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The Giant Dipole Resonance Effect in Coulomb Excitation of ^{10}B

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Abstract

Coulomb excitation of the 0·718 MeV, $J^{\pi} = 1^+$, first excited state of ^{10}B has been studied using projectile excitation by ^{208}Pb and observing the backward scattered particles. The results give a clear indication of the virtual excitation of the giant dipole resonance (GDR) as a second-order effect. The observed magnitude is consistent with the usual hydrodynamic model estimate and with a recent shell-model calculation.

Introduction

It has been known for a number of years (Eichler 1964; de Boer and Eichler 1968; Häusser *et al.* 1973) that the E1 GDR can play an important role in measurements of the reorientation effect in Coulomb excitation. The first experimental evidence of this effect was reported for ^6Li and ^7Li projectile excitation by targets of ^{208}Pb and ^{209}Bi (Disdier *et al.* 1971; Smilansky *et al.* 1972; Bamberger *et al.* 1972; Häusser *et al.* 1973; Scholz *et al.* 1977; Gemmeke *et al.* 1978). In this paper we report further experimental evidence of the GDR effect for ^{10}B projectile excitation by ^{208}Pb.

In the analysis of most measurements of the reorientation effect in Coulomb excitation it has been assumed that the GDR effect can be treated as a small correction and procedures for doing this, based on the hydrodynamic model, have been incorporated into the standard Coulomb excitation program of Winther and de Boer (see e.g. Häusser *et al.* 1973; Fewell 1978). It remains to be demonstrated, however, that the correction normally used is valid and does not, for example, introduce a small but significant error into B(E2) values extracted from Coulomb excitation studies. In the present investigation the original motivation was to measure the quadrupole moment Q_{1^+} of the first excited state of ^{10}B, partly in an attempt to shed light on a discrepancy between calculation and experiment for the strength of the γ-ray transition from the 2^+, $T = 1$, 5164 keV level to the 1^+, $T = 0$, 718 keV level of ^{10}B (Spear *et al.* 1979); see Fig. 1. It soon became evident, however, that the GDR effect dominated the reorientation effect due to the quadrupole moment to such a degree that it became virtually impossible to determine Q_{1^+}. On the other hand, the data show in a convincing manner that the GDR has an important effect in this case, and allow a quantitative measurement of its magnitude.

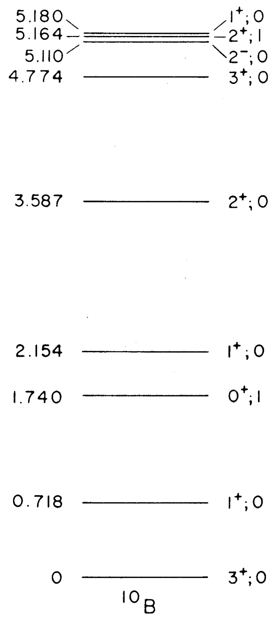

Fig. 1. Low-lying energy levels of ^{10}B, based on information from Ajzenberg-Selove (1979). The numbers shown for each level refer to excitation energy (MeV) and J^{π}; T assignments.

The GDR effect is taken into account by replacing the quadrupole interaction $V_0(t)$, in the Winther–de Boer multiple-Coulomb-excitation code (Winther and and de Boer 1966), with an effective interaction $V_{\mathrm{eff}}(t)$ which includes an additional term derived from the hydrodynamic model (Häusser *et al.* 1973; Häusser 1974). The expression is

$$V_{\mathrm{eff}}(t) = V_0(t)\left(1 - 0\cdot 0056\, k\frac{AE}{Z^2}\frac{a}{r_{\mathrm{p}}(t)}\right), \tag{1}$$

where a is half the distance of closest approach in a head-on collision, $r_{\mathrm{p}}(t)$ is the target–projectile distance, Z and A are the charge and mass numbers respectively of the nucleus being excited and E is the c.m. energy in MeV. The numerical factor $0\cdot 0056$ includes the factor $3\cdot 5$ which appears in the expression for σ_{-2}, the minus-two moment of the total photo-absorption cross section, namely $\sigma_{-2} = 3\cdot 5A^{5/3}$ μb MeV^{-1}. This formula is based on the hydrodynamic model and the numerical factor takes account (Levinger 1957) of experimental values of photo-absorption cross sections for $A \gtrsim 20$. Finally, the parameter k, which is used in subsequent discussion to express the relative magnitude of the GDR effect, is essentially the ratio of the actual effect to that predicted by the hydrodynamic model. The reader is referred to the papers of de Boer and Eichler (1968) and Häusser (1974) for details of the theory.

