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Coulomb Excitation of the 2·615 MeV (3^-) and 4.086 MeV (2^+) States of ^{208}Pb

W. J. Vermeer,[A] *M. T. Esat,*[A] *J. A. Kuehner,*[A,B] *R. H. Spear,*[A] *A. M. Baxter*[C] *and S. Hinds*[C]

[A] Department of Nuclear Physics, Research School of Physical Sciences, Australian National University, G.P.O. Box 4, Canberra, A.C.T. 2601.
[B] Permanent address: Department of Physics, McMaster University, Hamilton, Ontario L8S 4M1, Canada.
[C] Physics Department, Faculty of Science, Australian National University, G.P.O. Box 4, Canberra, A.C.T. 2601.

Abstract

Coulomb excitation studies of the 2·615 MeV (3^-) and 4·086 MeV (2^+) states of ^{208}Pb have been carried out using ^{12}C and ^{16}O projectiles at various energies and scattering angles. Results for the 3^- state are: $B(\text{E3};0^+\to3^-) = 0{\cdot}611\pm0{\cdot}012\,e^2\,\text{b}^3$; and the static quadrupole moment $Q_{3^-} = -0{\cdot}34\pm0{\cdot}15\,e\,\text{b}$, which is larger in magnitude than most theoretical calculations. Results for the 2^+ state imply that $Q_{2^+} = -0{\cdot}7\pm0{\cdot}3\,e\,\text{b}$ if a value for $B(\text{E2};0^+\to2^+)$ determined from electron scattering work is assumed.

1. Introduction

The doubly closed-shell nucleus ^{208}Pb has been an important testing ground for a variety of nuclear models and has been the subject of extensive experimental investigation. The first excited state ($J^\pi = 3^-$, $E_x = 2{\cdot}615$ MeV) of ^{208}Pb in particular has received much attention with its description as an octupole vibrational state being supported, among other things, by a strongly enhanced transition to the ground state (approximately 30 W.u.). This transition strength, $B(\text{E3};0^+\to3^-)$, has been measured experimentally very many times, mostly by model dependent analyses of electron- and hadron-scattering data. However, there is a wide scatter in the results, some of which are listed in Table 1, and there is a clear need for an accurate and model independent determination of $B(\text{E3};0^+\to3^-)$. Among other things this would assist in the evaluation of the hadron-scattering analyses.

In contrast there is very little experimental information on the static quadrupole moment Q_{3^-} of the first excited state, despite considerable theoretical interest in this quantity. The calculated values of Q_{3^-} range from $-0{\cdot}06$ to $-0{\cdot}20\,e\,\text{b}$, except for a calculation by Krainov (1968) who obtained $Q_{3^-} = 2{\cdot}4$'s.p.u.' but did not define the units used. This result has been interpreted as $-0{\cdot}79\,e\,\text{b}$ (Barnett *et al.* 1973) or $-0{\cdot}52\,e\,\text{b}$ (Sorensen 1971), both of which are considerably larger in magnitude than all the other calculated values, including a value of $-0{\cdot}17\,e\,\text{b}$ obtained by Speth (1973) from a similar calculation.

In 1969 Barnett and Phillips used the reorientation effect in Coulomb excitation to experimentally determine Q_{3^-}, and obtained a value of $-1{\cdot}3\pm0{\cdot}6\,e\,\text{b}$ from angular distribution measurements of inelastically scattered ^{4}He and ^{16}O ions. Subsequently, Barnett *et al.* (1973) studied γ rays emitted following Coulomb

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Table 1. Some experimental determinations of $B(\mathrm{E3};0^+\to3^-)$ for 2·615 MeV (3^-) state of ^{208}Pb

$B(\mathrm{E3};0^+\to3^-)$ ($e^2\,\mathrm{b}^3$)	Method	Reference
0·665±0·035	Coulex	Joye *et al.* (1977)
0·54 ±0·03	Coulex	Häusser *et al.* (1972)
0·60 ±0·07	Coulex	Grosse *et al.* (1971)
0·58 ±0·04	Coulex	Barnett and Phillips (1969)
0·612±0·013	(e, e′)	Goutte *et al.* (1980)
0·69 ±0·05	(e, e′)	Rothhaas *et al.* (1974)
0·62 ±0·04	(e, e′)	Friedrich (1972)
0·70 ±0·05	(e, e′)	Nagao (1972)
0·77 ±0·09	(e, e′)	Nagao and Torizuka (1971)
0·72 ±0·04	(e, e′)	Ziegler and Peterson (1968)
0·77 ±0·02	(α, α')	Corcalciuc *et al.* (1983)
0·58 ±0·03	(α, α')	Bertrand *et al.* (1980)
0·66 ±0·05	(α, α')	Lilley *et al.* (1980)
0·77	(α, α')	Morsch *et al.* (1980)
0·66	(α, α')	Harakeh *et al.* (1979)
0·69	(α, α')	Rutledge and Hiebert (1976)

