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Coulomb Excitation of ^{7}Li

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Abstract

Coulomb excitation of the 0·478 MeV, $J^\pi = \frac{1}{2}^-$, first excited state of ^{7}Li has been studied using beams of ^{7}Li ions and targets of ^{138}Ba and ^{208}Pb. Spectra of the scattered particles were measured at 171° using an annular Si surface-barrier detector (^{138}Ba and ^{208}Pb targets) and at 90° using an Enge split-pole magnetic spectrometer (^{208}Pb targets). For each experimental configuration, the bombarding energy at which nuclear interference became significant was determined experimentally. An analysis based upon the reorientation effect yielded the following results: the static electric quadrupole moment of the $J^\pi = \frac{3}{2}^-$ ground state ($Q_{3/2^-}$) is $-4{\cdot}0 \pm 1{\cdot}1\ e\,\mathrm{fm}^2$, the contribution of the giant dipole resonance (GDR) to the Coulomb-excitation cross section is $2{\cdot}7 \pm 0{\cdot}2$ times as great as would be calculated from the hydrodynamic model, and $B(\mathrm{E2};\frac{3}{2}^- \to \frac{1}{2}^-)$ is $7{\cdot}42 \pm 0{\cdot}14\ e^2\,\mathrm{fm}^4$. The value obtained for $Q_{3/2^-}$ is in excellent agreement with results reported from atomic- and molecular-beam spectroscopy and from Coulomb scattering of aligned ^{7}Li. Thus it provides a strong verification of the validity of the reorientation-effect technique for the determination of nuclear quadrupole moments, provided that the GDR effect is treated adequately.

1. Introduction

Coulomb-excitation measurements have been used extensively to determine static and dynamic electric quadrupole moments of nuclear excited states (see, e.g., Häusser 1974 and Spear 1981). The probability for Coulomb excitation of a particular excited state depends to first order on $B(\mathrm{E}\lambda)$, the reduced electric λ-pole transition probability between the ground state and the excited state, and to second order on the static electric quadrupole moments Q_{J^π} of the states concerned. The second-order process involving Q_{J^π} is referred to as the reorientation effect. Its theory and application have been comprehensively described by de Boer and Eichler (1968), Häusser (1974) and Alder and Winther (1975). Typical experiments have involved Coulomb excitation of the 2^+ first excited state of a doubly even nucleus; since the ground state has $J^\pi = 0^+$, and hence a static quadrupole moment of zero, two independent measurements of the excitation probability suffice to determine $B(\mathrm{E2};0^+ \to 2^+)$ and Q_{2^+}. In addition to the reorientation effect, other higher order processes must also be allowed for, but for most experiments they have been considerably smaller than the reorientation effect.

It is well known that one higher order process which may play a significant role, especially in the projectile excitation of light nuclei, is that involving virtual excitation of states in the GDR. It has usually been assumed that the GDR effect can be treated

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as a small correction, and procedures for doing this, based upon the hydrodynamic model, have been incorporated into the standard Coulomb-excitation program of Winther and de Boer (1966) (see Häusser *et al.* 1973; Fewell 1978). A parameter k, defined in equations (1), (2), (16) and (17) of Barker (1982*a*), has been used to express the magnitude of the actual GDR effect relative to that calculated from the hydrodynamic model as empirically modified by Levinger (1957). In most analyses it has been assumed that $k = 1$. The validity of this assumption is particularly dubious for light nuclei. There have been experimental determinations of k for some light nuclei, giving values ranging from $1\cdot3 \pm 0\cdot3$ for ^{10}B (Vermeer *et al.* 1982) to $5\cdot7 \pm 0\cdot4$ for ^{17}O (Kuehner *et al.* 1982*b*). Shell-model calculations by Barker (1982*a*, 1982*b*) gave general agreement with these results. Barker (1982*c*) and Kuehner *et al.* (1982*b*) have pointed out that values of k as large as that obtained for ^{17}O could lead to significant errors in values of B(E2) determined from Coulomb-excitation experiments on the assumption that $k = 1$, although for many experiments the corresponding effects on Q_{2^+} would be no greater than other experimental and analytical uncertainties.

The present paper describes a study of the Coulomb excitation of the 0·478 MeV first excited state of ^{7}Li, which has $J^\pi = \frac{1}{2}^-$ and therefore a static quadrupole moment of zero. By making three independent measurements of the Coulomb-excitation probability, it has been possible to determine simultaneously the three quantities $Q_{3/2^-}$ (the static quadrupole moment of the $\frac{3}{2}^-$ ground state), $B(\mathrm{E2}; \frac{3}{2}^- \to \frac{1}{2}^-)$ and k. Three substantially different experimental configurations were achieved by using ^{7}Li projectiles with targets of ^{208}Pb and ^{138}Ba for particle detection at 171°, and with targets of ^{208}Pb for particle detection at 90°. It is essential (Spear *et al.* 1978) that, for the data used in the determination of quadrupole moments from reorientation-effect experiments, effects of nuclear interference should be negligible compared with experimental uncertainties. Accordingly we have, for each experimental configuration, measured excitation probabilities over a sufficiently wide range of bombarding energies to permit a clear determination of the bombarding energy at which Coulomb–nuclear interference becomes significant, and only data obtained at bombarding energies less than or equal to the maximum 'safe energy' have been used in the Coulomb-excitation analysis.

