Nondynamical Structure of the $He^3(d,p)He^4$ Reaction*

PAUL L. CSONKA, MICHAEL J. MORAVCSIK, AND MICHAEL D. SCADRON
Lawrence Radiation Laboratory, University of California, Livermore, California
(Received 29 October 1965)

The parity-conserving reaction $\frac{1}{2}+1 \rightarrow \frac{1}{2}+0$ ($\frac{1}{2}$ denoting a particle of spin $\frac{1}{2}$, etc.) is completely described in terms of its six invariant amplitudes. All observables are listed, both for the case when the product of the four intrinsic parities is positive and for the case when this product is negative. The subclass structure of these observables is given. The specific example of the $He^3(d,p)He^4$ reaction is examined and consequences of the experimentally found relationship between polarization and asymmetry are derived. Specific further experiments are listed which could continue to narrow down the uncertainty in our knowledge of the form factors. Experiments determining the product of the four intrinsic parities are also discussed. All proposed experiments are within reach of present-day experimental techniques.

I. INTRODUCTION

A CONSIDERABLE amount of experimental information[1–3] has been accumulating on the $He^3(d,p)$-He^4 reaction up to about 15 MeV. In particular, it was found recently,[3] that over a wide range of angles and energies the polarization P of the proton is opposite in sign but equal in magnitude to the asymmetry A, measured with an unpolarized deuteron beam incident on a polarized He^3 target.

This latter result originated some theoretical papers[4,5] attempting to derive consequences of the above relationship between polarization and asymmetry. Refer- 4 investigated this problem from the point of view of potentials and concluded that certain special types of potentials are incompatible with this result. Reference 5 on the other hand, approached the reaction in terms of invariant amplitudes. It also gave some results in terms of angular momentum state amplitudes.

In this paper we will also utilize invariant amplitudes. Our purpose is to apply the general nondynamical formalism[6–14] of particle reactions to this case in order to derive some additional information. In particular, we will suggest further experiments which can pinpoint the part of the interaction which is responsible for the relationship between polarization and asymmetry that was found experimentally.

In Sec. II we derive the list of observables for this reaction. Our method results in a simpler and much more complete set of expressions for the observables than was given before, and also exhibits the subclass structure[11] of the observables. Using it, in Sec. III, we can suggest further relevant experiments. These experiments can also serve to determine the relative intrinsic parities of the particles in this reaction, and hence can be used to determine the parity assignment[15] of the He^3 ground state.

II. THE STRUCTURE OF THE OBSERVABLES

The general formalism to obtain observables has been discussed elsewhere[8,10,11] in some detail, so we will confine ourselves here to the barest essentials. The reaction in question is

$$\tfrac{1}{2}^+ + 1^+ \rightarrow \tfrac{1}{2}^+ + 0^+, \tag{2.1}$$

where s^+ denotes a particle of spin s and positive intrinsic parity. This reaction will be factorized into the irreducible constituents

$$0+1 \rightarrow 0+0 \tag{2.2}$$

and

$$\tfrac{1}{2}+0 \rightarrow \tfrac{1}{2}+0. \tag{2.3}$$

The observables and pseudo-observables for the second of these were given in Ref. 11. Those of the

* This work performed under the auspices of the U. S. Atomic Energy Commission.

1 L. Stewart, J. E. Brolley, Jr., and L. Rosen, Phys. Rev. **119**, 1649 (1960).
2 R. I. Brown and W. Haeberli, Phys. Rev. **130**, 1163 (1963).
3 S. D. Baker, G. Roy, G. C. Phillips, and G. K. Walters, Phys. Rev. Letters **15**, 115 (1965).
4 M. Tanifuji, Nucl. Phys. (to be published).
5 I. Duck, Nucl. Phys. (to be published).
6 Paul L. Csonka, Michael J. Moravcsik, and Michael D. Scadron, Phys. Letters **15**, 353 (1965).
7 Paul L. Csonka, Michael J. Moravcsik, and Michael D. Scadron, Phys. Rev. Letters **14**, 861 (1965).
8 Paul L. Csonka, Michael J. Moravcsik, and Michael D. Scadron, Ann. Phys. (N. Y.) (to be published).
9 Paul L. Csonka, Michael J. Moravcsik, and Michael D. Scadron, Nuovo Cimento (to be published).
10 Michael J. Moravcsik, in *Recent Developments in Particle Physics* (Gordon and Breach Science Publishers, Inc., New York, to be published).
11 Michael J. Moravcsik, in *Proceedings of the International Conference on Polarization Phenomena of Nucleons, Karlsruhe, 1965* (to be published).
12 Paul L. Csonka, Michael J. Moravcsik, and Michael D. Scadron, Phys. Letters (to be published).
13 Paul L. Csonka, Michael J. Moravcsik, and Michael D. Scadron, Phys. Rev. **143**, 1324 (1966).
14 Paul L. Csonka, Michael J. Moravcsik, and Michael D. Scadron (to be published).