excitation of ^{208}Pb by ^{12}C, ^{20}Ne, ^{32}S and ^{40}Ar ions and obtained $Q_{3^-} = -1{\cdot}1\pm0{\cdot}4\,e\mathrm{b}$. The result of this measurement depends on the value assumed for Q_{2^+} of ^{206}Pb; we have used the experimental value of Joye *et al.* (1978). Both of these results were in serious disagreement with theoretical predictions. A large quadrupole moment would also create difficulties for a theoretical interpretation of the energy levels in this mass region. For example, Bohr and Mottelson (1975) and Hamamoto (1977) have pointed out that $Q_{3^-} \approx -1{\cdot}1\,e\mathrm{b}$ would imply separations within the ($h_{9/2}\otimes3^-$) septuplet of ^{209}Bi substantially greater than observed. Similarly, states of ^{208}Pb formed by coupling two octupole phonons ($3^-\otimes3^-$) would have large energy splittings and the 0^+ member of the quartet in particular would be substantially depressed in energy; no such low-lying state has been observed.

Guidetti *et al.* (1975) calculated the range of values for Q_{3^-} and $B(\mathrm{E3};0^+\to3^-)$ which could simultaneously exist within a variety of configuration spaces. The spaces investigated included those of the Tamm–Dancoff approximation (TDA) and random phase approximation (RPA) particle–hole models, and models in which particle–hole excitations are coupled to a 2^+ phonon. They concluded that it would be extremely difficult for any of the models considered to explain simultaneously the measured values of Q_{3^-} and $B(\mathrm{E3};0^+\to3^-)$, and they even suggested that ^{208}Pb may be much less well described as a doubly closed-shell nucleus than previously supposed.

In 1977 Joye *et al.* measured Q_{3^-} at the Australian National University, using an annular detector to observe scattered ^{4}He and ^{16}O at 171·6°, and obtained $Q_{3^-} = -0{\cdot}42\pm0{\cdot}32\,e\mathrm{b}$. This result was consistent with theoretical expectation, and applying the correction they quoted for effects involving the giant dipole resonance (GDR) brings still closer agreement ($Q_{3^-} = -0{\cdot}26\pm0{\cdot}32\,e\mathrm{b}$). It has been suggested (Feng *et al.* 1976; Joye *et al.* 1977) that the large magnitude for Q_{3^-} reported by Barnett *et al.* was due to the use of bombarding energies sufficiently high for Coulomb–nuclear interference effects to be significant. Although the conflict between theory and experiment had been resolved by the result of Joye *et al.*, within the experimental accuracy quoted, it was clearly desirable to improve the precision of the measurement. The quoted uncertainty was mainly due to the relatively large statistical errors in the ^{4}He data (see Fig. 3 of Joye *et al.* 1977). In addition, Joye *et al.* were unable to demonstrate experimentally that their ^{4}He bombarding energies were 'safe', i.e. sufficiently low to justify the assumption of pure Coulomb excitation, although they argued that this assumption was probably sound.

In a recent experiment at the ANU involving Coulomb excitation of ^{12}C projectiles by ^{208}Pb (Vermeer *et al.* 1983), groups corresponding to target excitation of the 2·615 MeV (3^-) and 4·086 MeV (2^+) states of ^{208}Pb were observed in the spectra of particles scattered near 90°. As part of that experiment, spectra at angles near 90° were also obtained with ^{16}O projectiles. The information obtained on the 3^- state was similar to the ^{4}He data of Joye *et al.* (1977) in that it could be used in conjunction with their ^{16}O(171·6°) data to determine Q_{3^-}. The new data however are far superior to the ^{4}He data both in spectrum quality and in statistical accuracy. Spear *et al.* (1983) have reported briefly on the results obtained from these new data plus additional ^{16}O data (obtained at 171·6° in order to improve statistics and permit a better determination of safe bombarding energies). We present here a more detailed account of the experimental procedure, analysis and implications of the 3^- data and also give the results obtained for the 2^+ state.

