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Study of the Reaction ^{20}Ne($h,h_{0,1,2}$)^{20}Ne at 17.83 MeV*

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Angular distributions for the scattering of helions to the 0^+, 2^+, and 4^+ members of the ground-state rotational band of ^{20}Ne were measured at 17.83 MeV. An optical-model analysis of the elastic scattering was performed as well as a coupled-channels analysis of the inelastic data. Good agreement between the coupled-channels calculations and the experimental data was found for the 2^+ data, with β_2 in the range 0.42 to 0.48. These calculations gave a poor description of the 4^+ data, but from the shape of the angular distributions an upper limit of 0.05 for β_4 was assigned.

I. INTRODUCTION

Determination of both the quadrupole and hexadecapole deformation of rare-earth nuclei by the scattering of 50-MeV α particles has been demonstrated by Hendrie *et al.*[1] In the 2s-1d shell, α-scattering studies from the 0^+, 2^+, and 4^+ members of the ground-state rotational band of ^{24}Mg[2] and ^{20}Ne[3] at bombarding energies in the range 15–22 MeV have been successful in determining the quadrupole deformation of these nuclei. In the case of ^{20}Ne, Frickey, Eberhard, and Davis (FED)[3] extracted a hexadecapole deformation of $\beta_4 = 0.0$, in contrast with the value $\beta_4 = 0.28$ obtained by de Swiniarski *et al.*[4] from an analysis of proton scattering at 24.5 MeV on ^{20}Ne. However, because of the large compound contribution present in the α-particle scattering analysis some ambiguity in the extracted hexadecapole deformation does exist.

Since compound-nucleus contributions to helion (^{3}He) scattering are lower than for α-particle scattering, the scattering of helions from the 0^+, 2^+ (1.63 MeV), and 4^+ (4.25 MeV) members of the ground-state rotational band of ^{20}Ne has been measured at a bombarding energy of 17.83 MeV to determine the sensitivity of helion scattering to the presence of the hexadecapole deformation of ^{20}Ne. A coupled-channels analysis of the data was performed to extract the quadrupole and hexadecapole deformation of ^{20}Ne. In addition, the data of Artemov, Gol'dberg, and Rudakov (AGR),[5] who studied the same reaction at a bombarding energy of 35 MeV, was analyzed in terms of coupled channels to check the conclusions reached from the analysis of the 18-MeV data.

II. EXPERIMENTAL METHOD

An 18-MeV h^{++} beam obtained from the Florida State University model EN tandem Van de Graaff was used to bombard a gas cell mounted in a precision scattering chamber[6] containing ^{20}Ne enriched to 99.2%. The cell had an 0.5-μm Ni entrance foil. The 330-μm Si surface-barrier detector was positioned inside the gas cell to eliminate any energy loss or energy spreading effects from an exit foil. The energy loss by the beam in passing through the entrance foil and ^{20}Ne gas before reaching the target volume was 170 keV, making the effective bombarding energy 17.83 MeV. Energy spectra of helions and α particles were recorded in 2.5° intervals from 12.5 to 90°. The study of the reaction ^{20}Ne(h,α)^{19}Ne will be reported in a future publication[7] and only the helion data will be presented here. The yields were determined by fitting the peaks in the spectra to a Gaussian distribution. The details of this procedure along with the physical details of the gas cell have been discussed by Kemper, Haynes, and Fletcher.[8] It was possible to extract the elastic data over the whole angular range permitted by the gas cell, but the inelastic groups could only be extracted between 22.5 and 75° because of overlapping α-particle groups. The statistical errors were ~2–3% for the 0^+ and 2^+ data and 7% for the 4^+ data. The larger error for the 4^+ data arose from uncertainties in the background subtraction necessary in the lower-energy portion of the spectra. The absolute error in the cross sections, arising principally from uncertainties in the detector geometry, was estimated to be ~3–4%.

III. ANALYSIS AND RESULTS

Because of the large deformation of ^{20}Ne,[9] the inelastic scattering data must be analyzed in terms of coupled channels. To obtain beginning parameters for the coupled-channels calculations the elastic scattering data were analyzed in terms of a spherical optical potential with the code OPTIX1.[10] The form of the optical potential used is given by Eq. (1) of Tamura.[11] Several acceptable sets of potentials were found; however, the poten-

TABLE I. Optical-model potential parameters for helion scattering from ^{20}Ne.