15 At the present, this parity is generally accepted to be positive. This assignment is supported mainly by theoretical considerations based on energy-level calculations, which are quite convincing. There are also some experimental assignments which, however, are based on theoretical models whose validity has been questioned lately. It would therefore be of some value to undertake a direct, and theoretically completely clean, experimental determination of this parity.

TABLE I. Structure of observables for the reaction $\frac{1}{2}+1 \to \frac{1}{2}+0$. For notation of the observables and form factors, see Sec. II. The column left of the observables refers to the case when the product of the four intrinsic parities in the reaction is positive, while for the right-hand column, this product is negative. The table gives the coefficients which multiply the various bilinear combinations of form factors shown at the head of each subclass.

Parity product positive							Parity product negative					
$\|A_{20}\|^2$	$\|A_{22}\|^2$	$\|A_{11}\|^2$	$\|A_{13}\|^2$	$\|A_{31}\|^2$	$\|A_{33}\|^2$	Subclass I-1	$\|A_{21}\|^2$	$\|A_{23}\|^2$	$\|A_{10}\|^2$	$\|A_{12}\|^2$	$\|A_{30}\|^2$	$\|A_{32}\|^2$
+2	+2	+2	+2	+2	+2	$(0,0;0,0)_1$	+2	+2	+2	+2	+2	+2
+2	+2	−2	−2	−2	−2	$(m,0;m,0)_1$	−2	−2	+2	+2	+2	+2
−2	−2	+1	+1	+1	+1	$\frac{3}{2}(0,mm;0,0)_1$	−2	−2	+1	+1	+1	+1
−2	−2	−1	−1	−1	−1	$\frac{3}{2}(m,mm;m,0)_1$	+2	+2	+1	+1	+1	+1
+1	+1	−2	−2	+1	+1	$\frac{3}{2}(0,ll;0,0)_1$	+1	+1	−2	−2	+1	+1
+1	+1	+2	+2	−1	−1	$\frac{3}{2}(m,ll;m,0)_1$	−1	−1	−2	−2	+1	+1
+1	+1	+1	+1	−2	−2	$\frac{3}{2}(0,nn;0,0)_1$	+1	+1	+1	+1	−2	−2
+1	+1	−1	−1	+2	+2	$\frac{3}{2}(m,nn;m,0)_1$	−1	−1	+1	+1	−2	−2
+2	−2	+2	−2	+2	−2	$(l,0;l,0)_1$	+2	−2	+2	−2	+2	−2
+2	−2	−2	+2	−2	+2	$(n,0;n,0)_1$	−2	+2	+2	−2	+2	−2
−2	+2	+1	−1	+1	−1	$\frac{3}{2}(l,mm;l,0)_1$	−2	+2	+1	−1	+1	−1
−2	+2	−1	+1	−1	+1	$\frac{3}{2}(n,mm;n,0)_1$	+2	−2	+1	−1	+1	−1
+1	−1	−2	+2	+1	−1	$\frac{3}{2}(l,ll;l,0)_1$	+1	−1	−2	+2	+1	−1
+1	−1	+2	−2	−1	+1	$\frac{3}{2}(n,ll;n,0)_1$	−1	+1	−2	+2	+1	−1
+1	−1	+1	−1	−2	+2	$\frac{3}{2}(l,nn;l,0)_1$	+1	−1	+1	−1	−2	+2
+1	−1	−1	+1	+2	−2	$\frac{3}{2}(n,nn;n,0)_1$	−1	+1	+1	−1	−2	+2