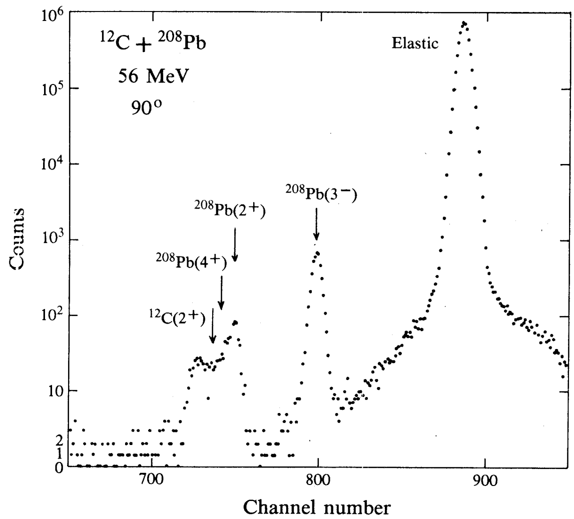

Fig. 1. Position spectrum obtained with an Enge split-pole spectrograph for 56 MeV ^{12}C ions scattered from ^{208}Pb at 90°. For display purposes this spectrum has been compressed by a factor of two by summing the contents of pairs of channels.

2. Experimental Procedure

Beams of $^{12}C^{5+}$ and $^{16}O^{6+}$ ions obtained from the ANU 14 UD pelletron accelerator at energies of 53–8 and 57–76 MeV respectively were used to bombard targets of ^{208}PbS evaporated onto thin carbon foils. The enrichment of ^{208}Pb was 98·7% and its partial thickness was typically about 40 μg cm^{-2}. Scattered particles were detected at a mean lab angle of 171·6° using an annular silicon surface barrier detector, and at angles from 75° to 110° with an Enge split-pole magnetic spectrograph.

The detector (Ophel and Johnston 1978) mounted in the focal plane of the spectrograph was long enough (50 cm) to observe all significant atomic charge states of the scattered particles ($^{12}C^{5+,6+}$ and $^{16}O^{6+,7+,8+}$) simultaneously. The detector also allowed easy discrimination between the scattered particles and particles from

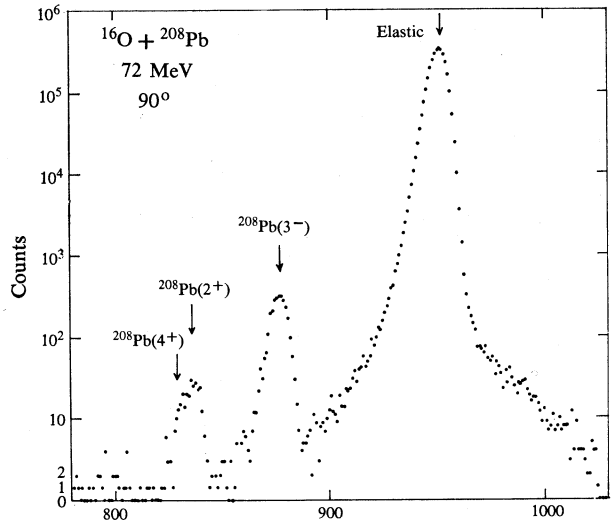

Fig. 2. Position spectrum obtained with an Enge split-pole spectrograph for 72 MeV ^{16}O ions scattered from ^{208}Pb at 90°.