The value of $Q_{3/2^-}$ has previously been determined using a number of techniques other than the reorientation effect in Coulomb excitation; namely, hyperfine spectroscopy with atomic and molecular beams, and Coulomb scattering of aligned ^{7}Li nuclei. Thus, in addition to the intrinsic interest of the three quantities determined, the present experiment has the further attraction that, to the extent that the corpus of results from other methods may be regarded as canonical, it provides a test of the general validity of the reorientation-effect technique for the determination of nuclear quadrupole moments. To the best of our knowledge, the only similar previous test was made by Thomson *et al.* (1973). They used the reorientation effect to determine the static quadrupole moment of the $\frac{3}{2}^-$ ground state of ^{53}Cr and obtained $Q_{3/2^-} = +4 \pm 7\, e\,\mathrm{fm}^2$, which agreed with the value $|Q_{3/2^-}| = 2\cdot6\, e\,\mathrm{fm}^2$ obtained from NMR data (Artman 1966). However, the significance of this test was marred by the relatively large experimental uncertainty and also by the fact that the NMR measurement used as a standard was insensitive to the sign of $Q_{3/2^-}$. Furthermore, the analysis of Thomson *et al.* assumed that the effects of virtual excitation of the GDR and of interference due to the $\frac{5}{2}^-$ second excited state were both negligible.

It should also be noted that a subsequent measurement of the ^{53}Cr quadrupole moment using electron–nuclear double resonance gave $Q_{3/2^-} = -2{\cdot}85\,e\,\mathrm{fm}^2$ (Manoogian and Auger 1974).

There have been two previous studies of the Coulomb excitation of ^{7}Li in which ^{7}Li projectiles were excited by heavy target nuclei. Using a particle–gamma coincidence technique and targets of ^{208}Pb, Häusser *et al.* (1972, 1973) determined excitation probabilities at various bombarding energies and angles. Their results provided the first experimental evidence for the GDR effect. Assuming $Q_{3/2^-} = -3{\cdot}66 \pm 0{\cdot}03\,e\,\mathrm{fm}^2$, as calculated by Green (1971) from molecular-beam data, they deduced $B(\mathrm{E2}; \frac{3}{2}^- \to \frac{1}{2}^-) = 8{\cdot}3 \pm 0{\cdot}6\,e^2\,\mathrm{fm}^4$ and a GDR effect corresponding to $k = 3{\cdot}6 \pm 0{\cdot}5$ (Barker 1982*a*). Bamberger *et al.* (1972) used targets of ^{208}Pb and ^{209}Bi and determined excitation probabilities for ^{7}Li from particle-singles measurements. Data were obtained for a range of bombarding energies and angles, but the results were not sufficiently accurate for a meaningful determination of the GDR contribution, and so $Q_{3/2^-}$ could not be determined directly. However, by using a theoretical estimate of the GDR effect they deduced that $Q_{3/2^-} = -1{\cdot}0 \pm 2{\cdot}0\,e\,\mathrm{fm}^2$ and $B(\mathrm{E2}; \frac{3}{2}^- \to \frac{1}{2})^- = 7{\cdot}4 \pm 0{\cdot}1\,e^2\,\mathrm{fm}^4$.

A brief account of the present work has been already published (Vermeer *et al.* 1984).

2. Experimental Procedure

Beams of $^7\mathrm{Li}^{3+}$ ions, with bombarding energies in the range 12·5–30 MeV and typical intensities of 200 nA, were obtained from the ANU 14UD Pelletron accelerator. The targets consisted of either ^{208}PbS or $^{138}\mathrm{BaCl_2}$ evaporated onto thin carbon foils. The isotopic enrichments of ^{208}Pb and ^{138}Ba were 98·7% and 99·7% respectively, and their partial thicknesses in the targets were typically 50 and 20 $\mu\mathrm{g\,cm^{-2}}$ respectively. Two different systems were used to detect scattered ions. In one, an annular silicon surface-barrier detector was used at a mean angle of 171°. In the other, ions were detected at 90° using an Enge split-pole magnetic spectrometer with a position-sensitive multi-electrode gas-filled proportional counter at its focal plane (Ophel and Johnston 1978). For the 90° data the mean scattering angle was measured to an accuracy of $\pm 0{\cdot}1°$ using the kinematic technique described by Kuehner *et al.* (1982*a*).

In the scattered-particle spectra obtained with the magnetic spectrometer, the fraction of ^{7}Li ions in the 3+ atomic charge state was observed to be greater than 99% at the beam energies used. For this reason, and since the fraction in the other charge states differs only slightly for the elastic- and inelastic-scattering groups, only the spectra of 3+ ions were used for determining excitation probabilities.

The ^{138}Ba targets were tested for contaminants which could produce elastic-scattering peaks in the region of interest by bombarding one of them with 14 MeV ^{6}Li ions. Since ^{6}Li has no excited states within the appropriate energy range, elastic-scattering peaks from contaminants would have been observable. None were observed and, at the level of twice the statistical uncertainty in the background in the region where the ^{7}Li inelastic peak would occur, an upper limit of 1·0%, in the worst case, could be placed on contributions of any such target contaminants to the measured excitation probabilities. The ^{208}Pb targets were not specifically checked in this manner. However, since these targets were used for two scattering angles (90° and 171°) and at a fairly wide range of bombarding energies below the Coulomb barrier, any significant contributions to the spectra from contaminants would have been apparent.