Parity product positive				Parity product negative		
$\mathrm{Re}A_{20}A_{22}^*$	$\mathrm{Im}A_{11}A_{13}^*$	$\mathrm{Im}A_{31}A_{33}^*$	Subclass I-2	$\mathrm{Im}A_{21}A_{23}^*$	$\mathrm{Re}A_{10}A_{12}^*$	$\mathrm{Re}A_{30}A_{32}^*$
+4	−4	−4	$(m,0;0,0)_1$	−4	+4	+4
+4	+4	+4	$(0,0;m,0)_1$	+4	+4	+4
−4	−2	−2	$\frac{3}{2}(m,mm;0,0)_1$	+4	+2	+2
−4	+2	+2	$\frac{3}{2}(0,mm;m,0)_1$	−4	+2	+2
+2	+4	−2	$\frac{3}{2}(m,ll;0,0)_1$	−2	−4	+2
+2	−4	+2	$\frac{3}{2}(0,ll;m,0)_1$	+2	−4	+2
+2	−2	+4	$\frac{3}{2}(m,nn;0,0)_1$	−2	+2	−4
+2	+2	−4	$\frac{3}{2}(0,nn;m,0)_1$	+2	+2	−4

Parity product positive				Parity product negative		
$\mathrm{Im}A_{20}A_{22}^*$	$\mathrm{Re}A_{11}A_{13}^*$	$\mathrm{Re}A_{30}A_{33}^*$	Subclass I-3	$\mathrm{Re}A_{21}A_{23}^*$	$\mathrm{Im}A_{10}A_{12}^*$	$\mathrm{Im}A_{30}A_{32}^*$
−4	+4	+4	$(l,0;n,0)_1$	+4	−4	−4
+4	+4	+4	$(n,0;l,0)_1$	+4	+4	+4
+4	+2	+2	$(l,mm;n,0)_1$	−4	−2	−2
−4	+2	+2	$(n,mm;l,0)_1$	−4	+2	+2
−2	−4	+2	$(l,ll;n,0)_1$	+2	+4	−2
+2	−4	+2	$(n,ll;l,0)_1$	+2	−4	+2
−2	+2	−4	$(l,nn;n,0)_1$	+2	−2	+4
+2	+2	−4	$(n,nn;l,0)_1$	+2	+2	−4

Parity product positive			Parity product negative	
$\mathrm{Im}A_{11}A_{31}^*$	$\mathrm{Im}A_{13}A_{33}^*$	Subclass I-4	$\mathrm{Im}A_{10}A_{30}^*$	$\mathrm{Im}A_{12}A_{32}^*$
−4	−1	$(0,m;0,0)_1$	−4	−4
+4	+4	$(m,m;m,0)_1$	−4	−4
−4	+4	$(l,m;l,0)_1$	−4	+4
+4	−4	$(n,m;n,0)_1$	−4	+4

Parity product positive			Parity product negative	
$\mathrm{Re}A_{13}A_{31}^*$	$\mathrm{Re}A_{33}A_{11}^*$	Subclass I-5	$\mathrm{Im}A_{12}A_{30}^*$	$\mathrm{Im}A_{10}A_{32}^*$
+4	−4	$(m,m;0,0)_1$	−4	−4
−4	+4	$(0,m;m,0)_1$	−4	−4
−1	−1	$(l,ln;n,0)_1$	−1	+1
−1	−1	$(n,ln;l,0)_1$	+1	−1

Parity product positive			Parity product negative	
$\mathrm{Im}A_{13}A_{31}^*$	$\mathrm{Im}A_{11}A_{33}^*$	Subclass I-6	$\mathrm{Re}A_{12}A_{30}^*$	$\mathrm{Re}A_{32}A_{10}^*$
−4	−4	$(l,m;n,0)_1$	+4	−4
−4	−4	$(n,m;l,0)_1$	−4	+4
−1	+1	$(m,ln;0,0)_1$	−1	−1
+1	−1	$(0,ln;m,0)_1$	−1	−1

Parity product positive			Parity product negative	
$\mathrm{Re}A_{11}A_{31}^*$	$\mathrm{Re}A_{13}A_{23}^*$	Subclass I-7	$\mathrm{Re}A_{10}A_{30}^*$	$\mathrm{Re}A_{12}A_{32}^*$
−1	−1	$(0,ln;0,0)_1$	−1	−1
+1	+1	$(m,ln;m,0)_1$	−1	−1
−1	+1	$(l,ln;l,0)_1$	−1	+1
+1	−1	$(n,ln;n,0)_1$	−1	+1