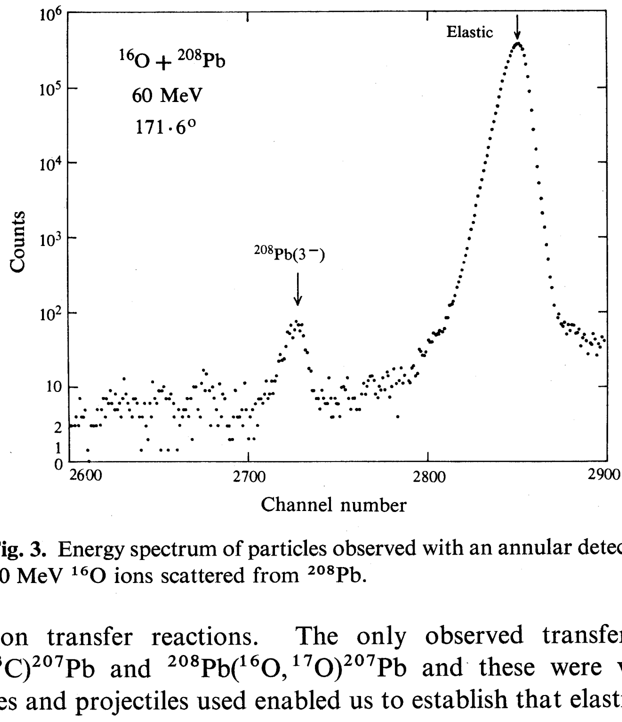

Fig. 3. Energy spectrum of particles observed with an annular detector for 60 MeV ^{16}O ions scattered from ^{208}Pb.

single nucleon transfer reactions. The only observed transfer reactions were $^{208}Pb(^{12}C,^{13}C)^{207}Pb$ and $^{208}Pb(^{16}O,^{17}O)^{207}Pb$ and these were very weak. The various angles and projectiles used enabled us to establish that elastic scattering from any contaminant in the target was negligible in the region of interest. Mean scattering angles were measured using the technique described by Kuehner *et al.* (1982).

For the annular detector data, peaks from single nucleon transfer reactions were too low in energy to overlap with the ^{208}Pb 3^- peak. The targets used with the annular detector work were checked for contaminants with a low energy (35 MeV) ^{16}O beam.

Typical spectra obtained are shown in Figs 1–3. For each spectrum the excitation probability for the 3^- state of ^{208}Pb was measured, where the excitation probability P is defined as the ratio of the inelastic scattering cross section to the elastic-plus-inelastic cross sections. In some cases it was also possible to measure excitation probabilities for the 2^+ state of ^{208}Pb.

Table 2. Excitation probabilities for 2·615 MeV (3^-) state of ^{208}Pb

Projectile	E (MeV)	Lab angle (degrees)	s (fm)	$10^4 P_{exp}$	P_{exp}/P_{Coul}
^{12}C	58·0	75	6·5	6·84±0·16	1·00±0·02
	53·0	90	6·5	4·99±0·09	1·03±0·02
	54·0	90	6·2	5·85±0·12	1·00±0·02
	56·0	90	5·6	8·24±0·26	0·98±0·03
	58·0	90	5·1	11·2 ±0·4	0·95±0·03
^{16}O	76·0	80	6·2	11·6 ±0·2	0·98±0·02
	70·0	90	6·6	6·95±0·25	0·98±0·03
	71·0	90	6·4	8·14±0·21	0·99±0·03
	72·0	90	6·1	9·38±0·31	0·99±0·03
	67·0	110	6·1	6·67±0·20	1·03±0·03
	57·0	171	7·3	0·79±0·03	0·97±0·03
	57·0	171	7·3	0·86±0·04	1·07±0·05
	58·0	171	7·0	1·07±0·05	1·03±0·05
	59·0	171	6·7	1·34±0·06	1·01±0·05
	59·0	171	6·7	1·25±0·06	0·94±0·05
	60·0	171	6·4	1·78±0·07	1·05±0·04
	60·0	171	6·4	1·62±0·07	0·95±0·04
	61·0	171	6·1	2·06±0·09	0·97±0·04
	62·0	171	5·9	2·49±0·10	0·94±0·04
	62·0	171	5·9	2·45±0·12	0·92±0·05
	64·0	171	5·4	3·89±0·16	0·96±0·04
	65·0	171	5·1	4·20±0·25	0·85±0·05
	66·0	171	4·9	5·11±0·20	0·85±0·03
	67·0	171	4·7	5·54±0·29	0·77±0·04
	68·0	171	4·4	5·75±0·26	0·67±0·03
	69·0	171	4·2	5·90±0·35	0·57±0·03

3. Analysis and Results for 2·615 MeV (3^-) State

Extraction of peak areas, and thus excitation probabilities, for the 3^- state was straightforward in all cases, and the techniques used for spectrum fitting have been described by Fewell *et al.* (1979). The experimental values determined for the excitation probabilities P_{exp} of the 3^- state are listed in Table 2. Also listed are P_{exp}/P_{Coul} and s, where P_{Coul} is the excitation probability calculated assuming pure