Experimental Procedure and Result

A beam of ^{10}B charge-four ions from the ANU 14UD accelerator was used to bombard a ^{208}Pb target. Beam currents ranged up to 200 nA. The scattered ^{10}B ions were detected with an annular Si surface-barrier detector located at 180° to the beam direction. The advantages of the axial geometry have been discussed at length by Esat *et al.* (1976).

The targets used consisted of isotopically enriched ^{208}Pb as PbS of thickness 15 μg cm^{-2} evaporated onto backings of 15 μg cm^{-2} carbon. The isotopic enrichment of the ^{208}Pb was 98·7%. Great care was taken in the preparation of the targets to ensure cleanliness of the evaporator in order to minimize target contaminants. Rutherford scattering measurements using beams of ^{16}O and ^{32}S ions with the same targets indicated that no contaminant peaks of any significance are present in the vicinity of the inelastic peak from the ^{10}B excitation.

The annular Si surface-barrier detector was mounted at a distance of 38 mm from the target, corresponding to a mean lab scattering angle of 170°. The detector mounting had an insulated, collinear, beam-defining aperture of 5 mm diameter. Cooling was provided to give optimum performance of the detector.

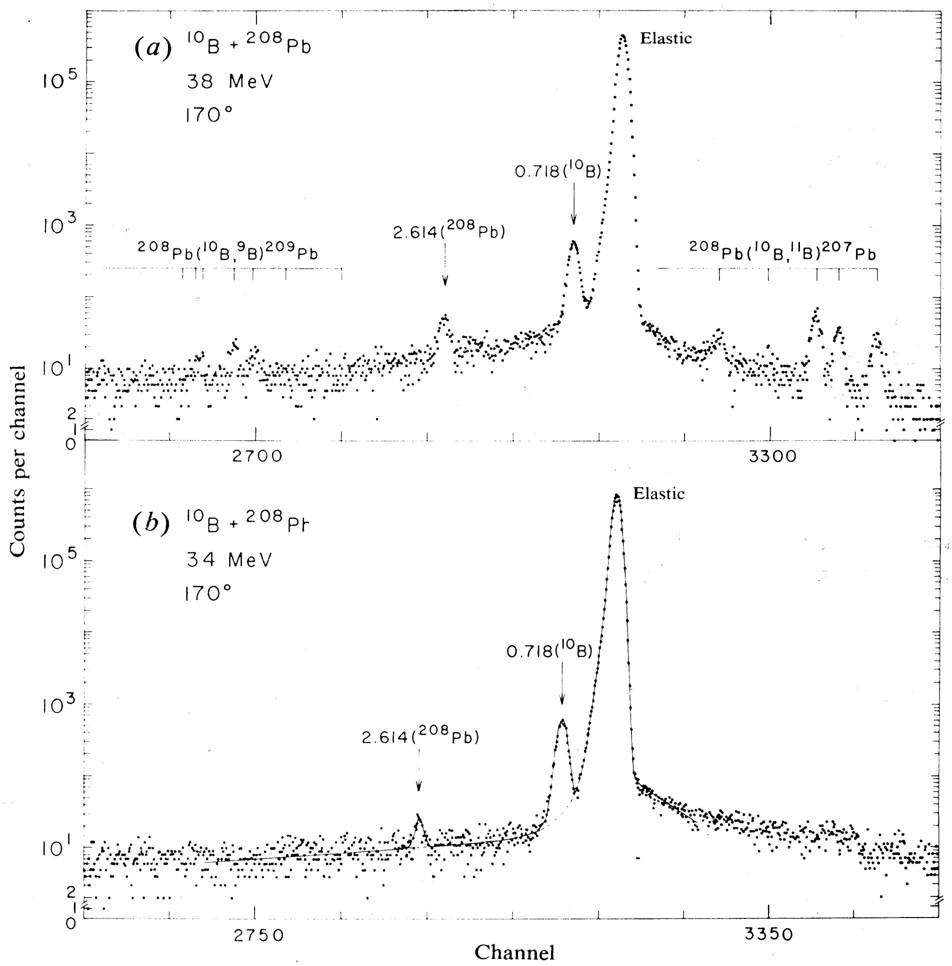

Fig. 2. Spectra obtained at (*a*) 38 MeV and (*b*) 34 MeV. Both spectra show peaks corresponding to elastic scattering, and to excitation of the 0·718 MeV 1^+ state of ^{10}B and the 2·614 MeV 3^- state of ^{208}Pb. Peaks due to single-nucleon transfer reactions are evident for the 38 MeV spectrum; channels corresponding to some available levels are indicated. The dispersions and gains used for the two spectra are not identical. The solid and dashed curves shown in (*b*) are fits to the data as described in the text.

