Table I. Mean intensity values of ^{216}Po recoil ions, normalized to charge +1, for two different pressures.

^{216}Po charge	Pressure in source volume (mm Hg) 10^{-5}	1.5×10^{-4}
−2	Not measurable (<0.03)	...
−1	0.70 ± 0.014	0.69 ± 0.020
0	28[a]	...
+1	1	1.03 ± 0.030
+2	0.69 ± 0.012	0.69 ± 0.040
+3	0.56 ± 0.015	0.62 ± 0.040
+4	0.50 ± 0.017	0.49 ± 0.030
+5	0.29 ± 0.012	0.29 ± 0.030
+6	0.21 ± 0.011	0.19 ± 0.030
+7	0.12 ± 0.010	0.10 ± 0.020
+8	0.053 ± 0.010	0.048 ± 0.015
+9	0.040 ± 0.010	0.039 ± 0.015
+10	not measured	...

[a]Estimated value reliable within a factor of 2 based on the transmission power of the charge analyzer.

counting, hence the detection efficiency depends only on the over-all gain of the circuitry. This dependence on gain was checked by measuring the coincidence counting rates versus multiplier voltage for charges from −1 to +4 [Fig. 2(c)]. Each curve reaches the plateau region at about 3 kV. Normal operating point was 3.5 kV.

In two months, the reproducibility of the relative-intensity measurements was about 5%. We set this value as maximum error in the reliability of the results. The mean intensity values of the ^{216}Po recoil ions normalized to charge +1 are given in the first column of Table I; the second column lists the spectrum obtained at a much higher pressure in the source volume. The good agreement between these spectra shows the results to be free of distortion due to charge-exchange collisions in the gas traversed by the ions.

Uncertainties quoted are standard errors on counting (typical true/random counting rate for charge +1 was about 2000/400 counts per hour).

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NONEXISTENCE OF THE TETRANEUTRON*

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We present in this note the results of an investigation concerned with the question of whether there exists a particle-stable state for the tetraneutron. At the present moment, there seems to be evidence both for and against the existence of such a state.[1-4]

The recent experiment of Ajdačić et al.[2] with the reaction $H^3(n,p)3n$ indicates that there is a bound state for the trineutron n^3, with a binding energy of about 1 MeV. Using the argument of Goldanskii[5] about the neutron pairing energy, this would imply that the tetraneutron n^4 would certainly exist. The fact that He^8 is particle-stable[6] with a mass excess between[7] 31.6 and 32.4 MeV implies that the maximum possible binding energy of n^4 is 3.1 MeV. If it were greater, then He^8 would decay into $\alpha + n^4$. Thus the maximum neutron pairing energy of a particle-stable n^4 is around 1 MeV, which seems rather low compared with the values of pairing energies for other light nuclei.[5]

On the other hand, there is seemingly stronger evidence against the existence of a bound tetraneutron. The search by Davis et al.[3] with the reaction $He^4(\pi^-,\pi^+)n^4$ turned up no evidence for the existence of either a bound or a resonant state for the n^4 system. Also, an attempt by Schiffer and Vandenbosch[4] to observe the tetraneutron as a fission product yielded a negative result.

In this investigation, we attempt to resolve the controversy by making a variational calculation on the energy of the n^4 system. A trial wave function with $S=0$ and $L=0$ will be chosen to describe the relative oscillation of two dineutron clusters. It has the form

$$\begin{aligned}\Psi &= A[\varphi_0(12;34)\alpha_1\beta_2\alpha_3\beta_4]\\ &= A[f_1(r_{12})f_1(r_{34})f_2(r_{13})f_2(r_{14})\\ &\quad\times f_2(r_{23})f_2(r_{24})\alpha_1\beta_2\alpha_3\beta_4],\end{aligned} \tag{1}$$

where A is the antisymmetrization operator and α,β denote the spin wave functions of the nucleon. The spatial functions f_1 and f_2 will be given in a later paragraph.

The neutron-neutron potential used here is, in singlet-even states,

$$\begin{aligned}V_S(r) &= \infty && (r<r_c),\\ &= -V_{0S}\exp[-\kappa_S(r-r_c)] && (r>r_c),\end{aligned} \tag{2}$$

with $V_{0S}=216.0$ MeV, $\kappa_S=1.97$ F^{-1}, and $r_c=0.35$ F.[8] This potential, augmented by the Coulomb interaction, gives a good fit to the p-p $^1S_0$ phase shift up to an energy of about 300 MeV in the laboratory system. We take the triplet-odd potential to be zero except for a hard core of radius r_c.