Coulomb excitation, and s is the distance of closest approach of the nuclear surfaces, defined by

$$s(\theta_{cm}) = \frac{0\cdot 72 Z_1 Z_2}{E_{lab}}(1 + A_1/A_2)\{1+\mathrm{cosec}(\tfrac{1}{2}\theta_{cm})\} - 1\cdot 25(A_1^{1/3}+A_2^{1/3}) \quad \mathrm{fm},$$

where Z_1, A_1 and Z_2, A_2 are the atomic numbers and masses of projectile and target respectively, θ_{cm} is the scattering angle in the c.m. system, E_{lab} is in MeV, and the nuclear radius is taken to be $1\cdot 25A^{1/3}$ fm. Fig. 4 shows a plot of P_{exp}/P_{Coul} as a function of s for the annular detector data (^{16}O projectile, $\theta = 171\cdot 6°$, $E = 57$–69 MeV). Clearly for $E > 64$ MeV ($s < 5\cdot 3$ fm) nuclear interference effects are significant, and may still be significant for $E = 61$–4 MeV ($s = 6\cdot 1$–$5\cdot 3$ fm). Therefore we have used only those data at $\theta = 171\cdot 6°$ with $E(^{16}\mathrm{O}) \leqslant 60$ MeV in the following analysis. For similar reasons the ^{12}C measurement for $\theta = 90°$, $E = 58$ MeV and $s = 5\cdot 1$ fm was also excluded from the analysis.

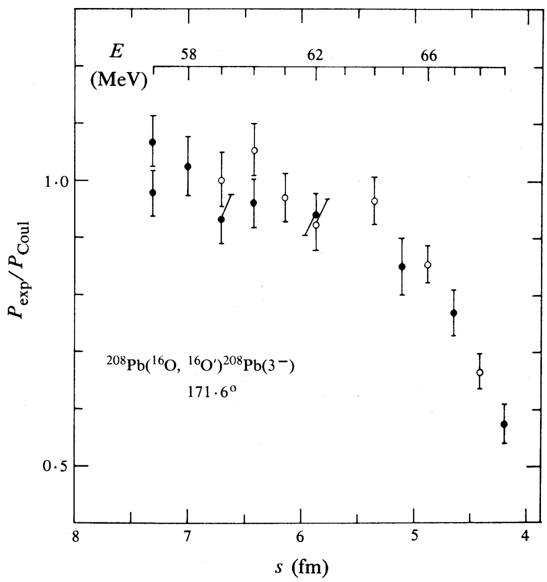

Fig. 4. 'Safe' energy plot for $^{16}\mathrm{O}+^{208}\mathrm{Pb}$ (171·6°), where P_{Coul} is the excitation probability for pure Coulomb excitation, calculated assuming $Q_{3^-} = -0\cdot 34\, e\mathrm{b}$ and $B(\mathrm{E3};0^+\to 3^-) = 0\cdot 611\, e^2\mathrm{b}^3$. The open circles are the data of Joye *et al.* (1977) and the solid circles are the present data. [From Spear *et al.* (1983).]

The data which were free from nuclear interference were analysed to determine Q_{3^-} and $B(\mathrm{E3};0^+\to 3^-)$ by performing a least-squares fit to the values of P_{exp}. The Winther–de Boer multiple Coulomb excitation code was used to calculate P for values of Q_{3^-} and B(E3) which were varied to obtain the best fit. Small corrections were applied (Fewell *et al.* 1979) for energy loss in the target, electron screening, vacuum polarization and nuclear polarization, giving net effects of $\Delta Q_{3^-} = -0\cdot 03\, e\mathrm{b}$ and $\Delta B(\mathrm{E3}) = +0\cdot 0017\, e^2\mathrm{b}^3$. The bombarding energy calibration was known to better than $\pm 0\cdot 1\%$ (Spear *et al.* 1977), corresponding to uncertainties of $\Delta Q_{3^-} = \pm 0\cdot 033\, e\mathrm{b}$ and $\Delta B(\mathrm{E3}) = \pm 0\cdot 0045\, e^2\mathrm{b}^3$. Effects involving virtual excitation of other states in ^{208}Pb were investigated using known matrix elements or reasonable estimates where they were not known. Only two low-lying states were found to contribute significantly to the excitation probabilities. The 3·198 MeV (5^-) state gave $\Delta Q_{3^-} = -0{\cdot}006$ or $+0{\cdot}019\, e\mathrm{b}$ and $\Delta B(\mathrm{E3}) = -0{\cdot}0001$ or $-0{\cdot}0007\, e^2\mathrm{b}^3$ depending on the relative phases of the matrix elements involved. We therefore applied corrections for this state of $\Delta Q_{3^-} = +0{\cdot}007 \pm 0{\cdot}013\, e\mathrm{b}$ and $\Delta B(\mathrm{E3}) = -0{\cdot}0004 \pm 0{\cdot}0003\, e^2\mathrm{b}^3$. Similarly, the corrections for the 4·086 MeV (2^+) state were $\Delta Q_{3^-} = +0{\cdot}027 \pm 0{\cdot}020\, e\mathrm{b}$ and $\Delta B(\mathrm{E3}) = -0{\cdot}0003 \pm 0{\cdot}0025\, e^2\mathrm{b}^3$, using $B(\mathrm{E1}; 2^+ \rightarrow 3^-) = 8 \times 10^{-5}\, e^2\mathrm{b}$ as estimated by Häusser *et al.* (1972).