Parity product positive			Parity product negative	
$\mathrm{Re}A_{22}A_{33}^*$	$\mathrm{Im}A_{20}A_{31}^*$	Subclass II-1	$\mathrm{Re}A_{32}A_{23}^*$	$\mathrm{Im}A_{30}A_{21}^*$
−4	+4	$(l,l;0,0)_1$	+4	−4
−2	+2	$(n,nm;m,0)_1$	−2	+2
+4	+4	$(0,l;l,0)_1$	−4	−4
−2	−2	$(m,nm;n,0)_1$	−2	−2

Parity product positive			Parity product negative	
$\mathrm{Re}A_{20}A_{31}^*$	$\mathrm{Im}A_{22}A_{33}^*$	Subclass II-2	$\mathrm{Re}A_{30}A_{21}^*$	$\mathrm{Im}A_{32}A_{23}^*$
+4	+4	$(n,l;m,0)_1$	−4	−4
−2	−2	$(l,nm;0,0)_1$	−2	−2
−4	+4	$(m,l;n,0)_1$	+4	−4
−2	+2	$(0,nm;l,0)_1$	−2	+2

TABLE I (*continued*)

Parity product positive			Parity product negative	
$\mathrm{Re}A_{22}A_{31}^*$	$\mathrm{Im}A_{20}A_{33}^*$	Subclass II-3	$\mathrm{Re}A_{32}A_{21}^*$	$\mathrm{Im}A_{30}A_{23}^*$
+4	+4	$(n,l;0,0)_1$	−4	−4
−2	−2	$(l,nm;m,0)_1$	−2	−2
−4	+4	$(0,l;n,0)_1$	+4	−4
−2	+2	$(m,nm;l,0)_1$	−2	+2

Parity product positive			Parity product negative	
$\mathrm{Re}A_{20}A_{33}^*$	$\mathrm{Im}A_{22}A_{31}^*$	Subclass II-4	$\mathrm{Re}A_{30}A_{23}^*$	$\mathrm{Im}A_{32}A_{21}^*$
−4	+4	$(l,l;m,0)_1$	+4	−4
−2	+2	$(n,nm;0,0)_1$	−2	+2
+4	+4	$(m,l;l,0)_1$	−4	−4
−2	−2	$(0,nm;n,0)_1$	−2	−2

Parity product positive			Parity product negative	
$\mathrm{Re}A_{22}A_{13}^*$	$\mathrm{Im}A_{20}A_{11}^*$	Subclass II-5	$\mathrm{Re}A_{12}A_{23}^*$	$\mathrm{Im}A_{10}A_{21}^*$
+4	−4	$(l,n;0,0)_1$	−4	+4
−2	+2	$(n,lm;m,0)_1$	−2	+2
−4	−4	$(0,n;l,0)_1$	+4	+4
−2	−2	$(m,lm;n,0)_1$	−2	−2

Parity product positive			Parity product negative	
$\mathrm{Re}A_{20}A_{11}^*$	$\mathrm{Im}A_{22}A_{13}^*$	Subclass II-6	$\mathrm{Re}A_{10}A_{21}^*$	$\mathrm{Im}A_{12}A_{23}^*$
−4	−4	$(n,n;m,0)_1$	+4	+4
−2	−2	$(l,lm;0,0)_1$	−2	−2
+4	−4	$(m,n;n,0)_1$	−4	+4
−2	+2	$(0,lm;l,0)_1$	−2	+2

Parity product positive			Parity product negative	
$\mathrm{Re}A_{22}A_{11}^*$	$\mathrm{Im}A_{20}A_{13}^*$	Subclass II-7	$\mathrm{Re}A_{12}A_{21}^*$	$\mathrm{Im}A_{10}A_{23}^*$
−4	−4	$(n,n;0,0)_1$	+4	+4
−2	−2	$(l,lm;m,0)_1$	−2	−2
+4	−4	$(0,n;n,0)_1$	−4	+4
−2	+2	$(m,lm;l,0)_1$	−2	+2

