on the opposite side of the proton beam from the He^3 spectrometer a well-shielded scintillation counter telescope was set up, as shown in Fig. 1. The half-angle subtended by the telescope was about 8 deg. Charged pions were detected by the coincidence 123, and γ rays by the coincidence $\bar{1}234$ with $\frac{1}{4}$ in. of Pb placed between 1 and 2.

The experiment was made possible by the installation in the cyclotron of the auxiliary dee system,[7] which increased the duty cycle by a factor of 50 to 100. Although the proton beam was stopped in the back wall of the same cave containing the target and counter telescope, this caused very little trouble. The important source of accidentals was other interactions in the D_2 target in the same rf pulse as a He^3 production.

Let us consider the kinematics of the pions and γ rays from the reactions

$$p+d\rightarrow He^3+\pi^++\pi^- \quad (1a)$$

and

$$p+d\rightarrow He^3+\pi^0+\pi^0 \quad (1b)$$

for a fixed He^3 laboratory angle. Just at threshold, i.e., $w\simeq 2m_\pi$ the pions move out in a narrow cone at roughly 90 deg to the incident beam direction. As w increases and the pions have more relative energy, the angle of

[5] N. E. Booth, A. Abashian, and K. M. Crowe, Phys. Rev. Letter **7**, 35 (1961).

[6] A. Abashian, N. E. Booth, and K. M. Crowe, Phys. Rev. Letters **5**, 258 (1960).

[7] Quentin A. Kerns, Lawrence Radiation Laboratory Electronic Engineering Note EET-743, 1961 (unpublished).

TABLE I. Some possible neutral mesons with $I=0$.[a]

J^{PG} [b]	Dominant decay mode Strong	Order e	Order e^2	Comments
0^{++}	$\pi\pi$			
0^{+-}		$2\pi\gamma$	$\pi^+\pi^-2\gamma$	$J_{\pi\pi}=2$ in $2\pi\gamma$ and $\pi^+\pi^-/\pi^0\pi^0=2/1$.
0^{-+}		$\pi^+\pi^-\gamma$	2γ	$J_{\pi\pi}=1$ in $\pi^+\pi^-\gamma$.
0^{--}		$2\pi\gamma$	$\pi^+\pi^-2\gamma$ $\pi^0e^+e^-$	$J_{\pi\pi}=2$ in $2\pi\gamma$ and $\pi^+\pi^-/\pi^0\pi^0=2/1$.
1^{++}		$\pi^+\pi^-\gamma$	$\pi^02\gamma$	$J_{\pi\pi}=1$ in $\pi^+\pi^-\gamma$.
1^{+-}		$\pi^0\gamma$		
1^{-+}		$\pi^+\pi^-\gamma$	$\pi^02\gamma$	$J_{\pi\pi}=1$ in $\pi^+\pi^-\gamma$.
1^{--}		$\pi^0\gamma$		

[a] This table is a summary of the more complete table given by E. M. Henley and B. A. Jacobsohn, Phys. Rev. 128, 1394 (1962).
[b] For neutral nonstrange mesons of $I=0$, we have $G=C$.

the cone rapidly increases and the axis of the cone rotates forward. For charged pions with $w=310$ MeV, the pion telescope is on the axis of the cone at 84 deg in the lab system and the half-angle of the cone is 30 deg. Figure 2 shows some of the lab angular distributions of the charged pions for the case of isotropic emission in the w-system center of mass. The dashed part of each curve corresponds to pions going backward in this center-of-mass (c.m.) system which, however, are confined to the forward cone in the lab system. Some of these pions cannot get through the counter telescope because of their low range. We therefore took pion data only with the $\frac{1}{4}$ in. of Pb in, so that none of these backward pions were detected. A range curve taken by placing Cu before counter 4 gave results consistent with the expected range for the high-energy group of pions.

The decay of neutral pions from reaction (1b) into γ rays destroys the cone, and although the angular distribution of the γ rays is still peaked along the p_w direction, it falls off so slowly that the detection efficiency of the telescope for γ rays varies slowly with w.