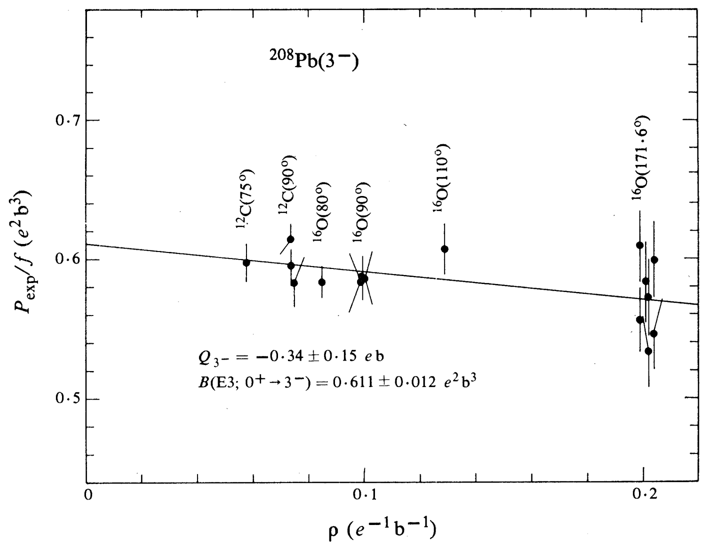

Fig. 5. Ratio P_{exp}/f plotted as a function of the sensitivity parameter ρ. The slope of the fitted line is equal to the product of Q_{3^-} and $B(\mathrm{E3}; 0^+ \rightarrow 3^-)$, and the intercept on the ordinate is equal to $B(\mathrm{E3}; 0^+ \rightarrow 3^-)$. [From Spear *et al.* (1983).]

Corrections were applied for virtual excitation of the GDR. The usual hydrodynamic model estimate of the GDR effect cannot be applied here because the electromagnetic transition from the GDR to the 3^- state is E2 instead of E1. To estimate the effect of the GDR it was treated as a single 1^- state at $E_x = 14$ MeV. For $B(\mathrm{E1}; 0^+ \rightarrow 1^-)$ we used a value of $0{\cdot}6\, e^2\mathrm{b}$ taken from the analysis of (e, e′) data by Pitthan and Buskirk (1977), with an uncertainty of $\pm 0{\cdot}2\, e^2\mathrm{b}$ assigned to encompass values from photonuclear measurements (Veyssiere *et al.* 1970; Berman and Fultz 1975). The value of $B(\mathrm{E2}; 1^- \rightarrow 3^-)$ is not known. It was found that even without including the E2 matrix element between the 1^- and 3^- states the GDR gave a relatively large effect of $\Delta Q_{3^-} = +0{\cdot}09 \pm 0{\cdot}03\, e\mathrm{b}$ and $\Delta B(\mathrm{E3}) = -0{\cdot}0012 \pm 0{\cdot}0004\, e^2\mathrm{b}^3$. This can be described as a depopulation effect where virtual excitation of the GDR reduces the ground state amplitude while the two nuclei are close together and thus reduces the probability of exciting the 3^- state. If the E2 matrix element is included and it is assumed that $B(\mathrm{E2}; 1^- \rightarrow 3^-) \leqslant 1$ W.u. then there are additional changes $|\Delta Q_{3^-}| \leqslant 0{\cdot}03\, e\mathrm{b}$ and $|\Delta B(\mathrm{E3})| \leqslant 0{\cdot}004\, e^2\mathrm{b}^3$. Therefore the corrections applied for the effect of the GDR were $\Delta Q_{3^-} = +0{\cdot}09 \pm 0{\cdot}04\, e\mathrm{b}$ and $\Delta B(\mathrm{E3}) = -0{\cdot}001 \pm 0{\cdot}004\, e^2\mathrm{b}^3$.

