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MONOPOLE EXCITATIONS IN ^4He , ^{12}C AND ^{24}Mg IN A COLLECTIVE MODEL DESCRIPTION

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Transition densities for monopole excitations have been derived from a simple collective model. Two different monopole modes are obtained, a surface vibration and a density mode which involves a change of the central nuclear density. The low lying monopole transition in ^{24}Mg is well described by a surface vibration. However, for the light systems ^4He and ^{12}C surface and density effects cannot be separated.

Shape transitions (without transfer of angular momentum) are directly related to compressional features of the nucleus. Apart from recent evidence for the compressional mode in heavy nuclei [1] this type of excitation has been studied experimentally only for light nuclear systems in electron [2,3] and hadron scattering [4–6]. The microscopic interpretation of these transitions is difficult because it depends sensitively on the amount of n -particle– n -hole configuration mixing in ground and excited 0^+ state (see ref. [4,5]). In the present letter we discuss a simple macroscopic model in which the experimental data are well described. Because of its large simplicity this model yields direct insight into the mechanism of these excitations.

A Taylor expansion of the nuclear density is used to derive collective monopole transition densities. This model is similar to that used by Satchler in a potential model approach [7]. The parameters x_i of the ground state density are treated as dynamical parameters, so the transition density $\Delta\rho(r)$ can be expressed by derivatives of the ground state density $\rho(r)$:

$$\Delta\rho(r) = \sum_{i=1}^n \delta x_i \frac{\partial \rho(r)}{\partial x_i} + \text{higher order terms (h.o.)} . \quad (1)$$

The orthogonality of initial and final state gives rise to the constraint $\int \Delta\rho(r) d\tau = 0$, this yields a relation between the different δx_i . Thus, eq. (1) represents a system of $(n-1)$ basis states representing $(n-1)$ different monopole excitation modes. The higher order terms of the form

$$\sum_{i,j} \delta x_i \delta x_j \frac{\partial \rho(r)}{\partial x_i \partial x_j} + \dots ,$$

are important for the large density changes in the light nuclei in question and give rise to anharmonic effects.

We discuss two different ground state shapes, a Gaussian $\rho(r) = \rho_0 \exp(-r^2/\gamma^2)$ and a Woods–Saxon density $\rho(r) = \rho_0(1 + \exp((r-R/a)))^{-1}$. For the Gaussian shape we obtain only one transition density

$$\Delta\rho(r) = \delta\rho_0 \frac{\partial \rho(r)}{\partial \rho_0} + \delta\gamma \frac{\partial \rho(r)}{\partial \gamma} + (\text{h.o.}) , \quad (2)$$

whereas the Woods–Saxon form gives rise to two different monopole modes with transition densities

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Table 1

Results in comparison with electron scattering data from ref. [1] and [2].

		$\delta\rho_0$	δa	$\langle r^2 \rangle$ (fm ²)	R_{TR} (fm)	Electron scattering	
						$\langle r^2 \rangle$ (fm ²)	R_{TR} (fm)
⁴ He	(1)	-0.31	—	1.1	3.35	1.10±0.16	3.0 ±1.0
	(2)	-0.38	—	1.1	3.06		
¹² C	(1)	-0.61	—	5.7	4.57	5.37±0.22	4.24±0.30
	(2)	-0.53	—	5.7	4.26		
²⁴ Mg		—	+0.09	+6.4	6.21	6.33±0.29	5.72±0.42
			-0.09	-6.4	5.96		

For ⁴He and ¹²C Gaussian ground state densities are used; (1) transition density eq. (2); (2) Tassie transition density.

$$\Delta\rho_1(r) = \delta\rho_0 \frac{\partial\rho(r)}{\partial\rho_0} + \delta R \frac{\partial\rho(r)}{\partial R} + (\text{h.o.}), \quad (3)$$

$$\Delta\rho_2(r) = \delta a \frac{\partial\rho(r)}{\partial a} + \delta R \frac{\partial\rho(r)}{\partial R} + (\text{h.o.}). \quad (4)$$

In the Woods—Saxon case, mode 1 represents a compressional (breathing) mode whereas mode 2 yields a diffuseness oscillation of the nuclear surface. The density mode implies a sizeable change of the central nuclear density and is estimated to be at rather high excitation energy [8]. The second mode involves a density change in the surface region only and thus corresponds to a low lying excitation.