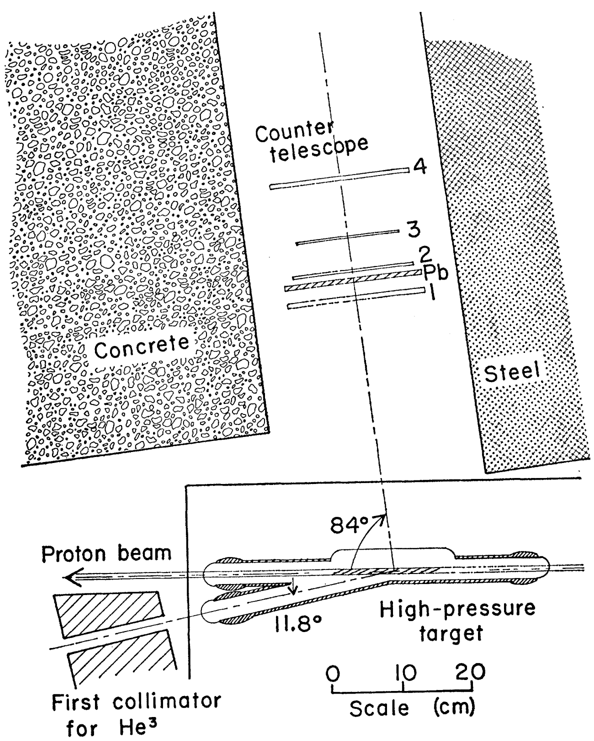

FIG. 1. Experimental arrangement showing D_2 target and π and γ telescope. The vertical and horizontal dimensions, respectively, of the scintillators were (1) 13 by 20 cm, (2) 10 by 18 cm, (3) 10 by 15 cm, and (4) 20 by 20 cm.

The fast coincidences $\pi=123$ and $\gamma=\bar{1}234$ were made in Wenzel coincidence circuits.[8] The counters were

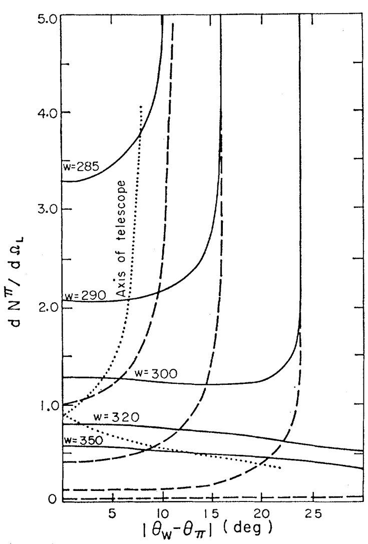

FIG. 2. Kinematics of charged pions from $p+d\rightarrow He^3+\pi^++\pi^-$ for $T_p=743$ MeV and a He^3 laboratory angle of 11.8 deg. The angle θ_W is the laboratory angle of the vector sum of the momenta of the two pions, θ_π is the pion laboratory angle, and $dN_\pi/d\Omega$ is the pion laboratory cross section.

delayed and plateaued and the circuits matched by placing the telescope in the 11.8-deg momentum-selected beam and setting the time of flight for pions. The outputs of the Wenzel circuits were put into coincidence with a pulse signifying an identified momentum-selected He^3, as well as a pulse from the first time-of-flight counter (S_1 in Fig. 6 of paper I). Three of these second circuits were used—one for the γ-He^3 coincidence and two for the π-He^3 coincidence. Of the latter, one was used to measure genuine coincidences and one to

[8] William A. Wenzel, Lawrence Radiation Laboratory Report UCRL-8000, October 1957 (unpublished).

measure π-He^3 accidentals— the roles of the two π-He^3 circuits being frequently interchanged.