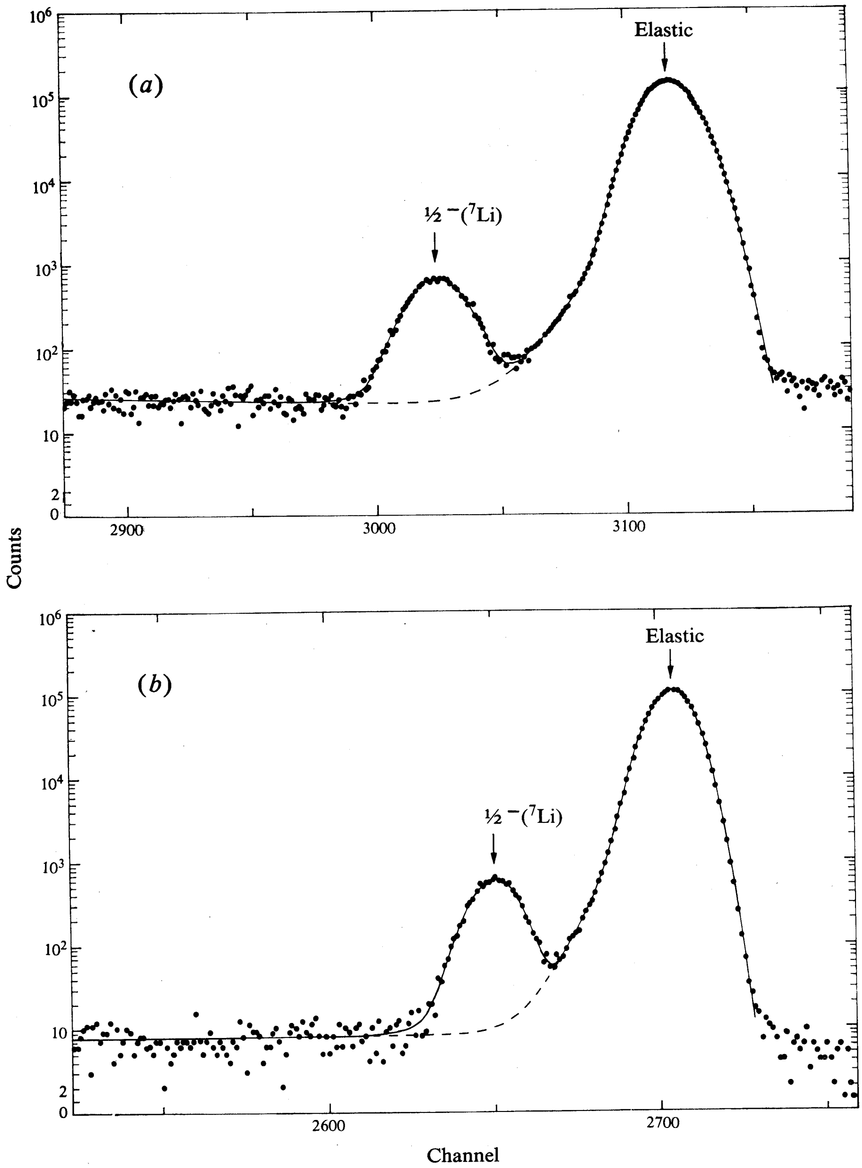

Fig. 1. Energy spectrum obtained with annular counter at 171° using (*a*) a ^{138}Ba target and 15·0 MeV ^{7}Li projectiles and (*b*) a ^{208}Pb target and 20 MeV ^{7}Li projectiles. The full curves are fits to the data obtained as described in Section 3. The dashed curves show the elastic-peak lineshape underneath the inelastic peak.

In some spectra obtained at bombarding energies above the Coulomb barrier, peaks due to the single-neutron transfer process (^{7}Li, ^{6}Li) were observed. However, the Q value of the (^{7}Li, ^{6}Li) reaction for either ^{138}Ba or ^{208}Pb is sufficiently negative that the ^{6}Li groups were too low in energy to interfere with the ^{7}Li scattering peaks at either 90° or 171°. For the 90° spectra it is possible that low-energy α particles from reactions of ^{7}Li with light elements (e.g. sulfur, carbon) in the target could

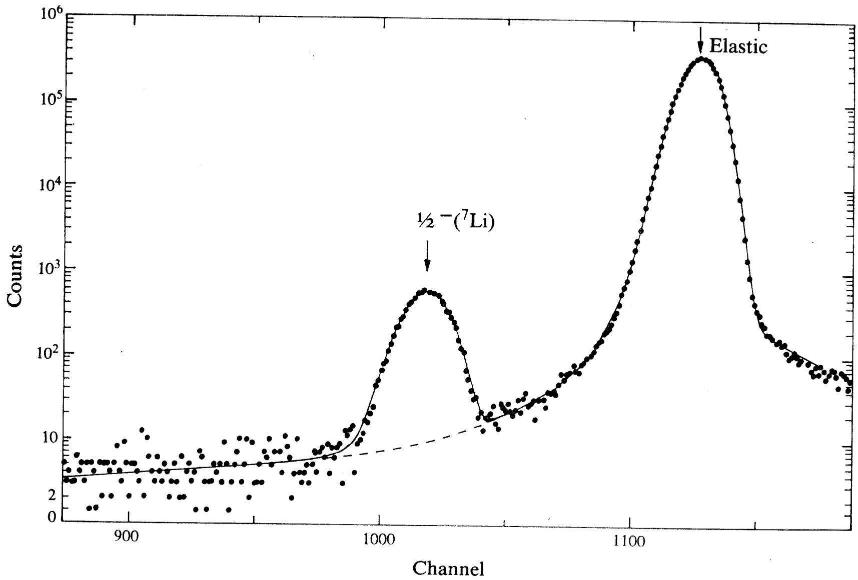

Fig. 2. Spectrum obtained in the detector at the focal plane of the magnetic spectrometer at 90° using a ^{208}Pb target and 19·0 MeV ^{7}Li projectiles. (The curves are as explained in the caption to Fig. 1.)

Table 1. Measured excitation probabilities for the $\frac{1}{2}^{-}$, 0·478 MeV state of ^{7}Li for the various targets, lab scattering angles and bombarding energies used in the present work

E (MeV)	$10^3\,P_{exp}$	E (MeV)	$10^3\,P_{exp}$	E (MeV)	$10^3\,P_{exp}$
^{138}Ba, $\theta = 171°$		^{208}Pb, $\theta = 171°$		^{208}Pb, $\theta = 90°$	
12·490	1·98±0·03	15·981	2·06±0·03	17·985	1·52±0·02
12·990	2·42±0·03	16·982	2·81±0·03	18·987	1·90±0·02
13·490	2·97±0·03	17·982	3·67±0·05	19·989	2·41±0·02
13·990	3·42±0·04	18·983	4·72±0·07	20·990	2·91±0·02
14·490	4·10±0·04	19·483	5·27±0·05	21·990	3·40±0·03
14·990	4·83±0·05	19·983	5·93±p·07	22·990	3·96±0·04
14·990	4·87±0·06	20·484	6·45±0·06	23·990	4·62±0·04
15·490	5·60±0·06	20·984	7·21±0·08	24·990	5·26±0·06
15·490	5·59±0·07	21·984	8·62±0·09	25·987	5·95±0·05
15·990	6·31±0·07	22·984	10·08±0·12	27·987	7·11±0·06
16·491	7·22±0·09	23·985	11·42±0·13	29·987	6·50±0·08
16·991	7·93±0·09	24·985	12·31±0·14		
17·491	8·69±0·12	25·985	12·76±0·13		
17·991	9·34±0·10	26·985	13·52±0·16		
18·491	9·90±0·12	27·985	17·06±0·17		
18·991	10·55±0·13				
19·491	10·86±0·12				
19·991	11·93±0·16				
20·491	13·02±0·17				
20·991	16·6 ±0·5				
21·491	22·5 ±0·6				