Parity product positive			Parity product negative	
$\mathrm{Re}A_{20}A_{13}^*$	$\mathrm{Im}A_{22}A_{11}^*$	Subclass II-8	$\mathrm{Re}A_{10}A_{23}^*$	$\mathrm{Im}A_{12}A_{21}^*$
+4	−4	$(l,n;m,0)_1$	−4	+4
−2	+2	$(n,lm;0,0)_1$	−2	+2
−4	−4	$(m,n;l,0)_1$	+4	+4
−2	−2	$(0,lm;n,0)_1$	−2	−2

first reaction are as follows:

$$\begin{aligned}
(0,0;0,0)_2^{++} &= -\tfrac{3}{2}(0,mm;0,0)_2^{++} = 3(0,ll;0,0)_2^{++} \\
&= 3(0,nn;0,0)_2^{++} = |a_2|^2, \\
(0,m;0,0)_2^{++} &= (0,ln;0,0)_2^{++} = 0, \\
(0,0;0,0)_2^{--} &= 3(0,mm;0,0)_2^{--} = |a_1|^2 + |a_3|^2, \\
(0,ll;0,0)_2^{--} &= -\tfrac{2}{3}|a_1|^2 + \tfrac{1}{3}|a_3|^2, \\
(0,nn;0,0)_2^{--} &= \tfrac{1}{3}|a_1|^2 - \tfrac{2}{3}|a_3|^2, \\
(0,m;0,0)_2^{--} &= -2\,\mathrm{Im}a_1a_3^*, \\
(0,ln;0,0)_2^{--} &= -\tfrac{1}{2}\,\mathrm{Re}a_1a_3^*,
\end{aligned} \tag{2.4}$$

and

$$\begin{aligned}
[0,l;0,0]_2^{+-} &= -ia_2a_3^* = 2i[0,nm;0,0]_2^{+-}, \\
[0,n;0,0]_2^{+-} &= ia_2a_1^* = -2i[0,lm;0,0]_2^{+-}, \\
[x,y;z,w]_2^{+-} &= ([x,y;z,w]_2^{-+})^*.
\end{aligned} \tag{2.5}$$

Here we denoted observables by curved brackets, and pseudo-observables by square brackets. The subscript i on the bracket refers to reaction (2.1), and the four arguments refer to the polarization states of the first initial particle, second initial particle, first final particle, and second final particle, respectively. The polarization states are described with the help of the vectors

$$\mathbf{l} \equiv (\mathbf{q}-\mathbf{q})/|\mathbf{q}-\mathbf{q}|, \quad \mathbf{m} \equiv \mathbf{q}\times\mathbf{q}'/|\mathbf{q}\times\mathbf{q}'|, \quad \mathbf{n} \equiv \mathbf{l}\times\mathbf{m}, \tag{2.6}$$

where $\mathbf{q}$ and $\mathbf{q}'$ are the initial and final c.m. momenta, respectively. The symbol "0" denotes unpolarized particles.[16] The two superscripts on the brackets refer to the superscripts of the two M matrices occurring in the trace which yields the particular observable or pseudo observable. The form factors a_1, a_2, and a_3 are defined by the forms of the M matrices $M_2^+ = a_2\mathbf{S}\cdot\mathbf{m}$ and $M_2^- = a_1\mathbf{S}\cdot\mathbf{l} + a_3\mathbf{S}\cdot\mathbf{n}$, where $\mathbf{S}$ is the spin-1 operator, $S_{[1]}(0,1)$.

The observables for Eq. (2.1) are then given by the following expressions:

$$\begin{aligned}
(x,y;z,w)_1^{++} = {} & (0,y;0,0)_2^{++}(x,0;z,w)_2^{++} \\
& + (0,y;0,0)_2^{--}(x,0;z,w)_3^{--} \\
& + [0,y;0,0]_2^{+-}[x,0;z,w]_3^{+-} \\
& + [0,y;0,0]_2^{-+}[x,0;z,w]_3^{-+}, \\
(x,y;z,w)_1^{--} = {} & (0,y;0,0)_2^{++}(x,0;z,w)_3^{--} \\
& + (0,y;0,0)_2^{--}(x,0;z,w)_3^{++} \\
& + [0,y;0,0]_2^{+-}[x,0;z,w]_3^{-+} \\
& + [0,y;0,0]_2^{-+}[x,0;z,w]_3^{+-}.
\end{aligned} \tag{2.7}$$

A given observable will involve only the first two or the last two lines of these expressions. Accordingly, it will be said[10] to belong to class I or class II. In addition, each class can be decomposed into subclasses[11] depending on which bilinear combinations of form factors appear. Each combination appears in one and only one subclass.