In order to increase the counting rate, the momentum-selecting grids were all connected together in the coincidence requirement. We took measurements at nine different values of the He^3 momentum, concentrating mainly on the anomaly but obtaining enough data on either side for comparison. Gamma-He^3 coincidences were measured with Pb in and Pb out. One π-He^3 circuit measured events with normal delay, while the other measured accidentals. Then another run was taken with the roles of the two π-He^3 circuits interchanged. Since the two π-He^3 circuits could have different thresholds for accidentals and because the π-He^3 accidentals were large (about 30%), the following criteria were used:

(a) If in two consecutive runs (roles of circuits interchanged between runs) there was no noticeable change of beam intensity or other conditions, we used the data from each circuit independently.

(b) If the beam intensity did change, we used the data from each run independently. Several runs were taken for each He^3 momentum. A mean π-He^3 rate for each momentum was obtained by weighting the results of the different runs according to the statistical errors. The ratio of deviation from the mean to statistical error was then computed for each measurement. A plot of the ratios for all the measurements is shown in Fig. 3. The shape of the plot is in good agreement with the normal distribution, shown as the dashed curve, but it is too wide. To take account of the indicated systematic error, we have increased the error of each measurement by 25%.

A similar plot for the γ-He^3 data indicated that the errors should be about 15% larger. Tables II and III, respectively, show typical sets of π and γ measurements. The results of all measurements are summarized in Table IV.

III. ANALYSIS

As the first step in the analysis we choose to divide out the kinematical factors in the π and γ rates. The relative efficiency for π and γ detection as a function of

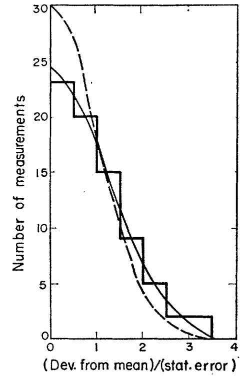

FIG. 3. Test of consistency of the measurements of the π-He^3 coincidence rates. The histogram shows the deviations of 76 separate measurements in terms of their statistical errors. The dashed curve is the normal distribution. The solid curve results if the errors on the measurements are increased by 25%.

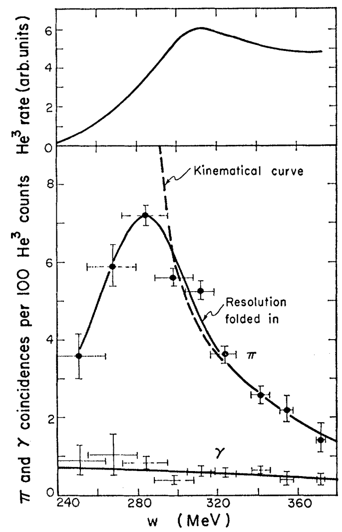

FIG. 4. Plot of the observed π-He^3 and γ-He^3 coincidence rates as a function of w, the total energy in the 2π barycentric system. The curve at the top of the figure shows the observed He^3 rate for comparison.

w must be computed. First, the He^3 momentum scale was translated to a scale of w. Then assuming that in 2π production the pions are emitted isotropically in the w system, the laboratory distributions of π's and γ's were weighted by the experimental angular resolution

TABLE II. Typical set of π data.[a]

Normal delay	Criterion for accidentals	Accidentals	Net rate
4.87±0.60	(b)	2.23±0.43	2.64±0.74
6.77±0.51	(b)	3.13±0.38	3.64±0.63
4.60±0.47	(a)	1.74±0.20	2.96±0.51
2.81±0.31	(b)	1.11±0.20	1.70±0.37
5.28±0.54	(b)	2.26±0.35	3.02±0.64
5.92±0.54	(b)	3.56±0.41	2.36±0.68
4.94±0.33	(a)	2.01±0.31	2.93±0.45
4.03±0.37	(b)	1.35±0.21	2.68±0.42
			Weighted mean = 2.58±0.18

[a] Magnets set for $p/z=610$ MeV/c. Mean value of w is 342 MeV. All rates are per 100 He^3 counts.

and resolution in w, the latter being determined by the momentum resolution. This gives the relative efficiency, which is compared with the experimental points in Fig. 4. Here we plot the observed γ and π rates versus w. The dashed curve is the prediction for the pion rate when the resolution is neglected. The effect of the

TABLE III. Typical set of γ data.[a]

Pb in	Pb out	Net
1.10±0.16	0.33±0.10	0.77±0.19
0.84±0.14	0.25±0.11	0.59±0.18
0.76±0.11	0.18±0.09	0.58±0.14
2.09±0.34	0.89±0.34	1.20±0.48
		Weighted mean = 0.65±0.09

[a] See footnote a, Table II.