appear at the same position in the focal plane of the spectrometer as the groups of interest. However, the focal-plane detector provides energy-loss information which enabled α particles and ^{7}Li ions of the same magnetic rigidity to be readily distinguished.

3. Data Analysis and Results

Typical spectra for each of the three experimental configurations are shown in Figs 1 and 2. Peak areas were extracted using a method similar to that described in previous publications (Esat *et al.* 1976; Fewell *et al.* 1979). The elastic-scattering

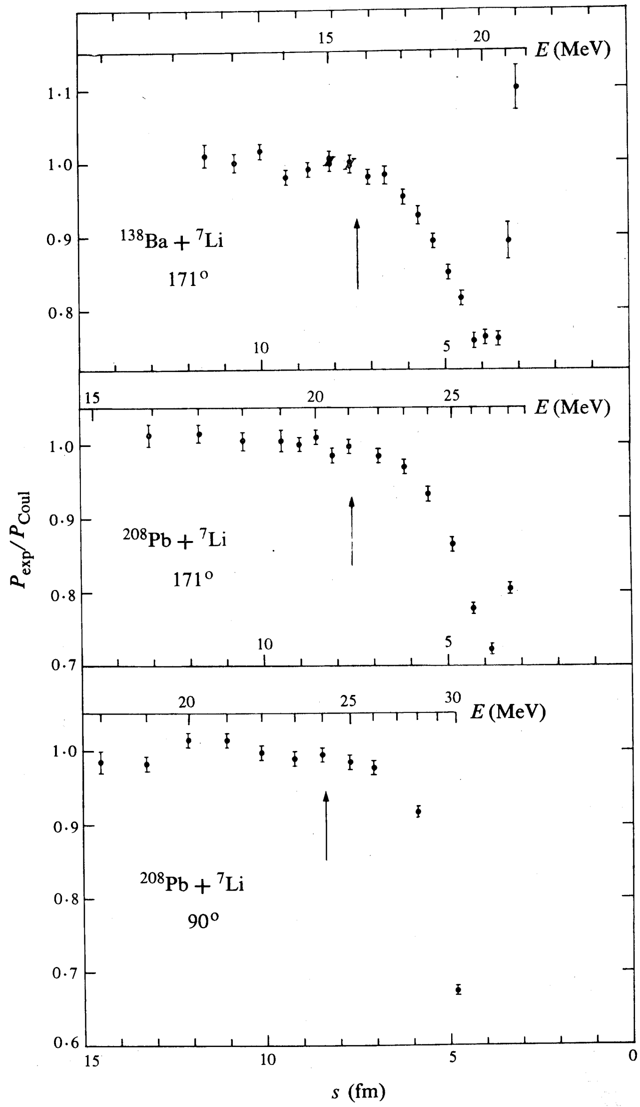

Fig. 3. Safe-energy plots of the ratio P_{exp}/P_{Coul} against bombarding energy E and the distance s of closest approach of the nuclear surfaces for the three cases indicated. The quantity P_{Coul} was calculated assuming $Q_{3/2^-} = -4{\cdot}0\,e\,\mathrm{fm}^2$, $k = 2{\cdot}7$ and $B(\mathrm{E2};\frac{3}{2}^- \to \frac{1}{2}^-) = 7{\cdot}42\,e^2\,\mathrm{fm}^4$ (see Section 3). The arrows indicate values adopted for maximum safe bombarding energies.

peak was fitted by the least-squares method with an analytic lineshape consisting of a skewed gaussian plus one or more exponential functions to represent the low-energy tail of the peak. This analytic lineshape was used to estimate the magnitude of the elastic-peak tail underneath the inelastic peak. The lineshape of the inelastic peak is broadened slightly due to the recoil of scattered ^{7}Li nuclei which undergo γ decay in flight. The experimental excitation probability P_{exp} of the ^{7}Li($\frac{1}{2}^-$) state was then calculated, this being defined as the ratio of the area of the inelastic $\frac{1}{2}^-$ peak to the sum of the areas of the inelastic and elastic peaks. Values of P_{exp} thus obtained are listed in Table 1; the bombarding energies given are effective values obtained after applying small corrections ($\sim$10 keV) to allow for the effects of finite target thickness.

Fig. 3 shows, for each of the experimental configurations, a plot of the ratio P_{exp}/P_{Coul} as a function of the bombarding energy E, and also of s, the distance of closest approach of the nuclear surfaces as defined by Fewell *et al.* (1979). The quantity P_{Coul} is the excitation probability calculated assuming a pure Coulomb interaction. The errors indicated are dominated by statistical uncertainties; they include smaller contributions from uncertainties involved in estimating the background to be subtracted. In each case the deviation of the values of P_{exp}/P_{Coul} from unity indicates the onset of Coulomb–nuclear interference as the bombarding energy is increased. For the data obtained at 171° with either target, the ratio is constant within experimental uncertainty for $s \geqslant 7\cdot5$ fm. Therefore, for the ^{138}Ba target and 171°, only data with $E \leqslant 15\cdot5$ MeV were used in the Coulomb-excitation analysis, while for the ^{208}Pb target and 171° the maximum safe energy was 21·0 MeV. For the third set of data (^{208}Pb target and 90°) only those points with $s \geqslant 8\cdot3$ fm, or $E \leqslant 24\cdot0$ MeV, were used.