Spectra were recorded for beam energies of 32, 34, 36 and 38 MeV in order to determine the maximum energy at which the Coulomb excitation could be studied with negligible contributions from other reaction mechanisms. Fig. 2 displays spectra obtained at 38 and 34 MeV. It is apparent from Fig. 2*a* that nuclear reactions are not negligible at 38 MeV. The peaks above the elastic peak can be identified with the transfer reaction $^{208}\mathrm{Pb}(^{10}\mathrm{B},{}^{11}\mathrm{B})^{207}\mathrm{Pb}$, while those below the elastic and inelastic peaks may be attributed to $^{208}\mathrm{Pb}(^{10}\mathrm{B},{}^{9}\mathrm{B})^{209}\mathrm{Pb}$. At 35 MeV these reaction peaks are much weaker, but still evident. At 34 MeV (see Fig. 2*b*) and at 32 MeV, the transfer reaction peaks are no longer in evidence and it is assumed that for these energies there is no significant contribution from transfer reactions to the intensity of the inelastic peak due to the Coulomb excitation of $^{10}\mathrm{B}$. At 34 MeV the distance of closest approach of the nuclear surfaces, calculated using the formula

$$s(\theta_{\mathrm{cm}}) = \frac{Z_1 Z_2 e^2}{2E_{\mathrm{lab}}}(1 + A_1/A_2)\{1+\mathrm{cosec}(\tfrac{1}{2}\theta_{\mathrm{cm}})\} - 1\cdot 25(A_1^{1/3}+A_2^{1/3}) \quad \mathrm{fm}, \tag{2}$$

has the large value of $8\cdot 1$ fm.

The solid curve shown in Fig. 2*b* is a fit to the data obtained using a function consisting of skewed gaussians and exponential tails. The procedures used are similar to those described previously (Esat *et al.* 1976; Fewell *et al.* 1977; Joye *et al.* 1977). An estimate of the uncertainty introduced into the inelastic excitation probability due to the fitting procedure is $0\cdot 6\%$, considerably smaller than the purely statistical uncertainty of $1\cdot 3\%$.

The basic number obtained from the experimental spectrum is the excitation probability of the first excited state, defined as

$$P_{\mathrm{exp}} = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)^{\mathrm{lab}}_{1+} \bigg/ \left\{\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)^{\mathrm{lab}}_{1+} + \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)^{\mathrm{lab}}_{3+}\right\}, \tag{3}$$

where the subscripts 1^+ and 3^+ refer to the first excited state and ground state respectively. The value obtained at 34 MeV is

$$P_{\mathrm{exp}} = (8\cdot 34 \pm 0\cdot 12)\times 10^{-4}.$$

The data obtained at 32 MeV were consistent with this but of considerably poorer statistical accuracy.

Extraction of Nuclear Parameters

The Winther–de Boer multiple-Coulomb-excitation code (Winther and de Boer 1966) was used to derive values of k and Q_{1^+} consistent with P_{exp} following procedures similar to those described in detail by Esat *et al.* (1976). Values of $B(\mathrm{E2};3^+\to 1^+)$ (derived from the lifetime of the 1^+ first excited state) and Q_{3^+}, both as adopted by Ajzenberg-Selove (1979), were used in the calculations. One higher state was included in the analysis, that at 2154 keV (1^+) (see Fig. 1), and was found to contribute at most $0\cdot 3\%$ to the excitation probability. Corrections have been applied for the effects of target thickness, electron screening (Saladin *et al.* 1969), vacuum polarization (Alder and Winther 1975), nuclear polarization (Beck and Kleber 1971), and the use of the semi-classical approximation (Alder *et al.* 1972). The net effect of these corrections is to increase the effective bombarding energy by 30 keV, which corresponds to an increase in the predicted excitation probability of $0{\cdot}5\%$. The only remaining parameters which affect the excitation probability are the GDR parameter k and the value of the quadrupole moment of the excited 1^+ state. Consequently, it is possible to obtain pairs of values of k and Q_{1^+} which are consistent with our value of $P_{\rm exp}$. Fig. 3 is a plot of these values. The band shown in Fig. 3 indicates the combined total uncertainty in the deduced values of k and Q_{1^+} due to the uncertainties in $P_{\rm exp}$ and in the values of B(E2) and Q_{3^+}, and due to the higher order effects discussed above.

