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.

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He^3+p Elastic Scattering below 1 MeV*

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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

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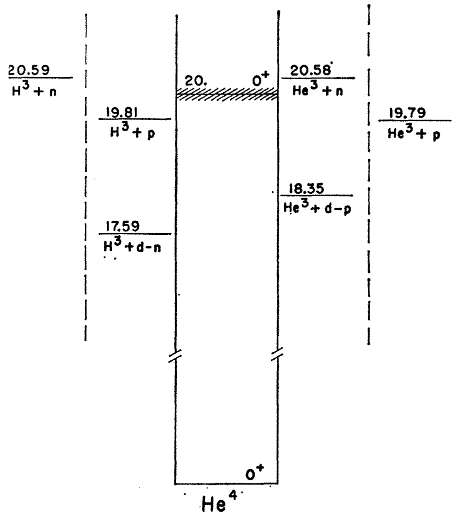

FIG. 1. Energy levels in the mass-4 system. Mass excesses are given in MeV above the He^4 ground state.

in the $He^3(p,p)$ reaction at a proton energy of about 470 keV (see Fig. 1). The present experiment was undertaken to search for such resonance behavior in the singlet s-wave phase shift, ${}^1\delta_0$. The elastic scattering at $\theta_{lab}=90°$ was examined over the proton energy range from 0.125 to 2.0 MeV; over the lower half of this range, ${}^1\delta_0$ is found to be well approximated by the values for a hard sphere of radius 3.4 F.

EXPERIMENTAL METHOD

Measurements were made using a small gas cell, about 8 mm diam by 9 mm long, with an entrance foil of 5000-Å nickel. The magnetically analyzed proton beam, typically 0.3 μA, from the 3-MV electrostatic accelerator was collimated to a diameter of 2 mm before striking the entrance foil. Particles scattered at 90° were collimated through a hole, 1.2 mm diam and 6 mm long, before striking the face of a surface-barrier silicon detector placed 1 cm from the beam axis. The cell and detector assembly were chilled with dry ice to improve the pulse-height resolution. In order to avoid the necessity of accurately stabilizing the geometry and beam-current integration as the beam energy was varied, a few percent of neon gas was added to the He^3, so that at every bombarding energy the scattering from He^3 could be normalized to the scattering from neon, which is essentially pure Rutherford scattering below 1 MeV. The ratio of partial pressures of the Ne and He^3 was determined to a precision of 3% or better from the scattering yields under fixed bombarding conditions for the separate gases at known pressures, and then for the mixture. Various total pressures from 3 to 30 cm Hg were used. Calibrations of beam energy ($\pm$4 keV), energy spread (16 keV), and foil thickness were made by observations of the 4.4-MeV γ ray from $N^{15}(p,\alpha\gamma)C^{12}$ at the narrow resonances at $E_p=429$ keV and $E_p=898$ keV, using enriched N^{15} gas in the target cell.

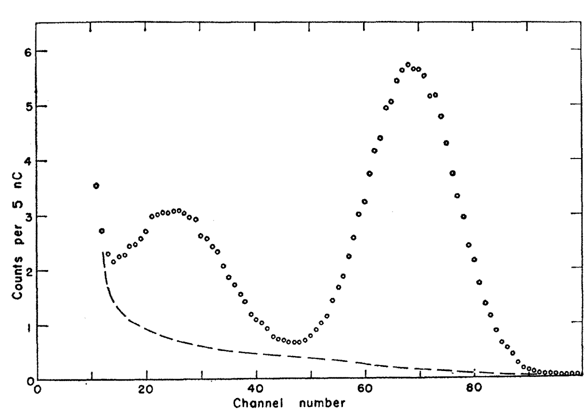

FIG. 2. Spectrum in a silicon detector of protons scattered at 90° (lab) from He^3 (lower peak) and Ne, for $E_p=125$ keV. The dashed curve shows the background spectrum taken with chamber evacuated. $P_{Ne}/P_{He}=0.106$.