Set	V (MeV)	W (MeV)	V_{so} (MeV)	$r_V = r_{so}$ (fm)	r_I (fm)	r_C (fm)	$a_V = a_{so}$ (fm)	a_I (fm)
A	186	18		1.07	1.60	1.40	0.72	1.04
B	130	28.5	10	1.31	1.43	1.40	0.71	1.01
C	230	18		1.07	1.40	1.40	0.72	1.04
D	190	18		1.03	1.60	1.40	0.68	0.88
E	210	18		1.03	1.60	1.40	0.68	0.88

tial Set A in Table I which corresponds most closely to the parameter set reported by Zurmühle and Fou,[12] who studied ^{20}Ne(h, h_0)^{20}Ne at 15 MeV, was chosen for the coupled-channels analysis. An alternative potential set suggested by Garrett, Middleton, and Fortune[13] in their analysis of the reaction ^{20}Ne(h, α)^{19}Ne was used as starting values for another parameter search and the final values are given by Set B in Table I. The results of the optical-model calculations along with the elastic scattering data are shown in Fig. 1. The calculations were insensitive to the presence of the spin-orbit potential of Set B.

The elastic and inelastic data were analyzed by use of Tamura's coupled-channel code JUPITOR.[11, 14] The target nucleus was assumed to be axially symmetric, and the Legendre expansion of the potential was used. Complex form factors were used in the calculation, and the adiabatic approximation was not made. Because of the long computation times involved only the parameters V, W, r_I, a_I, β_2, and β_4 were varied. When parameter Set A was used in the coupled-channels calculation with no parameter variations, the diffraction maximum found at 80° in the 0^+ data was not reproduced and the calculation of the inelastic scattering to the 2^+ state was out of phase with the data by about 10° in

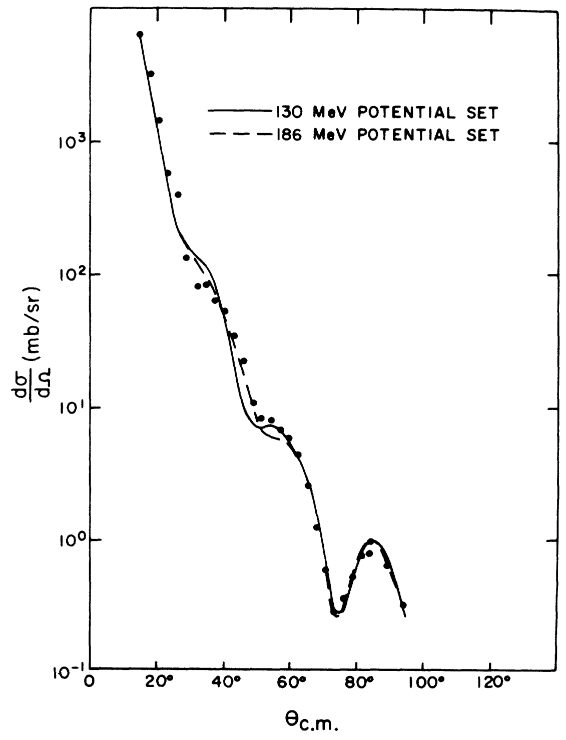

FIG. 1. Experimental data and optical-model calculations for ^{20}Ne(h,h_0) at 17.83 MeV. The two sets of potential parameters are given in Table I.