This model has been applied to monopole excitations in ⁴He, ¹²C and ²⁴Mg. E0 matrix elements and transition radii ($R_{\text{TR}}^2 = \langle r^4 \rangle / \langle r^2 \rangle$) are calculated (up to second order) which are compared with electron scattering results in table 1. The transition radius is sensitive to the details of the transition density (see ref. [9]) and allows to distinguish between the two different modes discussed above for Woods—Saxon shapes. In addition α scattering differential cross sections have been calculated; a double folding procedure has been used in which the monopole transition densities are folded into an effective nucleon-nucleon interaction and the ground state density of the corresponding projectile or target nucleus, respectively. For the nucleon-nucleon interaction a Gaussian shape with a range of 1.6 fm was used which yields a volume integral of 446 MeV fm³. This force has successfully been used in the microscopic analysis of ³He and α scattering (see ref. [4,5]). The optical

potentials of ³He and α scattering (see ref. [4,5]). The optical potentials for the calculation of scattering amplitudes were used as follows: $\alpha + ^{24}\text{Mg}$, 40 MeV: $V = 182.7$ MeV, $W = 26.6$ MeV, $r = 1.44$ fm, $a = 0.563$ fm; $\alpha + ^{12}\text{C}$, 40 MeV: $V = 145$ MeV, $r_0 = 1.59$ fm, $a = 0.55$ fm, $W = 29.5$ MeV, $r_W = 1.18$ fm, $a_W = 0.5$ fm; 65 MeV: $V = 186.1$ MeV, $r_0 = 1.36$ fm, $a = 0.60$ fm, $W = 53.8$ MeV, $r_W = 1.20$ fm, $a_W = 0.71$ fm. These optical potentials were found to give a good fit to the corresponding elastic scattering data. The results are compared with recent experimental data from Berkeley [6] and Michigan State [10].

First, transition densities are discussed for ²⁴Mg, they are shown in fig. 1. Large differences are found for compressional and surface mode which lead to quite different transition radii. In the lower part of fig. 1 mixtures of the two modes are assumed (which correspond to the general form of the transition density in eq. (1)) and $\delta\rho_0$ versus δa is plotted. The curves represent contours of constant E0 matrix element of ± 6.4 fm. The transition radius (given for several densities) is quite sensitive to the mixing of the two modes. The experimental transition radius of 5.7 ± 0.4 fm is in good agreement with that of a pure diffuseness vibration and also a good description of the α -scattering data in fig. 2 is obtained. Thus, the admixture of the compressional mode may be small in the 6.43 MeV state in ²⁴Mg, a conclusion which similarly has been obtained from a microscopic study of sd and $f_{7/2}$ shell nuclei [9].

This diffuseness oscillation mode may be related to effects of nuclear deformations. In this picture the

Fig. 1. Upper part: transition densities for compressional (dotted line) and surface mode (solid line) for ²⁴Mg. Lower part: $\delta\rho_0$ versus δa plot for ²⁴Mg. The solid lines correspond to monopole densities yielding a $\langle r^2 \rangle$ matrix element of ± 6.4 fm² and a transition radius as given.

change in diffuseness δa is directly related to changes in the deformation between ground and excited state. For the presently studied case of ²⁴Mg simple quadrupole deformations ($R = R_0(1 + \beta_2 Y_2)$) have been assumed. Then the diffuseness change δa of ± 0.09 corresponds to a change in the deformation parameter $\delta\beta_2$ of ± 0.28 . This is the same order as the ground state deformation parameter β_2 of about 0.3 [11].

Quite different results have been obtained for the lighter systems ⁴He and ¹²C. Here, the monopole transitions are described by shape transitions with

Fig. 2. Experimental and calculated angular distributions for α scattering from ¹²C and ²⁴Mg exciting the lowest 0^+ states in ⁴He, ¹²C and ²⁴Mg. The experimental data are from refs. [6] and [10].

positive sign for the E0 matrix element only. If the ground state density is assumed to be of Gaussian form, then in our simple model only one monopole excitation mode is obtained. In this mode surface effects and compression are mixed and the results are in good agreement with experiment (table 1). For ¹²C also a Woods-Saxon form has been used. However, the two transition densities obtained are not very different, e.g. is the transition

radius about equal ($\sim 4.5 \text{ fm}^2$) for both modes. This indicates that for the light systems surface and density effects cannot be separated as for heavier nuclei. Finally in table 1 a comparison is made with results using a Tassie density [12]

$$\Delta\rho(r) = 3\rho(r) + r \frac{\partial\rho(r)}{\partial r},$$

which also yields a good fit to the electron scattering data on ^4He and ^{12}C . The fits to the α scattering data are quite good except for the ^4He excitation. In this case only the absolute cross section is reproduced, the calculation fails to describe the detailed angular distribution. This may be due to difficulties in the optical model description of very light nuclear system, in particular of the α^* channel with high excitation energy of 20.1 MeV.

In conclusion a simple collective model of shape transitions has been applied to monopole excitations in light nuclei. In this model diffuseness as well as density effects are included which gives rise to a low energy surface mode and a high energy compressional mode. For very light nuclei the ground state shape changes from Woods–Saxon to Gaussian form this leading to only one monopole mode. With only one free parameter both electron and α scattering data are well described. The success of this simple model makes

a detailed comparison with microscopic models desirable, especially of the low energy surface mode. This has a rather different structure than in microscopic models in which it is described by the mixing of n -particle– n -hole configurations.

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