TABLE IV. Summary of π and γ coincidence data.

$(p/z)_s$ Observed He^3 momentum (MeV/c)	Mean value of w (MeV)	π Coincidences per 100 He^3	π Errors Statistical	π Errors Total	γ Coincidences per 100 He^3	γ Errors Statistical	γ Errors Total
680	251	3.59	0.48	0.60	0.91	0.35	0.40
670	268	5.91	0.44	0.55	1.04	0.47	0.54
660	284.5	7.20	0.22	0.27	0.83	0.13	0.15
650	298	5.62	0.18	0.22	0.40	0.09	0.10
640	312	5.27	0.20	0.25	0.62	0.12	0.14
630	324	3.64	0.18	0.22	0.57	0.10	0.12
610	342	2.58	0.18	0.22	0.65	0.09	0.10
590	355	2.22	0.27	0.34	0.43	0.16	0.18
550	372	1.47	0.30	0.37	0.38	0.14	0.16

resolution is easily calculated for $w>300$ MeV. However, it is very difficult to estimate for w near $2m_\pi$ because the pion cone is changing so rapidly. In the absence of an exact calculation we have chosen to draw a smooth curve through the first three points and to join it to our resolution calculation at $w=300$ MeV. The solid curve through the γ points also has the resolution folded in. The only factor neglected here is the dependence of the detection efficiency upon γ-ray energy. This has been neglected beacuse it is a smooth slowly varying function of w. The solid curves are close to that expected for $I=0$ production of two pions only. We see from Fig. 4 that there is no marked deviation of the data from the solid curves or the hypothesis of 2π production in the region of $w=310$ MeV.

TABLE V. Goodness of fit and its probability for four possible decay modes.

Assumed decay of anomaly	Spin and parity	χ^2	$P(\chi^2)$ (%)
2π	0^+	8.7	40
$\pi^+\pi^-\gamma$	1^-	7.2	50
2γ	0^-	18.2	2
$\pi^0\gamma$	1^+ or 1^-	21.8	1
Expected $\chi^2=9-1=8$			

To facilitate comparison with the results to be expected from some of the other decay modes of Table I we have divided the values of experimental points by values of the corresponding points from the solid curves of Fig. 4. The results are shown in Fig. 5.

Before computing the expected results for some other decay mode, we must consider two factors. Firstly, there is a more or less constant background of charged pions due to $I=1$ production. This can be determined from our measurements of $p+d\rightarrow H^3+\pi^++\pi^0$, and is easily taken into account. Secondly, the other decay modes of Table I may have rather complicated angular distributions. We neglect this fact since we have no idea what the angular distribution might be and consider each decay mode only on the basis of the *numbers* of charged pions and γ rays.

With these considerations we have plotted in Fig. 5 the expected results for each of several of the decay modes listed in Table I. Note that in Fig. 5 the pion data excludes any mode consisting only of neutral pions and γ rays. The 2π, $2\pi\gamma$, $\pi^+\pi^-\gamma$, and $\pi^+\pi^-2\gamma$ modes fit the pion data reasonably well. Of these, the 2π and $\pi^+\pi^-\gamma$ modes fit the γ-ray data well. The $2\pi\gamma$ and $\pi^+\pi^-2\gamma$ modes fit the γ ray rather poorly (with χ^2 probabilities of 1 and 6% respectively). We consider them to be possible but not very likely candidates.[9]

