Excitation of the GDR and the Compressional Isoscalar Dipole State by $\alpha$ scattering

J.A. Christley$^a$, E.G. Lanza$^{b,e}$, S.M. Lenzi$^c$, M.A. Nagarajan$^d$, and A. Vitturi$^c$

\textit{a) Department of Physics, University of Surrey, Guildford, GU2 5XH, UK} \\
\textit{b) Dipartimento di Fisica and INFN, Catania, Italy} \\
\textit{c) Dipartimento di Fisica and INFN, Padova, Italy} \\
\textit{d) Department of Physics, UMIST, Manchester M60 1QD, UK} \\
\textit{e) Departamento de Física Atomica, Molecular y Nuclear, Sevilla, Spain}

Abstract

The excitation of the isovector giant dipole resonance (GDR) by alpha scattering is investigated as a method of probing the neutron excess in exotic nuclei. DWBA calculations are presented for $^{28}$O and $^{70}$Ca and the interplay of Coulomb and nuclear excitation is discussed. Since the magnitude of the Coulomb excitation amplitude is strongly influenced by the Q–value, the neutron excess plays an important role, as it tends to lower the energy of the GDR. The excitation of the compressional isoscalar dipole state in $^{70}$Ca by $\alpha$ scattering is also investigated. It is shown that the population of this latter state may be an even more sensitive probe of the neutron skin than the isovector GDR.

PACS numbers: 21.60.Jz, 24.30.Cz, 25.45.De

Keyword list: DWBA for $\alpha$ scattering on $^{28}$O, $^{70}$Ca, isoscalar and isovector dipole resonance.
During recent years, there has been considerable interest in the study of the structure of nuclei with large neutron excess [1]. Relativistic and non-relativistic self–consistent Hartree-Fock Bogoliubov approaches [2] to the structure predict that the neutron and proton densities in the neutron-rich nuclei have different shapes, with the neutron densities extending quite a bit further than the proton densities. It had been pointed out by Clement, Lane and Rook [3] as well as by Satchler [4] that the excitation of the isovector giant dipole resonance by isoscalar hadronic interaction becomes possible if the neutron and proton densities have different shapes. There have been experiments with $\alpha$ particle probes to test this idea [5] and theoretical interpretation of the excitation mechanism with a macroscopic model for the GDR has been given by various authors [6].

Isoscalar compressional dipole states (IDR) which are generated by the operator $\sum z_i r_i^2$ were first considered by Harakeh and Dieperink [7] and by Van Giai and Sagawa [8]. Recently, the effect of the neutron excess on the GDR transition density and the IDR transition density were studied within a Hartree-Fock plus RPA with Skyrme interaction [9,10]. In the case of the GDR, it was observed that the effect of neutron excess was to fragment the strength distribution together with a shift of the centroid to lower energy (cf. also [11]). In the case of the IDR, a strong concentration of the strength at low energy was predicted in nuclei with neutron excess.

In this note, we present the results of DWBA calculations of $\alpha$-inelastic scattering related to the excitation of the GDR and the IDR. We consider the very neutron rich nuclei $^{28}$O and $^{70}$Ca in order to assess the effect of the neutron excess on the cross sections. We also study the effect of the Q–value on the Coulomb and nuclear amplitudes.

We first consider the excitation of the GDR in $^{28}$O by scattering of alpha particles. The GDR is assumed to have an energy of $80 A^{-\frac{1}{3}} \approx 26$ MeV. The distorting potential for the DWBA calculation was taken to consist of real and imaginary Woods-Saxon form factors of depths $V_0=29$ MeV, $W_0 = V_0/2$ with the same radius and diffuseness parameters, $R_0= 5.05$ fm and $a_0 = 0.63$ fm [12]. The hadronic and Coulomb transition potentials were obtained by folding the RPA transition densities of Catara et al. [9] with the $\alpha$-nucleon and the Coulomb potentials, respectively. They are shown in figure 1. Figures 2 and 3 show the cross section and partial wave cross section for excitation of the GDR in $^{28}$O.

It is seen that in this case the low value of $Z$ combined with the very large excitation energy of the GDR strongly suppress the Coulomb excitation cross
section. The partial wave cross sections (left part of figure 3) show that the nuclear contribution is dominant for all partial waves. Still the smaller Coulomb contribution gives appreciable interference effects. As predicted in refs. [4,9], due to the fact that the isoscalar dipole transition density $\delta \rho_n + \delta \rho_p$ has different sign at small and large radii, while the isovector one $\delta \rho_n - \delta \rho_p$ has a definite sign, one finds a destructive Coulomb-nuclear interference for small partial waves and a constructive one for large partial waves. As a result, one cannot observe the constructive Coulomb-nuclear interference except at very small angles.

One should note, however, that for neutron-rich nuclei, the average excitation energy of the GDR is shifted to lower energies than that given by the hydrodynamical value. In view of the strong Q-value dependence of the Coulomb dipole excitation amplitude, it is necessary to use the correct energy of the GDR. In the case of $^{28}$O, the average excitation energy of GDR predicted by the RPA [9] is around 15 MeV. If we use this Q-value, the hadronic and
Fig. 2. GDR excitation cross section for $\alpha$ scattering at $E_L = 68$ MeV on $^{28}\text{O}$ for two different energy of the GDR: $Q=26$ MeV (left part) and $Q=15$ MeV (right part).