It should be added that no correction has been made for relativistic effects (Fewell 1978; Winther and Alder 1979) because of the uncertainty in the validity of the estimates of these effects. It is estimated that the inclusion of these effects might increase the value of k by $0{\cdot}1$–$0{\cdot}2$; the modified value would still lie comfortably within the range of errors associated with the value of k deduced from the present data.

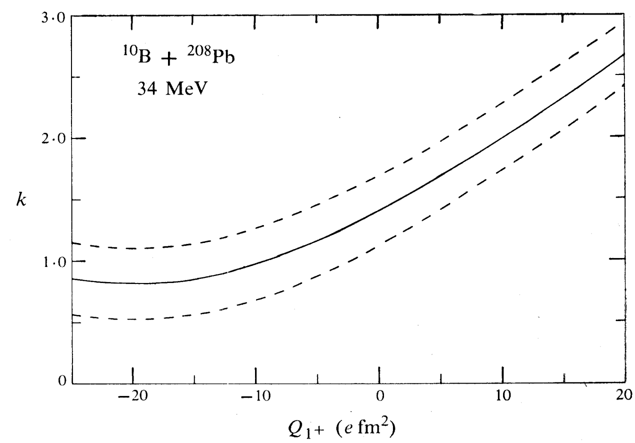

Fig. 3. Plot of the GDR parameter k versus Q_{1^+} for the Coulomb excitation of the $0{\cdot}718$ MeV 1^+ state of ^{10}B. The dashed curves indicate the range of uncertainty in the derived values (see text).

Discussion

From Fig. 3 one can say that for any value of Q_{1^+} the data require

$$k > 0{\cdot}5,$$

a clear indication of the observation of the GDR effect. However, it should be noted that $k \approx 0{\cdot}5$ requires an unreasonably large value of $|Q_{1^+}|$.

A crude estimate of an upper limit on $|Q_{1^+}|$ can be obtained by scaling the quadrupole moment for a very deformed nucleus, e.g. ^{24}Mg, where the adopted value of the quadrupole moment of the 2^+ first excited state is $-18\,e\,{\rm fm}^2$ (Spear 1981). Using the relation (Preston 1962)

$$Q = Q^* \frac{J(2J-1)}{(J+1)(2J+3)} \frac{3}{(5\pi)^{\frac{1}{2}}} Z R_0^2, \tag{4}$$

we obtain $|Q_{1^+}| \lesssim 1\cdot 5\, e\,\mathrm{fm}^2$ for ^{10}B. If one sets such a limit on Q_{1^+} one obtains

$$k = 1\cdot 4 \pm 0\cdot 4$$

from our data (see Fig. 3).

There have been two calculations of Q_{1^+} published in the literature: $-0\cdot 8\, e\,\mathrm{fm}^2$ from shell-model calculations (Barker 1981) and $-2\cdot 2\, e\,\mathrm{fm}^2$ from a projected Hartree–Fock calculation (Bouten and Bouten 1981). Using these values of Q_{1^+} one obtains

$$k = 1\cdot 3 \pm 0\cdot 3$$

from our data.

The values of k deduced above from the present measurements and reasonable assumptions regarding the value of Q_{1^+} show that the GDR effect in ^{10}B is consistent with that which would be calculated using the standard hydrodynamic model assumed in most Coulomb excitation codes. This is somewhat surprising for such a light nucleus, where one might expect details of the nuclear structure to play a dominant role. From a structure point of view it is probably more meaningful to compare the experimentally determined value of k with a calculation using a shell-model approach, which gives $k \approx 1\cdot 2$ (Barker 1982, present issue p. 291).

The results for ^{10}B are in marked contrast with the cases of ^{6}Li and ^{7}Li, where the observed effect of the GDR gives values of k in the range $2\cdot 6$ to $3\cdot 9$. An important question from the point of view of extracting quadrupole moments and B(E2) values from Coulomb excitation experiments is to know how the GDR effect compares with the estimate of the hydrodynamic model for other values of Z and A and whether there might be a discrepancy which could introduce systematic errors into derived values of the quadrupole moment and B(E2). Clearly, measurements of the GDR effect in other favourable cases are desirable.

Acknowledgments

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