Table 2. Results from projectile-excitation studies of ^{7}Li

B(E2; $\frac{3}{2}^- \to \frac{1}{2}^-$) ($e^2$ fm^4)	k	$Q_{3/2^-}$ (e fm^2)	Reference
$7\cdot42 \pm 0\cdot14$	$2\cdot7 \pm 0\cdot2$	$-4\cdot0 \pm 1\cdot1$	Present work
$8\cdot3 \pm 0\cdot6$	$3\cdot6 \pm 0\cdot5$	$-3\cdot66^A$	Häusser *et al.* (1972, 1973)
$7\cdot4 \pm 0\cdot1$	$1\cdot8^A$	$-1\cdot0 \pm 2\cdot0$	Bamberger *et al.* (1972)

[A] These values were *assumed* in the analysis.

Values of the excitation probability were calculated using the multiple Coulomb-excitation program of Winther and de Boer (1966), and values of B(E2; $\frac{3}{2}^- \to \frac{1}{2}^-$), k and $Q_{3/2^-}$ were varied to obtain the best fit to the 24 data points, as indicated by the minimum value of χ^2. In these calculations the effect of the strong M1 transition between the ground and first excited state was included using B(M1; $\frac{3}{2}^- \to \frac{1}{2}^-$) = $(2\cdot74 \pm 0\cdot13) \times 10^{-2}\, e^2$ fm^2, as calculated from the lifetime (Ajzenberg-Selove 1979). Effects of M1 reorientation and of interference from the 4·63 MeV ($\frac{7}{2}^-$) and 6·68 MeV ($\frac{5}{2}^-$) states were investigated using matrix elements derived from Lauritsen and Ajzenberg-Selove (1966) and Ajzenberg-Selove (1979); they were each found to be negligible [it was assumed that B(E4; $\frac{7}{2}^- \to \frac{1}{2}^-$) and B(E2; $\frac{5}{2}^- \to \frac{1}{2}^-$) both have strengths of 10 W.u.]. Multipole–multipole effects were also found to be negligible. Small corrections were applied for the effects of electron screening (Saladin *et al.* 1969), vacuum polarization (Alder and Winther 1975), nuclear polarization (Beck and Kleber 1971), and use of the semiclassical approximation, i.e. the quantal correction (Alder *et al.* 1972); they were all much smaller than the experimental uncertainties. The quantal correction for k was not estimated owing to the lack of a quantum-mechanical treatment which includes the effect of the GDR. The results obtained are shown in Table 2, together with those from the experiments of Häusser *et al.*

(1972, 1973) and Bamberger *et al.* (1972) described here in the Introduction; it should be noted that the values of k attributed to these authors are as deduced by Barker (1982*a*). The principal sources of error were the statistical uncertainties and the uncertainties in beam-energy calibration (Spear *et al.* 1977) and in determination of the true scattering angle when detecting particles at 90° with the magnetic spectrometer; the magnitudes of these uncertainties are given in Table 3.

Table 3. Various contributions to uncertainties in the present results

Source	$B(\mathrm{E2};\frac{3}{2}^-\to\frac{1}{2}^-)$ ($e^2\,\mathrm{fm}^4$)	k	$Q_{3/2^-}$ ($e\,\mathrm{fm}^2$)
Statistics	$\pm 0\cdot 13$	$\pm 0\cdot 21$	$\pm 0\cdot 89$
Energy calibration	$\pm 0\cdot 03$	$\pm 0\cdot 02$	$\pm 0\cdot 14$
Scattering angle	$\pm 0\cdot 04$	$\pm 0\cdot 01$	$\pm 0\cdot 57$

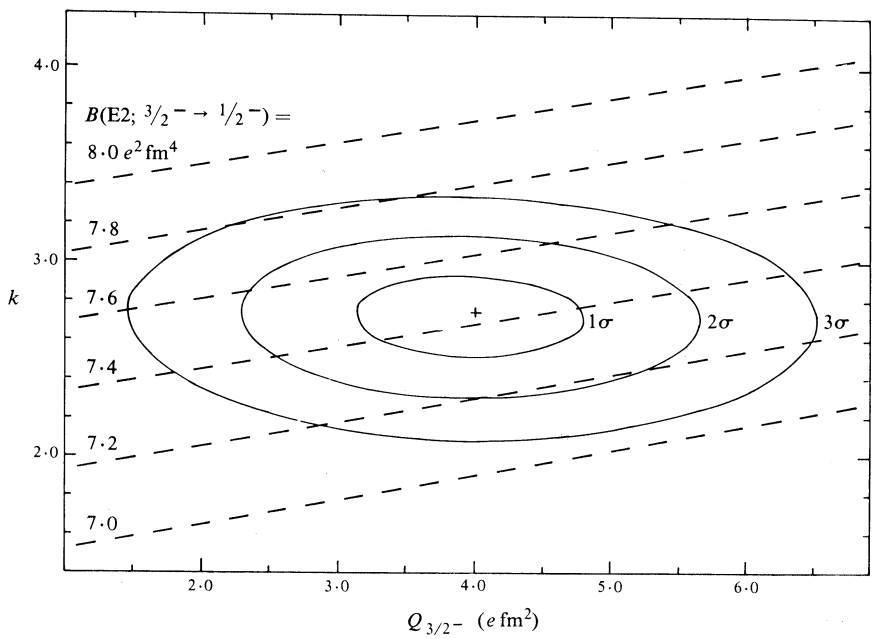

Fig. 4. Contour diagram of χ^2 as a function of k and $Q_{3/2^-}$, where χ^2 is minimized with respect to $B(\mathrm{E2};\frac{3}{2}^-\to\frac{1}{2}^-)$ for each pair of values of k and $Q_{3/2^-}$. The solid curves give various contours for χ^2, with the values of the contours being chosen to show the 1σ, 2σ and 3σ limits for k and $Q_{3/2^-}$ (i.e. $\chi^2 - \chi^2_{\min} = 1$, 4 and 9 respectively). The dashed lines show values of $B(\mathrm{E2};\frac{3}{2}^-\to\frac{1}{2}^-)$ required to minimize χ^2 as a function of k and $Q_{3/2^-}$.