The form factors we use can be defined by writing down the M matrices we use

$$\begin{aligned}
M_1^+ = {} & A_{20}\mathbf{S}\cdot\mathbf{m} + A_{22}\mathbf{S}\cdot\mathbf{m}\boldsymbol{\sigma}\cdot\mathbf{m} + A_{11}\mathbf{S}\cdot\mathbf{l}\boldsymbol{\sigma}\cdot\mathbf{l} + A_{31}\mathbf{S}\cdot\mathbf{n}\boldsymbol{\sigma}\cdot\mathbf{l} \\
& + A_{13}\mathbf{S}\cdot\mathbf{l}\boldsymbol{\sigma}\cdot\mathbf{n} + A_{33}\mathbf{S}\cdot\mathbf{n}\boldsymbol{\sigma}\cdot\mathbf{n}, \\
M_1^- = {} & A_{21}\mathbf{S}\cdot\mathbf{m}\boldsymbol{\sigma}\cdot\mathbf{l} + A_{23}\mathbf{S}\cdot\mathbf{m}\boldsymbol{\sigma}\cdot\mathbf{n} + A_{10}\mathbf{S}\cdot\mathbf{l} \\
& + A_{30}\mathbf{S}\cdot\mathbf{n} + A_{12}\mathbf{S}\cdot\mathbf{l}\boldsymbol{\sigma}\cdot\mathbf{m} + A_{32}\mathbf{S}\cdot\mathbf{n}\boldsymbol{\sigma}\cdot\mathbf{m},
\end{aligned} \tag{2.8}$$

where $\boldsymbol{\sigma}$ is the Pauli spin-$\frac{1}{2}$ operator ($\sigma^2 = 3$), and $\mathbf{S}$ the spin-1 operator, $S_{[1]}(0,1)$.

The subclasses are given in Table I. Although we are immediately interested only in the case when the product of intrinsic parities is positive, the other case is also listed for the purpose of some remarks we will make later about the parity of the He^3.

[16] In Refs. 10 and 11, an unpolarized particle was denoted by "1." We believe, however, that "0" is a more appropriate notation and intend to use it in future publications.

The number of observables[10,14] for this reaction is 72, of which 40 are in class I and 32 in class II. In Table I actually 48 observables are listed in class I, but there are eight relations between them (independently of form factor considerations), because

$$(x,ll;z,0)_1+(x,mm;z,0)_1+(x,nn;z,0)_1\equiv 0. \quad (2.9)$$

III. COMPARISON WITH EXPERIMENT

As mentioned in the introduction, experiments[2,3] have shown that from 6 to 10 MeV, and from 30° to 100°, to a very good approximation

$$P\equiv(0,0;m,0)=-(m,0;0,0)\equiv -A. \quad (3.1)$$

These two observables are in subclass I-2. For the parity product being positive (which is the case we deal with here if the He^3 groundstate has positive parity, since the d and He^4 parities are definitely known to be positive), Eq. (3.1) is satisfied if

$$\mathrm{Re}A_{20}A_{22}^*=0. \quad (3.2)$$

This can occur if one or several of the following conditions are satisfied:

$$\text{(a)}\quad A_{20}=0, \quad (3.3a)$$

$$\text{(b)}\quad A_{22}=0, \quad (3.3b)$$

$$\text{(c)}\quad A_{20}\perp A_{22}\quad (A_{20},A_{22}\neq 0). \quad (3.3c)$$

It is of interest to determine experimentally which of these three possibilities hold. This can be done as follows:

1. Measure two appropriate subclass I-3 observables. The simplest pair is $(l,0;n,0)_1^{++}$ and $(n,0;l,0)_1^{++}$. If these two observables are equal to each other, we must have

$$\mathrm{Im}A_{20}A_{22}^*=0, \quad (3.4)$$

and hence Eq. (3.3c) is not an adequate explanation of Eq. (3.1) but instead either Eq. (3.3a) or (3.3b), or both must hold. If $(l,0;n,0)_1^{++}\neq(n,0;l,0)_1^{++}$, this, combined with Eq. (3.1), means that Eq. (3.3c) holds.