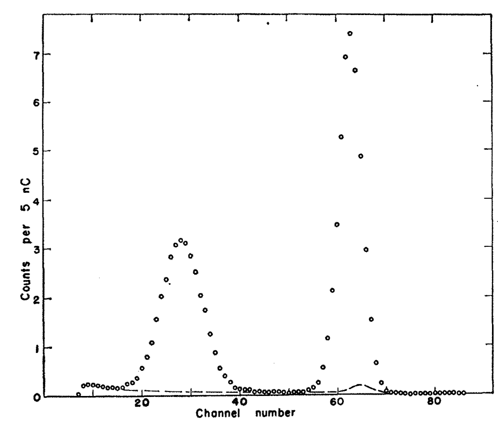

FIG. 3. Spectrum of protons at 90° for $E_p=373$ keV.

Figure 2 shows the spectrum recorded at the lowest bombarding energy attempted, E_p(lab) = 125 keV (270-keV accelerator energy less 145-keV loss in the entrance foil). The required ratio of He^3 to Ne scattering yields was obtained at the lowest bombarding energies by estimating counts in the high-energy halves of the peaks, since the lower parts are poorly defined. The spectra and accuracy of the yield ratio improve rapidly as the bombarding energy is raised. Figure 3 shows the spectrum taken at E_p(lab) = 373 keV. At this and higher energies, the probable error in the yield ratio was about 1%, deteriorating to about 6% at the lowest energy. Background runs at all energies below $E_p=400$ keV were taken with the target cell evacuated; periodic checks were made at higher energies.

DATA ANALYSIS

The $He^3(p,p)$ scattering cross section can be expressed in terms of the measured yield and partial-pressure ratios, and the Ne(p,p) scattering cross section, as

$$\left(\frac{\sigma}{\sigma_R}\right)_{\mathrm{He}^3} \Big/ \left(\frac{\sigma}{\sigma_R}\right)_{\mathrm{Ne}} = 26.8\times\frac{Y_{\mathrm{He}^3}}{Y_{\mathrm{Ne}}}\times\frac{P_{\mathrm{Ne}}}{P_{\mathrm{He}^3}},$$

where σ_R is the Rutherford cross section; Fig. 4 shows a plot of this ratio as a function of proton energy. The scatter in the data below about 0.2 MeV is attributed to the background difficulty mentioned above in connection with Fig. 2. Otherwise, the values rise smoothly except near the known $\mathrm{Ne}^{20}(p,p)$ resonances at $E_p=1.81$ and 1.955 MeV.[9] The cross shown at 1.01 MeV is from the data of Famularo *et al.*,[10] using the value 1.013 for $(\sigma/\sigma_R)_{\mathrm{Ne}}$, which obtains if the Ne(p,p) phase shift at this proton energy is that for s waves from a hard charged sphere of radius 5.2 F. Their value, about 5% higher than ours, agrees within the quoted errors.

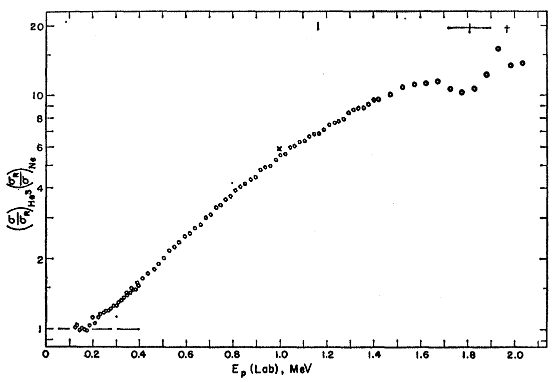

FIG. 4. The measured ratio of $\mathrm{He}^3(p,p)$ and Ne(p,p) scattering cross sections at 90° (lab) as a function of proton energy. Known resonances in $\mathrm{Ne}^{20}(p,p)$ at $E_p=1.81$ MeV ($\Gamma=150$ keV) and 1.955 MeV ($\Gamma=5$ keV) are marked with crosses indicating their locations and widths. A narrow resonance in $\mathrm{Ne}^{20}(p,p)$ at 1169 keV is not seen. The cross at $E_p=1.01$ MeV has been extracted from the data of Ref. 10.