It is noteworthy that, if the value of k is set at zero, the present data would give $B(\mathrm{E2};\frac{3}{2}^-\to\frac{1}{2}^-) = 6\cdot 14\pm 0\cdot 14\,e^2\,\mathrm{fm}^4$, substantially smaller than the best-fit value, and $Q_{3/2^-} = -3\cdot 9\pm 1\cdot 1\,e\,\mathrm{fm}^2$, which is not significantly different from the best-fit value. The value of χ^2 per degree of freedom would be $7\cdot 56$, as against $1\cdot 13$ for the best fit. This relative independence of k and $Q_{3/2^-}$ can best be seen in Fig. 4, which is a contour plot of χ^2 against these two variables. Values of χ^2 are obtained after

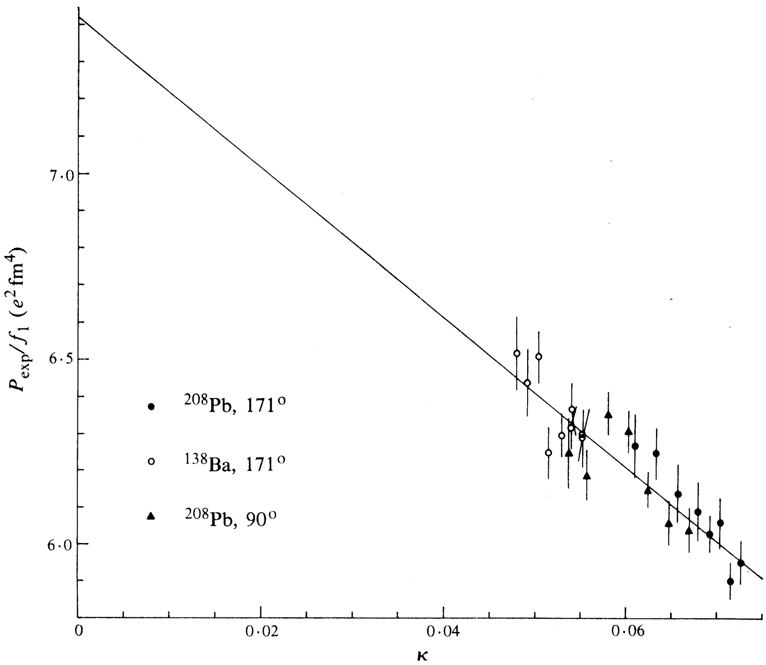

Fig. 5. Plot of P_{exp}/f_1 as a function of κ, where f_1 and κ are defined in Section 3.

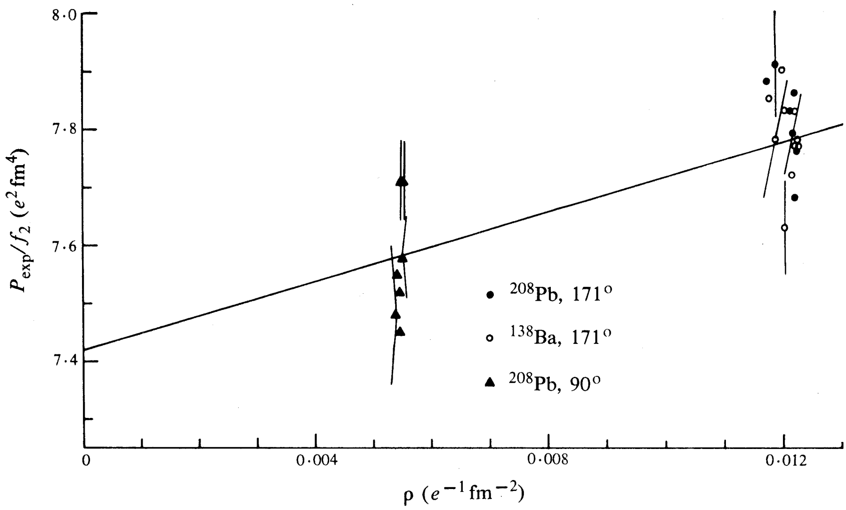

Fig. 6. Plot of P_{exp}/f_2 as a function of ρ, where f_2 and ρ are defined in Section 3. Error bars are shown for representative points only.

minimizing with respect to $B(E2; \frac{3}{2}^- \rightarrow \frac{1}{2}^-)$ for each pair of values of k and $Q_{3/2^-}$. The important feature is the orientation of the contours with respect to the axes. This shows that there is no significant correlation between k and $Q_{3/2^-}$.

In order to visualize the influence of each set of data on the determination of k and $Q_{3/2^-}$, an approximate expression of the form

$$P = fB(\mathrm{E2})(1-\kappa k)(1-\rho Q_{3/2^-})$$

is useful. The quantities f, κ and ρ are functions of experimental parameters (energy, angle etc.) and are calculated from the Winther–de Boer program using the values of B(E2), k and Q which give minimum values of χ^2. Figs 5 and 6 show plots of P_{exp}/f_1 as a function of κ and P_{exp}/f_2 as a function of ρ, where $f_1 = f(1-\rho Q_{3/2^-})$ and $f_2 = f(1-\kappa k)$. The fit to the data is then represented by a straight line with an intercept on the vertical axis equal to B(E2), and slopes of $-B(\mathrm{E2})k$ for Fig. 5 and $-B(\mathrm{E2})Q_{3/2^-}$ for Fig. 6. It is evident from Fig. 5 that the two sets of data at 171° would suffice to determine k, i.e. that the 90° data are not essential for this purpose. On the other hand, Fig. 6 shows that $Q_{3/2^-}$ may be determined from the 90° data and a single set of 171° data.

Typical values of κk and $\rho Q_{3/2^-}$ are 0·20 and 0·05 respectively. Thus, for the present experiment the GDR effect is about four times as great as the reorientation effect.