Fig. 3. Partial-wave cross sections for the same reaction of Fig. 2: $Q=26$ MeV (left part) and $Q=15$ MeV (right part).
Coulomb amplitudes are more comparable in magnitude and become dominant at low and high partial waves respectively. One can then observe a strong Coulomb-nuclear interference (right part of figure 2). This is also apparent in Fig. 3 (right part) where we present the partial cross section for the GDR at 15 MeV.

We consider now the case of the excitation of dipole states in $^{70}$Ca. Following the results of the RPA calculation [4], the GDR for $^{70}$Ca is assumed to be at 13.7 MeV and the IDR at 9.4 MeV. The corresponding hadronic transition potentials obtained by folding these transition densities are shown in Fig. 4, together with the contributions coming from the nuclear and Coulomb parts. We note that, although the total form factors have almost the same radial shape the composition of the two is quite different: in the case of the IDR the Coulomb contribution is smaller than in the GDR, while the nuclear part is higher. As a consequence, in the IDR case the form factor is given, in the peripheral region around 10 fm, essentially by the nuclear contribution, which is clearly an effect to be related to the neutron excess. The distorting potential for the DWBA calculation were obtained by double folding the M3Y potential [13] with a gaussian $\alpha$–particle density and the Hartree-Fock $^{70}$Ca [4] density. The imaginary part of the potential has been assumed to be half the real part. The excitation cross section for the GDR is shown in the right part of figure 5, while the left part of the same figure shows the corresponding cross section for exciting the IDR. In both cases the same bombarding energy of the $\alpha$–particle was chosen ($E_L = 40$ MeV). As can be seen in the figures, whereas both the Coulomb and the hadronic excitations contribute to the GDR, the contribution from nuclear field is strongly enhanced in the case of the excitation of the IDR. The larger cross section obtained for the excitation of the IDR with respect to the GDR can be strictly related to their form factors (Fig. 4). Effects due to the smaller excitation energy may also play a role. Since the low energy peak of the IDR is originated by the presence of the neutron skin, its excitation results in a direct probe of neutron excess.

To summarize, we note that the nuclear excitation of GDR by hadronic probes becomes more feasible in neutron-rich nuclei. In these nuclei, the GDR strength is strongly fragmented with some of the strength extending to lower excitation energy. Both Coulomb and nuclear excitations are strongly affected by the Q-values favoring lower Q-values. The variation of the amplitudes with the Q-value is so strong that even though the low energy components of the GDR carry a small fraction of the B(E1) strength, this is more than compensated by the enhanced amplitudes. A second type of dipole state which can be strongly excited by isoscalar probes is the compressional isoscalar dipole state. In neutron-rich nuclei, the corresponding strength distribution is fragmented, pushing a large fraction of the strength to lower excitation energies. Thus,
Fig. 4. Transition potentials for the excitation of the GDR (right) and IDR (left) in the $\alpha + ^{70}\text{Ca}$ system.

Fig. 5. Cross section for the excitation of the GDR (right) and IDR (left) in $^{70}\text{Ca}$ in the reaction $\alpha + ^{70}\text{Ca}$ at $E_L = 40$ MeV. The single contributions from nuclear and Coulomb excitations are shown together with the total result.
these states are amenable to strong excitation by isoscalar probes, providing a direct sensitivity to neutron excess.

References

[1] cf. e.g. Report on “Scientific opportunities with an advanced ISOL facility”, ISOL Panel, November 1997

[2] J. Dobaczewski et al., Z. Phys. A354 (1996) 27. G.A. Lalazissis et al., Nucl. Phys. A632 (1998) 363.

[3] C.F. Clement, A.M. Lane and J.R. Rook, Nucl. Phys. A66 (1965) 273.

[4] G.R. Satchler, Nucl. Phys. A195 (1972) 1.

[5] A. Krasznahorkay et al., Nucl. Phys. A567 (1994) 521.

[6] S. Shlomo et al., Phys. Rev. C36 (1987) 1317. G.R. Satchler, Nucl. Phys. A472 (1987) 215. K. Nakayama and G.F. Bertsch, Phys. Rev. Lett. 59 (1987) 1053. C.H. Dasso et al., Nucl. Phys. A627 (1997) 349.

[7] H. P. Morsch et al., Phys. Rev. Lett. 45 (1980) 337. M.N. Harakeh and A.E.L. Dieperink, Phys. Rev. C23 (1981) 2329.

[8] N. Van Giai and H. Sagawa, Nucl. Phys. A371 (1981) 1.

[9] F. Catara et al., Nucl. Phys. A624 (1997) 449.

[10] I. Hamamoto et al., Phys. Rev. C57 (1998) R1064.

[11] P. Van Isacker et al., Phys. Rev. C45 (1992) R13.

[12] R.A. Broglia and A. Winther, Heavy Ion Reactions (Addison-Wesley Publishing Company 1991) p.114

[13] G. R. Satchler, Direct Nuclear Reactions (Oxford University Press, 1983) chapter 12.3.