In order to seek possible resonance behavior of the singlet s waves, it is useful to calculate ${}^1\delta_0$ from the data below 1 MeV, assuming the triplet s-wave phase shift, ${}^3\delta_0$, to be that from a hard sphere for various choices of radius a, and the p-wave phase shifts to be equal and small, diminishing quadratically below 1 MeV from the value $\delta_1=3.7°$ found by Tombrello *et al.*[11] at 1 MeV. D-wave and higher phase shifts are set equal to zero.[12]

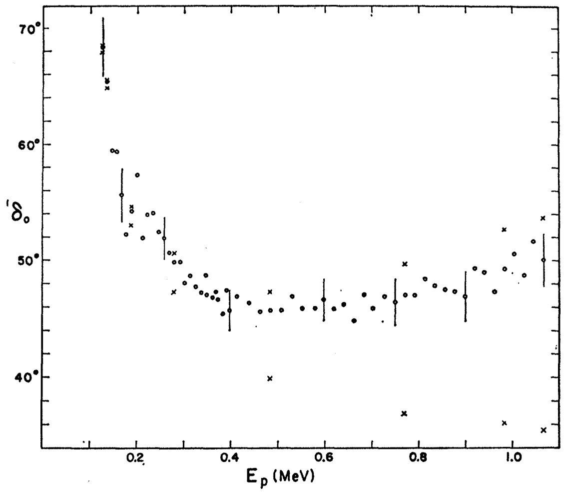

FIG. 5. The rejected solution for the phase shift ${}^1\delta_0$. The points were calculated using the radius $a=3.4$ F to determine the hard-sphere phase shift used for ${}^3\delta_0$ and the upper and lower crosses were found using $a=3.2$ F and $a=4.0$ F, respectively. Typical error bars are shown for ±3% errors in the data of Fig. 4.

Again, the scattering from neon is assumed to be that from a hard charged sphere of radius 5.2 F.

With these assumptions, two solutions for ${}^1\delta_0$ are

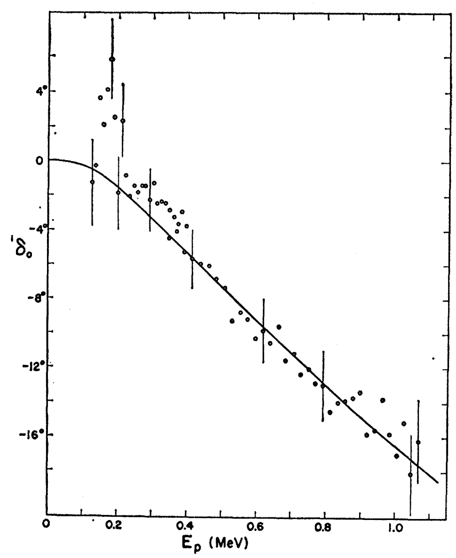

FIG. 6. The accepted solution for the phase shift ${}^1\delta_0$. The points were calculated for $a=3.4$ F, and the curve is the hard-sphere phase shift. Error bars are shown for ±3% errors in the data of Fig. 4.

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$$\sigma(\theta)=\tfrac{3}{4}|{}^3f(\theta)|^2+\tfrac{1}{4}|{}^1f(\theta)|^2.$$

With our assumptions for $\mathrm{He}^3(p,p)$ at $\theta_{\mathrm{lab}}=90°$, this becomes

$$\begin{aligned}\sigma/\sigma_R=&1+0.543E^{5/2}\cos(2\zeta-\xi)\\&+\tfrac{3}{4}\{17.89E\sin^2({}^3\delta_0)-8.46E^{1/2}\sin({}^3\delta_0)\cos({}^3\delta_0-\xi)\\&-1.15E^3\sin2({}^3\delta_0-\zeta)\}-1.15E^3\sin2\zeta+\tfrac{1}{4}\{17.89E\sin^2({}^1\delta_0)\\&-8.46E^{1/2}\sin({}^1\delta_0)\cos({}^1\delta_0-\xi)-1.15E^3\sin2({}^1\delta_0-\zeta)\}.\end{aligned}$$