Table 4. Comparison of experimental values of k with shell-model predictions

Nucleus	Experiment	Calculation
^{6}Li	3·6[A,B], 2·6[C]	1·9[H]
^{7}Li	3·6±0·5[B], 2·7±0·2[D]	2·3[H]
^{10}B	1·3±0·3[E]	1·2[H]
^{12}C	<1·5[F]	0·8[H]
^{17}O	5·7±0·4[G]	2·6[I]

[A] Disdier *et al.* (1971), as deduced by Barker (1982*a*).
[B] Häusser *et al.* (1973), as deduced by Barker (1982*a*).
[C] Gemmeke *et al.* (1978), as deduced by Barker (1982*a*).
[D] Present work. [E] Vermeer *et al.* (1982).
[F] Deduced from Fig. 3 of Vermeer *et al.* (1983) on the conservative assumption that the quadrupole moment of the first excited state of ^{12}C cannot be greater than 8 $e\,\mathrm{fm}^2$.
[G] Kuehner *et al.* (1982*b*). [H] Barker (1982*a*). [I] Barker (1982*b*).

4. Discussion of Results

Reduced Transition Probability $B(\mathrm{E2};\frac{3}{2}^-\to\frac{1}{2}^-)$

As is evident from Table 2, the present result for $B(\mathrm{E2};\frac{3}{2}^-\to\frac{1}{2}^-)$ is in good agreement with that of Bamberger *et al.* (1972), and both are smaller than the substantially less precise value of Häusser *et al.* (1972, 1973). Our measured value corresponds to a strongly enhanced E2 transition, i.e. 18·5±0·4 W.u. It is in excellent agreement with the value of 7·55 $e^2\,\mathrm{fm}^4$ obtained by Walliser *et al.* (1983) from resonating-group calculations which have been very successful in describing other features of the mass-7 system. A strongly enhanced value of 6·26 $e^2\,\mathrm{fm}^4$ was also obtained by Bouten and Bouten (1981) from intermediate-coupling calculations in a projected Hartree–Fock basis.

GDR Parameter k

The present result for k, i.e. $2 \cdot 7 \pm 0 \cdot 2$, is smaller than the value $3 \cdot 6 \pm 0 \cdot 5$ obtained by Häusser *et al.* (1973). Nevertheless, both results indicate that the GDR contribution to the Coulomb excitation of the first excited state of ^{7}Li is substantially greater than would be predicted on the basis of the hydrodynamic model. Our value is in reasonable agreement with Barker's (1982*a*) shell-model prediction of $k = 2 \cdot 3$.

Experimental values for k are now available for ^{6}Li, ^{7}Li, ^{10}B, ^{12}C and ^{17}O; they are summarized in Table 4. Barker's (1982*a*, 1982*b*) shell-model predictions are also presented; they give a fairly good overall account of the experimental results. Since the GDR effect can be very significant in the analysis of data from projectile-excitation experiments, it is clearly desirable that experimental determinations of k be extended to heavier nuclei, particularly those of the 2s–1d shell where many projectile-excitation experiments have been performed. Presumably k will approach unity for sufficiently heavy nuclei.

Table 5. Comparison of $Q_{3/2^-}$ from present work with results from 'standard' techniques

$Q_{3/2^-}$ ($e\,$fm^2)	Technique	Reference
$-4 \cdot 0 \pm 1 \cdot 1$	Reorientation effect	Present work
$-3 \cdot 4 \pm 0 \cdot 6$[A]	Coul. scatt. aligned ^{7}Li	Egelhof *et al.* (1980)
$-4 \cdot 1 \pm 0 \cdot 6$	Atomic beam	Orth *et al.* (1975)
$-4 \cdot 5 \pm 0 \cdot 5$	Molecular beam	Kahalas & Nesbet (1963); Wharton *et al.* (1964)
$-3 \cdot 43 \pm 0 \cdot 02$	Molecular beam	Cade & Huo (1967); Green (1971)
$-4 \cdot 34$	Molecular beam	Bender & Davidson (1969); Green (1971)
$-4 \cdot 3$	Molecular beam	Browne & Matsen (1964)
$-3 \cdot 66 \pm 0 \cdot 03$	Molecular beam	Green (1971)
$-4 \cdot 8$	Molecular beam	Lu & Present (1970)

[A] Egelhof *et al.* (1982) have recently reported a preliminary value of $Q_{3/2^-} = -3 \cdot 7 \pm 0 \cdot 3$ $e\,$fm^2 from an improved measurement using the same technique.

Ground-state Quadrupole Moment $Q_{3/2^-}$

Our value for $Q_{3/2^-}$ is compared in Table 5 with values from atomic- and molecular-beam spectroscopy and from Coulomb scattering of aligned ^{7}Li. Values of $Q_{3/2^-}$ have also been reported from electron-scattering measurements (Suelzle *et al.* 1967; Hutcheon and Caplan 1969; van Niftrik *et al.* 1971). However, the extraction of $Q_{3/2^-}$ from such data is model dependent and, as pointed out by Orth *et al.* (1975), the results obtained should be regarded as a test of the applied nuclear model rather than as a measurement of the quadrupole moment.

It should be noted that all six molecular-beam results listed in Table 5 are based on a single measurement of the quadrupole coupling constant of ^{7}Li in the LiH molecule made by Wharton *et al.* (1962). The six different determinations of $Q_{3/2^-}$ represent various calculations of the electric field gradient at the Li nucleus in the molecule. It is difficult to assess the comparative reliability of these calculations. Some have no estimate of uncertainty, and among the others the precision claimed by the authors varies by more than an order of magnitude.