2. Assuming that Eq. (3.4) is established, one must then decide whether Eq. (3.3a) or Eq. (3.3b) holds. In order to do this, a class-II type experiment must be carried out, since A_{20} or A_{22} appear in no other class-I type experiment except those in subclasses I-2 and I-3. Since *all* class-II observables involve polarized deuterons, such an experiment goes beyond those carried out so far or combinations thereof. The simplest appropriate class-II type observables, however, should fall within presently available experimental techniques. They are of the type $(x,y;0,0)$ or $(0,x;y,0)$. In particular, (if the observables below are nonzero), the following relations can be used to distinguish between the two cases:

$$(l,l;0,0)_1^{++}=\mp(0,l;l,0)_1^{++}, \quad (3.5a)$$

$$(n,l;0,0)_1^{++}=\mp(0,l;n,0)_1^{++}, \quad (3.5b)$$

$$(l,n;0,0)_1^{++}=\mp(0,n;l,0)_1^{++}, \quad (3.5c)$$

$$(n,n;0,0)_1^{++}=\mp(0,n;n,0)_1^{++}, \quad (3.5d)$$

where the upper signs hold if Eq. (3.3a) holds, and the lower signs if Eq. (3.3b) holds.

It should be emphasized that all results in this paper are valid at any energy and angle, so that, in order to use them to disentangle the reasons for $P=-A$, one would have to carry out the proposed experiments only at one convenient energy and angle (assuming, of course, that the same reasons hold in the whole energy and angular range under consideration).

3. If *both* Eq. (3.3a) and Eq. (3.3b) hold, then the eight observables appearing in Eqs. (3.5a)–(3.5d) are all identically zero. In this case, we also have the following relations for subclass I-1 observables:

$$(0,0;0,0)_1^{++}=-(m,0;m,0)_1^{++}, \quad (3.6a)$$

$$(l,0;l,0)_1^{++}=-(n,0;n,0)_1^{++}. \quad (3.6b)$$

The first of these probably represents an experiment which is easier than those in Eq. (3.5).

Let us now briefly investigate what the situation would be if the intrinsic parity of the He^3 were negative. In this case $P=-A$ would mean

$$\mathrm{Re}A_{10}A_{12}^*+\mathrm{Re}A_{30}A_{32}^*=0. \quad (3.7)$$

Then, proceeding to the $(x,y;0,0)$ and $(0,x;y,0)$ type observables,

$$(l,0;n,0)_1^{--}=(n,0;l,0)_1^{--} \quad (3.8)$$

would imply

$$A_{10}A_{12}^*+A_{30}A_{32}^*=0. \quad (3.9)$$

In this case, therefore, if we make no further measurements, we cannot distinguish between the two parity cases. If, however, Eq. (3.8) turned out not to hold, and one measured the $(x,y;0,0)_1^{--}$ and $(0,x;y,0)_1^{--}$ type observables, it would now not be true that they would have to be pairwise equal in magnitude as they were in Eq. (3.5). Thus, if the set of relations

$$(m,0;0,0)_1=-(0,0;m,0), \quad (3.10a)$$

$$(l,0;n,0)_1=(n,0;l,0), \quad (3.10b)$$

$$(l,l;0,0)_1\neq\pm(0,l;l,0) \quad (3.10c)$$

were established experimentally, this would prove that the parity of the He^3 is negative.

It might be remarked, however, that there are easier nondynamical ways to determine the parity of the He^3 experimentally. Probably the simplest such experiment is

$$(m,m;0,0)=\mp(0,m;m,0). \quad (3.11)$$

This is well within the capabilities of present day experimental techniques, particularly because only the signs and not the magnitudes of these two quantities would have to be determined. As long as parity is conserved, the magnitudes of these two observables must be equal to each other at all energies and angles, regardless of parity assignments and, of course, regardless of the forces acting between the particles.

In summary we might conclude that considerable amount of additional information could be gained from experiments in which *two* of the participating particles are characterized by *vector* polarization. In fact, such a set of experiments would, except in pathological cases, lead to the determination of all six form factors. It cannot be emphasized enough that theoretical models cannot be considered verified unless they predict correctly all individual form factors. In particular, in the case of a reaction as complex in spin space as the present one, a correct prediction of the differential cross section alone is an extremely weak test of any theory.