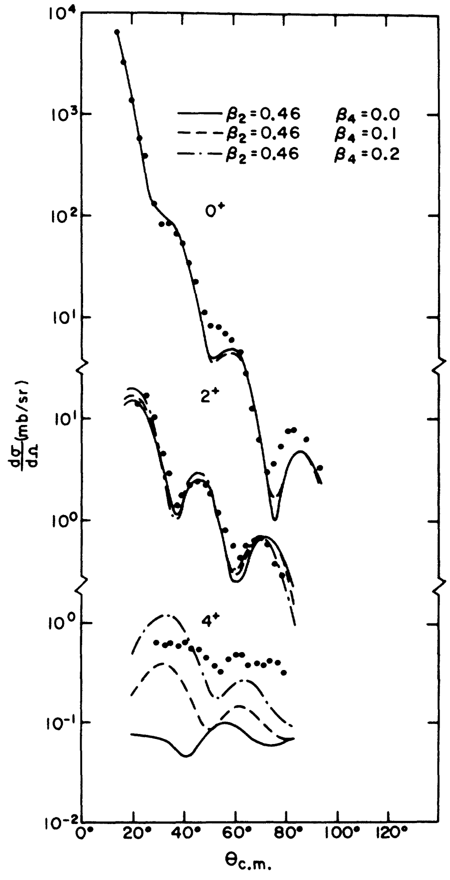

FIG. 2. Results of the coupled-channels calculations carried out with potential parameter set C of Table I and the experimental data for ^{20}Ne(h,$h_{0,1,2}$) at 17.83 MeV. The 0^+ calculations with $\beta_4 = 0.2$ are quite close to those with $\beta_4 = 0.1$ and are not shown.

the region of $\theta_{c.m.} = 45°$. To reproduce the diffraction maximum in the 0^+ cross section the real well depth was increased to 210 MeV. To move the phasing out to larger angles for the 2^+ cross section the reduced imaginary radius was decreased to 1.4 fm. The parameters were then varied again to give the best fit to both the 0^+ and 2^+ data. Throughout these calculations, it was necessary to include the coupling to the 4^+ state, as the calculation for the 0^+ state in the region of 80° was very sensitive to its presence. The final value for the optical potential is Set C in Table I, and the results of the calculations are shown in Fig. 2. While the exact value of the deformation parameter, β_2, depends on the particular choice of the imaginary well parameters, its value must be in the range 0.42 to 0.48 if the peak-to-valley ratio of the computed 2^+ cross section is to agree with the observed ratio. This range of values is consistent with the results found by de Swiniarski *et al.*[4] and FED.[3]

The calculations for the 4^+ cross section are also shown in Fig. 2 for different sets of deformation parameters. The general shapes of the 4^+ cross sections were not affected by variations in the potential parameters within 10% of the values given by Set C in Table I. The inclusion of a 10-MeV spin-orbit potential gave better agreement for the 0^+ state but did not improve the 4^+ state. Inclusion of Coulomb excitation had no effect on the calculated 2^+ and 4^+ cross sections. To obtain the order of magnitude of the 4^+ cross section a value for β_4 of 0.2 is necessary. However, the presence of a hexadecapole deformation in the calculation introduces structure which is not present in the experimental data. The calculations

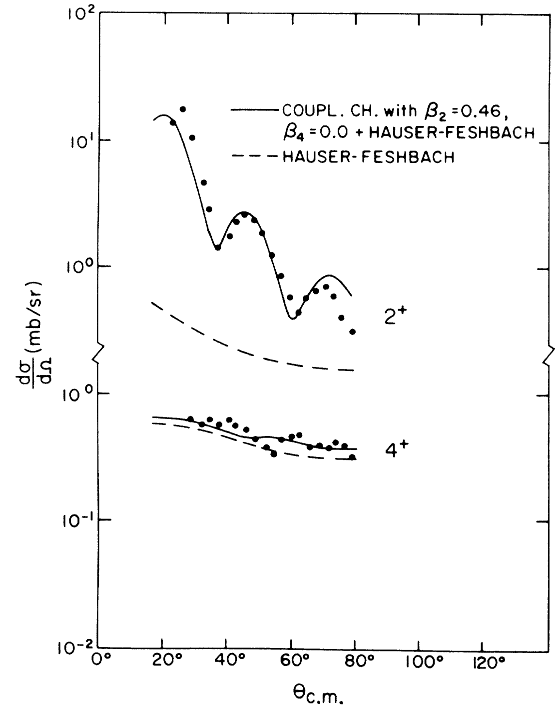

FIG. 3. Results of the coupled-channels calculations with the inclusion of a Hauser-Feshbach-type estimate of the compound contribution for ^{20}Ne$(h, h_{1,2})$ at 17.83 MeV.