The experimental value for $Q_{3/2^-}$ is relatively large in magnitude, as may be seen from consideration of the usual rotational-model expression

$$Q_{J^\pi} = \frac{3K^2-J(J+1)}{(J+1)(2J+3)}Q_0,$$

where Q_0 is the intrinsic quadrupole moment. The two possible values of the quantum number K, namely $\frac{3}{2}$ and $\frac{1}{2}$, give $Q_0 = -19\pm1$ and $+19\pm1\ e\,\mathrm{fm}^2$ respectively. (For the purposes of the present discussion, we have assumed that $Q_{3/2^-} = -3\cdot8\pm0\cdot2\ e\,\mathrm{fm}^2$, a value consistent with the experimental results listed in Table 5.) The following argument renders the negative value of Q_0 unlikely. The intrinsic quadrupole moment of a nucleus is defined as $Ze\langle 3z^2-r^2\rangle$, or equivalently $Ze\{\langle 2z^2\rangle-\langle x^2+y^2\rangle\}$, where Ze is the nuclear charge (see, e.g., Evans 1955). Thus its value must lie in the range

$$-Ze\langle r^2\rangle \leqslant Q_0 \leqslant 2Ze\langle r^2\rangle,$$

where the upper limit is obtained if all the charge is on the z-axis, while the lower limit corresponds to the charge being confined to the x–y plane. The mean-square radius of ^{7}Li has been measured as $\langle r^2\rangle = 5\cdot5\pm0\cdot5\ \mathrm{fm}^2$ (Ajzenberg-Selove 1984). This gives the limits

$$-16\cdot5\pm1\cdot5 \leqslant Q_0 \leqslant 33\pm3\ e\,\mathrm{fm}^2.$$

Thus the value $Q_0 = -19\pm1\ e\,\mathrm{fm}^2$ corresponds to an unrealistically extreme oblate shape. It appears, then, that ^{7}Li in its ground state is prolate with $K=\frac{1}{2}$, although small admixtures of $K=\frac{3}{2}$ are probably not excluded. This conclusion is in agreement with previous collective-model interpretations of ^{7}Li (Clegg 1961; Chesterfield and Spicer 1963; Lawson 1980). Adopting $K=\frac{1}{2}$, and assuming the usual rotational-model expression

$$B(\mathrm{E2};\tfrac{3}{2}K\to\tfrac{1}{2}K) = (5/16\pi)Q_0^2(\tfrac{3}{2}2K0\,|\,\tfrac{1}{2}K)^2,$$

one obtains $|Q_{3/2^-}| = 3\cdot86\pm0\cdot04\ e\,\mathrm{fm}^2$ from the experimental value of $B(\mathrm{E2};\frac{3}{2}^-\to\frac{1}{2}^-)$. Thus, the experimental value of $Q_{3/2^-}$ is similar to the rotational-model value.

The notion of substantial collectivity for ^{7}Li is supported by the strongly enhanced value of $B(\mathrm{E2};\frac{3}{2}^-\to\frac{1}{2}^-)$ noted above, and also by the fact that shell-model calculations performed in the simplest configurations, without the introduction of effective charges, greatly underestimate quadrupole strengths. For example, Barker (1982*a*) obtained $B(\mathrm{E2};\frac{3}{2}^-\to\frac{1}{2}^-) = 1\cdot54\ e^2\,\mathrm{fm}^4$ and Walliser *et al.* (1983) obtained $1\cdot75\ e^2\,\mathrm{fm}^4$, and calculations using the wavefunctions of Cohen and Kurath (1965) yielded $Q_{3/2^-} = -1\cdot8\ e\,\mathrm{fm}^2$ (Correll *et al.* 1983). In contrast, the projected Hartree–Fock calculations of Bouten and Bouten (1981), which introduced deformation into the wavefunctions, gave $B(\mathrm{E2};\frac{3}{2}^-\to\frac{1}{2}^-) = 6\cdot26\ e^2\,\mathrm{fm}^4$ which, as noted above, is close to the experimental value, and $Q_{3/2^-} = -3\cdot62\ e\,\mathrm{fm}^2$, which falls comfortably within the range of experimental values listed in Table 5. Recent calculations in an α–t cluster model by Kajino *et al.* (1984) also provided reasonable agreement with the experimental values of both $Q_{3/2^-}$ and $B(\mathrm{E2};\frac{3}{2}^-\to\frac{1}{2}^-)$.

Finally, the question arises as to whether the results of the present experiment can be used to support the validity of the reorientation-effect technique for the determination of nuclear quadrupole moments. It is apparent from Table 5 that the value of $Q_{3/2^-}$ obtained in the present work is in excellent agreement with the results obtained using other techniques, namely atomic- and molecular-beam spectroscopy and Coulomb scattering of aligned ^{7}Li. Therefore it may be concluded that, insofar as the results of those techniques are considered reliable, the present results provide a strong verification of the underlying theory and practical application of the reorientation-effect technique, provided that the GDR effect is treated adequately. It is worth reiterating that the reorientation effect in the present experiment is only one-quarter the size of the GDR effect. Thus the present determination of $Q_{3/2^-}$ constitutes a particularly stringent test of the reorientation-effect technique.

5. Summary

Coulomb excitation of the first excited state of ^{7}Li has been studied using three significantly different experimental configurations and taking care to ensure that data used were free from the effects of nuclear interference. This has permitted the simultaneous determination that $B(\mathrm{E2};\frac{3}{2}^-\to\frac{1}{2}^-) = 7\cdot42\pm0\cdot14\,e^2\,\mathrm{fm}^4$, $Q_{3/2^-} = -4\cdot0\pm1\cdot1\,e\,\mathrm{fm}^2$ and $k = 2\cdot7\pm0\cdot2$. The major conclusions drawn from these results are as follows:

(i) the large values of $Q_{3/2^-}$ and $B(\mathrm{E2};\frac{3}{2}^-\to\frac{1}{2}^-)$ support the view that ^{7}Li has a strongly collective nature;

(ii) the contribution of the GDR to the Coulomb excitation of ^{7}Li is substantially greater than would be predicted using the hydrodynamic model; and

(iii) the value obtained for $Q_{3/2^-}$ provides strong verification of the validity of the reorientation-effect technique for the determination of nuclear quadrupole moments.

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