ACKNOWLEDGMENTS

We became aware of the problem discussed in this paper when one of us (M.J.M.) attended the International Conference on Polarization Phenomena of Nucleons, in Karlsruhe in September 1965. It gave us an opportunity to apply a formalism, which was developed originally with elementary-particle reactions in mind, to a reaction in nuclear physics. This incident might well illustrate how one can profit from specialized but interdisciplinary conferences. We are also indebted to G. C. Phillips for providing us with preprint copies of Refs. 4 and 5, and for enhancing our interest in this problem.

PHYSICAL REVIEW VOLUME 143, NUMBER 3 MARCH 1966

He^3+p Elastic Scattering below 1 MeV*

R. W. KAVANAGH AND P. D. PARKER†
California Institute of Technology, Pasadena, California
(Received 26 July 1965; revised manuscript received 29 November 1965)

The cross section at 90° (lab) for elastic scattering of protons by He^3 has been measured from $E_p=0.125$ MeV to above 1 MeV. No significant departure of the *s*-wave phase shifts from the hard-sphere value is seen. Experimental upper limits for the dimensionless reduced width of a $J=0^+$ state vary from 4×10^{-3} at the lowest energy to 10^{-4} at 1 MeV, and lead to the assignment of $T=0$ to the 0^+ state at 20 MeV in He^4.

INTRODUCTION

THE possibility of the existence of a particle-stable Li^4 was considered by Bethe[1] in his classic review article on energy generation in stars, and from time to tome since then, revivals of interest in the subject have occurred as a result of new theoretical considerations or experimental data. A summary of the astrophysical aspects has recently been given by Parker *et al.*,[2] and we need only mention that previous experimental work, including the limit on solar neutrino emission,[3] indicates that the mass of Li^4 lies at least 20 keV above the mass of ${}_1H^1+{}_2He^3$. The region from 1 to 11.5 MeV above the proton threshold has been examined with elastic scattering at several laboratories, and a phase-shift analysis has recently been published[4] indicating *P*-wave triplet states at 4.7, 6.1, and 7.9 MeV above the H^1+He^3 mass and possibly a *P*-wave singlet state at 9.8 MeV. Werntz and Brennan[5] had previously suggested that the 0^+ state observed in He^4 at an excitation of 20 MeV has isobaric spin $T=1$ and that the analog 0^+ states, with reduced widths near the Wigner limit, should lie in H^4 at 0.17 ± 0.13 MeV below the $n+H^3$ mass and in Li^4 at 0.35 ± 0.03 MeV above the H^1+He^3 mass. The evidence from recent experiments searching for $H^4(\beta^-\bar{\nu})He^4{}_{gs}$,[6] $H^4(\beta^-\bar{\nu})He^{4*}$,[7] and $H^3(d,p)H^4$,[8] strongly indicates that H^4 is not particle stable, in contradiction to the prediction of Werntz and Brennan. However, this evidence cannot rule out the possibility that the 0^+, 20-MeV state in He^4 is $T=1$, since if H^4 were only 40 keV more massive than Werntz and Brennan's upper limit it would be unstable to neutron emission and would have been missed in these searches for neutron-stable H^4. If the 0^+, 20-MeV state in He^4 is $T=1$, then in Li^4 the analog state should be seen as an *s*-wave scattering resonance

* Supported in part by the Office of Naval Research Contract Nonr-220(47).
† Present address: Physics Department, Brookhaven National Laboratory, Upton, Long Island, New York.
1 H. A. Bethe, Phys. Rev. **55**, 434 (1939).
2 P. D. Parker, J. N. Bahcall, and W. A. Fowler, Astrophys. J. **139**, 602 (1964).
3 R. Davis, Phys. Rev. Letters **12**, 303 (1964); J. N. Bahcall, Phys. Rev. **135**, B137 (1964).
4 T. A. Tombrello, Phys. Rev. **138**, B40 (1965).
5 C. Werntz and J. G. Brennan, Phys. Letters **6**, 113 (1963).
6 B. M. Spicer, Phys. Letters **6**, 88 (1963); B. M. K. Nefkens and G. Moscati, Phys. Rev. **133**, B17 (1964); W. L. Imhof, F. J. Vaughn, L. F. Chase, H. A. Grench, and M. Walt, Nucl. Phys. **49**, 81 (1964).
7 J. Janecke, Z. Physik **183**, 499 (1965).
8 P. C. Rogers and R. H. Stokes, Phys. Letters **8**, 320 (1964).