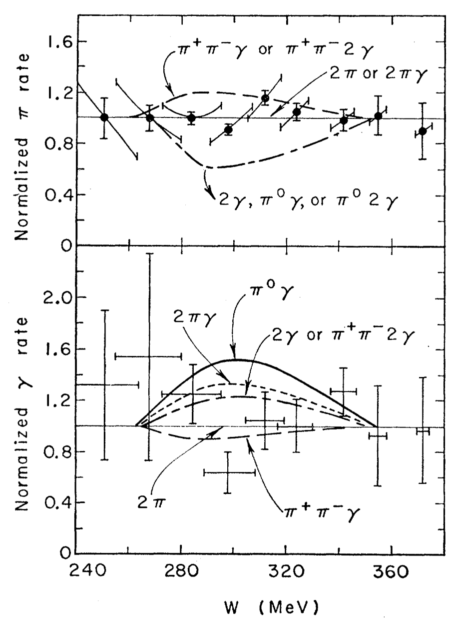

FIG. 5. Values of the pion and gamma rates divided by the corresponding points on the solid curves of Fig. 4. If the anomaly is an enhancement in the 2π production, then a horizontal straight line is expected in the two cases. The curves correspond to various assumptions about the decay mode of the anomaly.

[9] There is also the suggestion of Akimov *et al.* that the anomaly may be associated with threshold effects due to the endothermic process $\pi^0+\pi^0\rightarrow\pi^++\pi^-$ [see Yu. K. Akimov, V. I. Komarov, K. S. Marish, O. V. Savchenko, and L. M. Soroko, Nucl. Phys. **30**, 258 (1962)]. This would give effectively a $2\pi^0$ decay scheme for the anomaly, which fits our data poorly. However, we cannot exclude this effect as being partially responsible for the anomaly.

IV. RESULTS

Referring to Table I, we conclude the following regarding possible J^{PG} assignments:

0^{++}: The dominant mode of decay is into two pions, and this assignment is *allowed* on the basis of our data.

0^{+-}: The $J=2$ barrier in the $2\pi\gamma$ mode tends to favor the $\pi^+\pi^-2\gamma$ mode. On the basis of the data, neither mode seems very likely. We conclude that this assignment is possible but *not so likely*.

0^{-+}: This is the same assignment as the η and it seems very probable that the 2γ mode dominates over $\pi^+\pi^-\gamma$ for a mass of 310 MeV. Therefore this assignment appears *very unlikely*.

0^{--}: Here we come to a conclusion similar to that for 0^{+-} *not so likely*.

1^{++}: Jacobsohn and Henley calculated the ratio $\pi^+\pi^-\gamma/\pi^0 2\gamma$ to be 25/1 for a mass of 550 MeV.[10] We would expect this ratio to be much less at 310 MeV for two reasons. The $J=1$ angular-momentum barrier in $\pi^+\pi^-\gamma$ is much more important so close to threshold. Also, the relative phase space is decreased. Therefore, we might expect the $\pi^0 2\gamma$ mode to be dominant. However, this type of consideration is subject to criticism, and therefore the 1^{++} assignment is *not excluded*.

1^{+-}: The $\pi^0\gamma$ mode appears *very unlikely* on the basis of our data.

1^{-+}: We have the same situation as for 1^{++}, i.e., *not excluded*.

1^{--}: We have the same situation as for 1^{+-}, i.e., *very unlikely*.

V. CONCLUSIONS

The measurements of charged pions and γ rays in coincidence with He^3 in the region of the ABC anomaly gives no indication that the anomaly is anything other than an enhancement in the $I=0$ two-pion production. However, the possible assignments 0^{+-}, 0^{--}, 1^{++}, and 1^{-+}, are not definitely excluded. The first two of these appear not so likely on the basis of the data. The last two appear doubtful on the basis of an extrapolation of the calculations of Henley and Jacobsohn.[10] However, these considerations are not sufficient to exclude them as possible assignments.

In the following paper (IV) the width of the anomaly is compared with the experimental resolution. The apparent lifetime of the order of 10^{-23} sec makes 0^{++} the only reasonable assignment. All other modes are expected to have lifetimes 10^3 to 10^4 times this.

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[10] E. M. Henley and B. A. Jacobsohn. Phys. Rev. **127**, 1829 (1962).