No correction was applied for relativistic effects because no appropriate theory exists. An order-of-magnitude estimate using the formalism of Winther and Alder (1979) gave $\Delta Q_{3^-} = -0{\cdot}06\, e\mathrm{b}$ and $\Delta B(\mathrm{E3}) = -0{\cdot}007\, e^2\mathrm{b}^3$. Likewise no correction was applied for quantal effects since no relevant information was available for E3 excitation. Joye *et al.* (1977) argued that such effects would be small, and for the present data they should be even smaller because the exclusion of ^{4}He data means that the Sommerfeld parameters η are substantially larger.

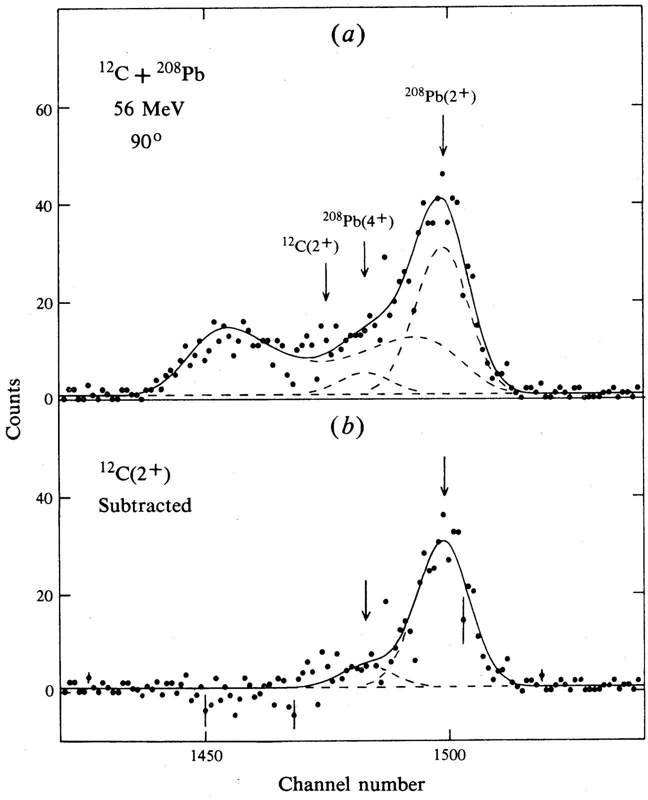

Fig. 6. (*a*) Part of the position spectrum for 56 MeV ^{12}C projectiles on ^{208}Pb. The solid curve shows a least-squares fit to the data as described in Section 4. Contributions to the fit for each peak are shown as dashed curves, with the arrows indicating peak centroids expected on the basis of the spectrum energy calibration. (*b*) As for (*a*) except that the contribution from the 4·439 MeV (2^+) state of ^{12}C has been subtracted.

Fig. 5 shows a plot of P_{exp}/f as a function of the sensitivity parameter ρ (the fractional change in excitation probability per unit quadrupole moment) for all the data used to obtain Q_{3^-} and $B(\mathrm{E3}; 0^+ \rightarrow 3^-)$. The quantities f and ρ, defined by Esat *et al.* (1976) and calculated using the Winther–de Boer code, are used to provide a visual presentation of the data. Comparison with Fig. 3 of Joye *et al.* (1977) shows that the present data are greatly superior in quantity and quality. The results obtained are $Q_{3^-} = -0\cdot34\pm0\cdot15\, e$b and $B(\mathrm{E3};0^+\to3^-) = 0\cdot611\pm0\cdot012\, e^2\,\mathrm{b}^3$. The errors are almost entirely due to the uncertainties in the values of P_{exp}.