Here, E is the proton energy in MeV, $\zeta=\tan^{-1}\alpha=\tan^{-1}(0.316E^{-1/2})$, and $\xi=-\alpha\ln[\sin^2(\tfrac{1}{2}\theta_{\mathrm{c.m.}})]=0.1278E^{-1/2}$. The hard-sphere phase shift used for ${}^3\delta_0$ is defined in Ref. 13.

found, and are shown in Figs. 5 and 6. The first of these must be rejected because it has unphysical properties, as may be seen by plotting the corresponding R function versus bombarding energy from the expression

$$R_{0^+}=\frac{\tan({}^1\delta_0+\phi)}{P+S\tan({}^1\delta_0+\phi)}.$$

Here, in the notation of Lane and Thomas,[13] P is the penetration function, S is the shift function, and $-\phi$ is the hard-sphere phase shift. Using the first solution for the phase shift leads to an R function with negative slope (which is inadmissible for physical R functions) over the entire range considered.

The second solution (Fig. 6) is indistinguishable from that of a hard sphere of radius 3.4 F. Noticeably poorer fits were obtained for $a=3.3$ F and $a=3.5$ F, with the extracted phase shifts for the smaller radius tending to be more negative than the corresponding hard-sphere values. The data were taken in two different overlapping runs (for $E_p\leq 396$ keV and $E_p\geq 346$ keV), which are subject to a systematic difference due to errors ($<3\%$) in the relative partial pressures of helium and neon. The tendency of the data below $E_p=400$ keV to lie above the curve may be due to such a pressure error; if these data are considered alone, a better fit is achieved for $a=3.2$ F.

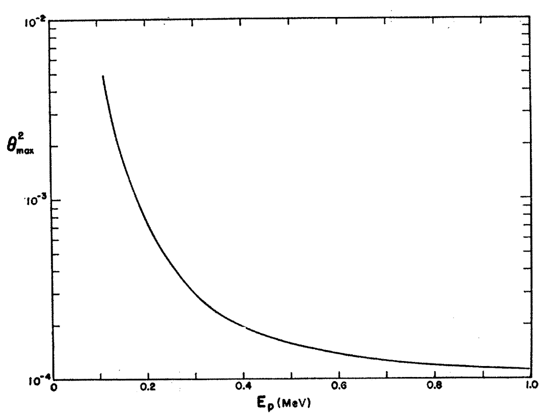

FIG. 7. Experimental upper limit for the reduced width $\theta^2\equiv\gamma^2/(3\hbar^2/2Ma^2)$ for a 0^+ resonant level in the He^3+p system as a function of proton energy.

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The solution of Fig. 6 is consistent with the recent analysis by Tombrello[4] of all available data for $E_p\geq 1$ MeV, while our rejected solution is not. He also found two solutions, one of which was rejected only because it was inconsistent with the results presented here.

DISCUSSION

The presence of a $J^\pi=0^+$ resonance with a width comparable to or greater than our experimental resolution ($\sim$16 keV) would appear in Fig. 4 as a somewhat asymmetric anomaly, falling to a value about three-fourths, and then rising to about twice the observed cross section. From the fact that such an effect is *not* present with more than 5% of the observed cross section, an upper limit has been calculated[14] for the reduced width as a function of proton energy, with results as shown in Fig. 7. Even at the lowest energy, the result is more than two orders of magnitude less than the values proposed by Werntz and Brennan, and we conclude therefore that a state analogous to the 20-MeV state in He^4 does not exist in the He^3+p system with a mass greater than H^1+He^3+93 keV. The He^4 state has been studied by a number of groups[15] and excitation energies are given ranging from 19.94 ± 0.02 MeV to 20.3 ± 0.1 MeV. For our purposes, probably the most pertinent number to cite is the excitation, 20.2 MeV, at which the nuclear part of the H^1+H^3 phase shift passes through 90°.[16] In any case, the expected location for the analog of this state in the H^1+He^3 system for any excitation in the range of quoted values is included in the energy region covered by the present experiment, and we conclude that the 20-MeV state in He^4 has isospin $T=0$.

ACKNOWLEDGMENTS

We have enjoyed stimulating discussions with J. N. Bahcall, R. F. Christy, W. E. Meyerhof, and T. A. Tombrello.

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