The potential described above, together with a suitably chosen potential in the triplet-even states, has been used in the investigation of the properties of the light nuclei H^3, He^3, He^4,[9] and Li^6.[10] In all these cases, we have found that good agreement with the experimentally determined values of the binding energies and rms radii can be obtained.

For the functions $f_i(r)$ with $i=1,2$, we use the form

$$\begin{aligned}f_i(r) &= u_i(r)/r && (r<d_i),\\ &= A_i r^{n_i}[\exp(-a_i r)+B_i\exp(-b_i r)] && (r>d_i),\end{aligned} \tag{3}$$

where $u_i(r)$ is a solution of the equation

$$-\frac{\hbar^2}{m}\frac{d^2}{dr^2}u_i(r)+[c_iV_S(r)-e_i]u_i(r)=0. \tag{4}$$

The constants A_i, B_i, and b_i are adjusted such that the functions $f_i(r)$ and their first and second derivatives are continuous at the separation distance d_i. There are a total of eight variational parameters in this trial function, namely, a_1, c_1, d_1, e_1, a_2, c_2, d_2, and e_2. The parameters n_1 and n_2 are not varied in this calculation; they are taken as -1 and $-\frac{1}{4}$, being so chosen as to give the correct asymptotic behavior when the two dineutron clusters are far apart.

The expectation value of the four-body Hamiltonian is calculated by a Monte-Carlo method. As this method has been thoroughly discussed previously,[8,11] we shall not further describe it here.

Our search procedure in the parameter space is as follows. Let us, for simplicity, call G the group of parameters a_1, c_1, d_1, e_1, c_2, d_2, and e_2. The procedure is then to assign different values to G and vary a_2. This might seem at first to be a tedious procedure, but is not actually so, since we have learned from our past experience with this type of trial function that it is not necessary to use an equally fine grid for all the parameters in G. For example, if e_1 is carefully varied, then c_1 need be only crudely scanned.

In Fig. 1, the solid curve shows typical behavior of the energy of the n^4 system (E) as a function of the rms radius (R). This curve is obtained when the parameter a_2 is varied from 0.025 to 0.17 F^{-1}, while the parameters in G are given the following values: $a_1=0.15$ F^{-1}, $c_1=1.0$, $d_1=1.25$ F, $e_1=0$, $c_2=0.8$, $d_2=1.25$ F, and $e_2=0$. It is seen that the energy goes down monotonically as the rms radius increases. This indicates that the two clusters want to fly apart and, consequently, there is no bound state for the tetraneutron. Also, we note that there is no relative minimum in this curve, which means that n^4 cannot even form a resonant state.

Some proposed nucleon-nucleon potentials, that of Gammel and Thaler,[12] for instance, have a weakly attractive component in the triplet-odd states. To see if such attraction might affect our conclusion, we have also calculated with a triplet-odd potential which is the same as our singlet-even potential. The result for E is plotted as the dashed curve in Fig. 1, where the parameters in G are the same as those given in the preceding paragraph. By comparing these two curves we see that, even for an

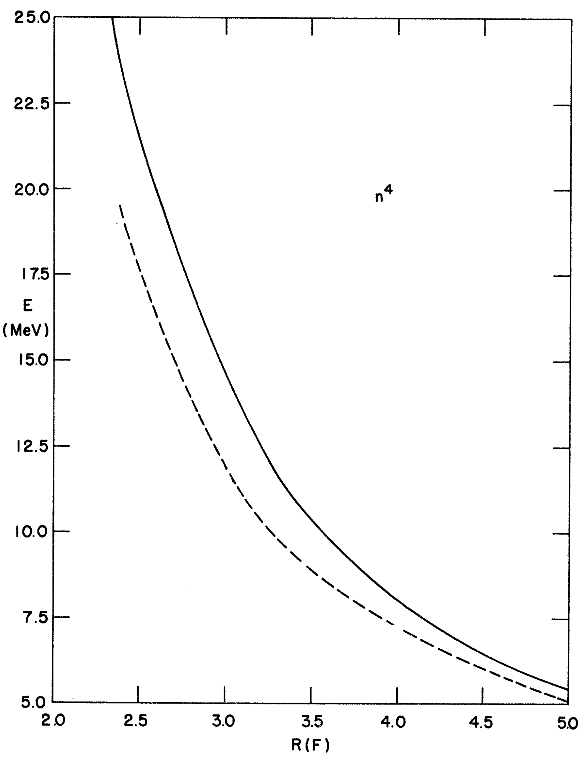

FIG. 1. Typical variation of the energy of the n^4 system as a function of the rms radius. The parameter a_2 is varied between 0.025 and 0.17 F^{-1}, while the other parameters have the values $a_1=0.15$ F^{-1}, $c_1=1.0$, $d_1=1.25$ F, $e_1=0$, $c_2=0.8$, $d_2=1.25$ F, and $e_2=0$.

interaction which is strongly attractive in the triplet-odd states, the shape of the curve is hardly affected. This is, of course, physically reasonable, since for a rather extended n^4 system the kinetic energies of the neutrons are small enough such that only interaction in even states plays a major role.