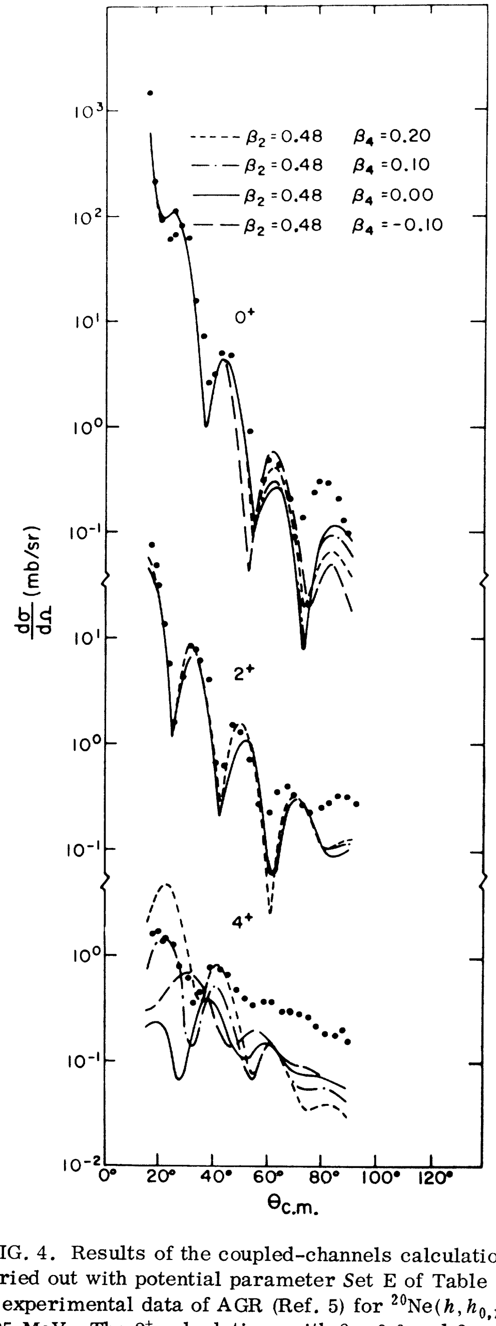

FIG. 4. Results of the coupled-channels calculations carried out with potential parameter Set E of Table I and the experimental data of AGR (Ref. 5) for ^{20}Ne$(h, h_{0,1,2})$ at 35 MeV. The 2^+ calculations with $\beta_4 = 0.0$ and $\beta_4 = -0.10$ are similar to those with $\beta_4 = 0.10$ and are not shown.

with $\beta_4 = 0.0$ have a shape which corresponds most nearly to the structureless features of the data but the magnitude of the cross section is too low by a factor of 10. One possible explanation for this difference is that the 4^+ state is excited by a combination of compound and direct processes instead of the purely direct mechanism assumed in the calculations. To estimate the effects of the compound process on the elastic and inelastic scattering the Hauser-Feshbach (HF) type expression (19) given by Eberhard *et al.*[15] was evaluated for all three states. Details of the method of calculation have been given by Eberhard and Robson.[2] The necessary transmission coefficients were generated with the optical-model code OPTIX1, and the spin-cutoff parameter σ and level-density parameter $\rho(E)$ were obtained by extrapolating the parameters reported for lower excitations[16,17] assuming the Fermi-gas model. Variations in these parameters were made until the difference between the coupled-channels 4^+ cross section and the observed cross section was attained. The final values of the parameters were $\sigma = 4$ and $\rho(E) = 750$, and the resulting HF cross sections are shown in Fig. 3. The result of adding the HF cross section incoherently to the coupled-channel calculation with $\beta_2 =$ $= 0.46$ and $\beta_4 = 0.0$ for the 2^+ and 4^+ states is also shown in Fig. 3. For the 0^+ case the compound cross section was negligible and is not shown. These calculations are able to give a much better description of the 4^+ data than the calculations done for $\beta_2 = 0.46$ and $\beta_4 = 0.20$ although it too gives the proper magnitude for the 4^+ cross section. On the basis of the shape of the angular distribution an upper limit of $\beta_4 = 0.05$ is indicated by the helion scattering, while the value obtained from proton scattering[4] is $\beta_4 = 0.28$. To insure that the difference between the proton result and the helion result is not due to differences in the coupled-channels codes, the calculations of de Swiniarski *et al.*[4] were repeated and the results showed excellent agreement for the two codes.

To better understand the 4^+ results, coupled-channels calculations were performed for the experimental data of AGR,[5] who measured helion scattering from the 0^+, 2^+, and 4^+ members of the ground-state rotational band at a bombarding energy of 35 MeV. Using the Fermi-gas model to extrapolate the HF parameters found in the 18-MeV analysis, the compound cross section is found to be negligible at this energy. Optical-model parameters for the 35-MeV elastic scattering data were obtained by variation of all the parameters of Set A, Table I as starting values. The final values for the parameters are given by Set D in Table I. In the coupled-channels calculation, the results of which are shown in Fig. 4, the parameters of Set D, Table I, were modified slightly to produce a maximum near 80° in the elastic scattering. These final parameters are listed as Set E, Table I. The quadrupole-deformation parameter was increased to 0.48, since this value gave the best fit to the 2^+ cross section.