Also, we have examined this problem with a singlet-even potential with the shape given by Eq. (2), but with $r_c=0.45$ F, $V_{os}=230.5$ MeV, and $\kappa_s=2.033$ F^{-1}.[13] Here again, we find that there is neither a bound nor a resonant n^4 system.

It is perhaps appropriate to mention here that we believe rather firmly that our trial wave function would have enough flexibility to describe properly the n^4 system if it formed a bound or a resonant state. This type of trial function has been examined quite critically in the triton and alpha-particle problems.[9] By computing both the upper and the lower bounds to the eigenvalue, it has been found that the upper bound yielded by this type of trial function is always rather close to the eigenvalue.

By a crude estimate, we have found from our calculation that for n^4 to have a resonant state, the interaction strength in the singlet-even states would have to be approximately 30% stronger. From this, we speculate that the system n^6 is also unbound, since it seems rather unlikely that the extra attraction provided by two additional neutrons could make up for the lack of strength of the singlet-even potential. Thus, together with the conclusion reached by Brueckner, Gammel, and Tubis[14] and Levinger and Simmons[15] that the neutron gas is also not bound, we venture to say that systems containing only neutrons do not form bound states. For a system to be bound, there must be the presence of other strongly interacting particles, such as the protons, the Λ particles, etc.

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IMPORTANCE OF THE IMAGINARY TERM IN DISTORTED-WAVE BORN-APPROXIMATION CALCULATIONS OF ^{3}He INELASTIC SCATTERING*

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The collective-model and distorted-wave Born-approximation (DWBA) description of the inelastic scattering of nucleons[1] and alpha particles[2] has proven quite successful. In this theory the amplitude for excitation of low-lying collective states takes the form

$$T_{if}=\beta_l\int d\vec{r}\chi_f^{(-)*}(\vec{k}_f,\vec{r}_f)\{i^l Y_l^m(\theta',\varphi')\times\left[R_r\frac{dV(r)}{dr}+iR_w\frac{dW(r)}{dr}\right]\chi_i^{(+)}(\vec{k}_i,\vec{r}_i)\Big\},\qquad(1)$$

where the χ's are the distorted waves generated from the optical potential U used to fit the scattering data. Here

$$U(r)=-[V(r)+iW(r)]=-V_0f(x)-iW_0f(x');$$
$$f(x)=(1+e^x)^{-1};$$
$$x=(r-R_0)/a;$$
$$x'=(r-R_w)/a_w;\qquad(2)$$

and β_l is the usual deformation parameter. In this analysis β_l is the only free parameter, since the optical potential is determined from the elastic scattering and is taken to be the same in both channels.

Equation (1) implies, as usual, that the density distribution is aspherical, and furthermore that the imaginary interaction follows the motion of the nucleus as well as the real interaction. Formally, the imaginary part of the form factor arises in the same manner as the imaginary part of the spherical optical potential.

Most previous analyses of inelastic scattering have made use of the real part of the form factor. Recently the complex form has been applied to inelastic alpha-particle scattering[3] and found to produce somewhat better agreement with the data, but with a small correction to β_l. Similar analyses of nucleon inelastic scattering[4] show a definite improvement over calculations using the real form factor. Here the corrections to β_l are of the order of 10 to 20% for 40-MeV protons. The present Letter presents evidence that the complex form factor in Eq. (1) is necessary to describe the inelastic scattering of ^{3}He ions; indeed, almost all of the cross section arises from the imaginary term.

The experimental data were obtained by scattering 22-MeV ^{3}He ions obtained from the Los Alamos variable-energy cyclotron from thin-foil targets of ^{56,58}Fe and ^{58}Ni. The elastic- and inelastic-scattered particles were detected by means of an $E\times dE/dx$ solid-state counter telescope and displayed on a 400-channel analyzer suitably gated by the multiplier so that only ^{3}He particles were accepted. The angular range of the elastic measurements was from 9° to 150°. The small-angle elastic data were found to be Rutherford, and this allowed normalization of the elastic and inelastic data to obtain accurate absolute cross sections. Only the 2^+ and the 3^- single-phonon states of the three targets were analyzed, these being the most prominent levels found. Analysis of the inelastic states was limited at forward angles because of a low-energy component from the elastic peak due to scattering of the incident beam from collimating slits and the analyzing magnet located in front of the 20-in. scattering chamber.

The elastic data were fitted using the optical-