The discrepancy between the measured cross section for the 4^+ state and that calculated by the coupled-channels formalism still persists at E_h $= 35$ MeV. The shape of the cross section could be reproduced by use of $\beta_4 \sim 0.05$, but the calculated cross section would be low by a factor of 3. Whereas a compound-nucleus contribution, when added incoherently to the coupled-channels cross section, can explain the excitation of the 4^+ state with $\beta_4 = 0.0$ at $E_h = 18$ MeV, no such contribution appears likely to explain the result at $E_h = 35$ MeV. The final result of the analysis is to give an adequate description of helion scattering leading to the 0^+ and 2^+ states of ^{20}Ne and to yield deformation parameters of $\beta_2 = 0.46$ and $\beta_4 \lesssim 0.05$. It is apparent, however, that additional reaction mechanisms or a coherent sum of reaction contributions will be required to satisfactorily describe the 4^+ cross section. The actual value of β_4 for ^{20}Ne is then left in question.

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Level Structure of ^{42}Ca by ^{41}K(^{3}He, d)^{42}Ca and ^{39}K(α, p)^{42}Ca Reactions at 10 MeV

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The level structure of ^{42}Ca, below 6 MeV in excitation, has been studied by ^{41}K(^{3}He,d)^{42}Ca and ^{39}K(α,p)^{42}Ca reactions at 10-MeV bombarding energy. Particles detection was achieved with a surface-barrier detector telescope. Comparison of 12 measured (^{3}He,d) angular distributions with zero-range distorted-wave Born-approximation calculations indicated a predominance of $l = 3$ and $l = 1$ transfers, and gave information about states arising from the $(1f_{7/2}1d_{3/2}{}^{-1})$ and $(2p_{3/2}1d_{3/2}{}^{-1})$ configurations. Shell-model calculations have been performed to investigate the level scheme in ^{42}Ca arising from the $(1f_{7/2}{}^3 1d_{3/2}{}^{-1})_{JT}$ configuration using four different sets of effective interaction parameters between the $1f_{7/2}$ particle and $1d_{3/2}$ hole. The resulting wave functions were used to calculate spectroscopic factors, which have been compared with the experimental ones. The measured (α,p) angular distributions analyzed with Hauser-Feshbach calculations indicated a predominance of compound-nucleus mechanism for this reaction. Good agreement has been found between the integrated experimental and theoretical cross section.

I. INTRODUCTION

Low-lying negative-parity states in ^{42}Ca may arise from excitation of an odd number of nucleons from the *sd* shell to the *fp* shell or from the excitation of a valence neutron, outside an inert ^{40}Ca core, to the *g* shell. However, since the *g* shell is well above the *fp* shell, the dominant and simplest configuration expected for the negative-parity states of ^{42}Ca is that of a $1d_{3/2}$ hole coupled to particles in the *fp* shell. In addition, there is experimental and theoretical evidence that core excited states play an important role also in the low-lying positive-parity states. In fact the ^{40}Ca(t, p)-^{42}Ca reaction of Bjerregaard *et al.*[1] has exhibited six $J^\pi = 0^+$ and seven $J^\pi = 2^+$ states below 7-MeV excitation energy, and Federman and Pittel[2] have shown that some of these 0^+ states can be understood in terms of 2p-0h and 4p-2h configurations. The complexity of ^{42}Ca spectrum suggested a further investigation of the nuclear structure of ^{42}Ca, paying attention to the negative-parity states described mainly by excited-core components. One way to determine experimentally such negative-parity states is to study the ^{42}Ca spectrum through the ^{41}K(^{3}He, d)^{42}Ca reaction. The ^{41}K nucleus in the simple shell-model picture is described in its ground state by the $(1f_{7/2}{}^2 1d_{3/2}{}^{-1})$ configuration. Thus, in (^{3}He, d) reaction we should expect to excite the 0^+ ground state of ^{42}Ca by a $1d_{3/2}$ proton transfer and then several negative-parity states by f-p proton transfer. The ^{39}K(α, p)^{42}Ca reaction in the direct-interaction region should provide complementary information about such negative-