4. Analysis and Results for 4·086 MeV (2$^+$) State

Excitation probabilities for the 4·086 MeV (2$^+$) state of ^{208}Pb were determined for those data which had sufficient statistical accuracy. Extraction of the 2$^+$ peak areas was complicated by an unresolved peak from the 4·323 MeV (4$^+$) state of ^{208}Pb. The height of the 4$^+$ peak was typically about 10% of the 2$^+$ peak height. For the spectra taken using ^{12}C there is in addition a broad structure present from projectile excitation of the ^{12}C 4·439 MeV (2$^+$) state. This inelastic group is broadened due to the emission in flight of γ rays from the scattered nuclei. The broadened lineshape was calculated as described for example by Beene and de Vries (1976), taking into account the unbroadened lineshape, the maximum energy shift of the recoiling nucleus, the angular distribution of the emitted γ rays, and the aberration of the γ-ray distribution due to the motion of the γ-emitting nucleus.

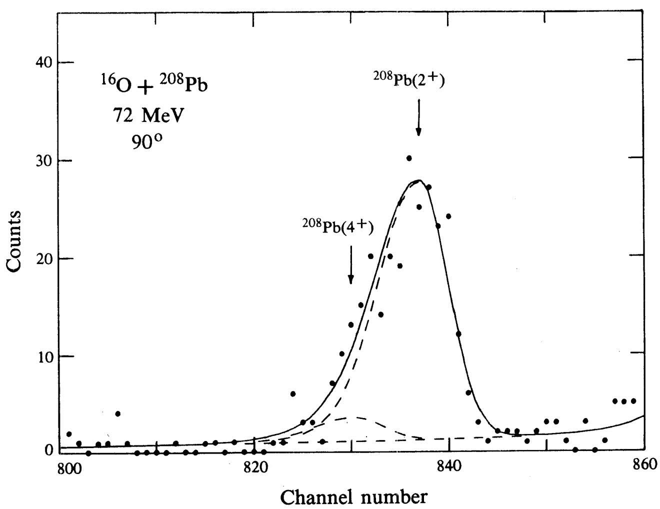

Fig. 7. Part of the position spectrum for 72 MeV ^{16}O projectiles on ^{208}Pb. The solid curve shows a least-squares fit to the 2$^+$,4·086 MeV and 4$^+$,4·323 MeV states of ^{208}Pb, where the heights of both peaks were varied to obtain the best fit. The dashed curves show the contributions from each peak.

The unbroadened lineshape was determined from the elastic peak, and the γ-ray angular distribution was calculated assuming pure Coulomb excitation. It was possible to let the angular distribution parameters vary to fit the observed lineshape but the best fit was generally not significantly different from the calculated lineshape. Fig. 6*a* shows one of the ^{12}C spectra together with a least-squares fit obtained using the known peak positions and lineshapes and only allowing the heights to vary. Fig. 6*b* shows the same spectrum after subtracting off the contribution from the ^{12}C 4·439 MeV (2$^+$) state. From the region which is clear of the ^{208}Pb states it can be seen that the subtraction is satisfactory.

The spectra obtained with ^{16}O projectiles had slightly worse resolution than the ^{12}C spectra presumably due to target thickness effects. The ^{208}Pb 2^+ peak area was extracted by performing a least-squares fit to the ^{208}Pb $2^+,4^+$ doublet and making use of the accurately known separation between then. It was possible either to let the ^{208}Pb 4^+ peak height vary in the fit, or to fix its height at a value calculated assuming pure Coulomb excitation and a $B(E4;0^+\to4^+)$ value from (e, e′) work; both gave consistent results. Fig. 7 shows the region of interest for one of the ^{16}O spectra and a fit to the $2^+,4^+$ peaks.

Table 3. Excitation probabilities for 4·086 MeV (2^+) state of ^{208}Pb

Projectile	Energy (MeV)	Lab angle (degrees)	s (fm)	$10^5 P_{exp}$	$B(E2;0^+\to2^+)$ ($e^2 b^2$)
^{12}C	53·0	90	6·5	3·43±0·24	0·284±0·020
	54·0	90	6·2	4·16±0·28	0·256±0·017
	56·0	90	5·6	7·49±0·55	0·266±0·020
	58·0	90	5·1	14·1 ±0·9	0·300±0·019
^{16}O	76·0	80	6·2	12·7 ±0·6	0·278±0·013
	70·0	90	6·6	4·70±0·65	0·270±0·037
	71·0	90	6·4	5·55±0·68	0·253±0·031
	72·0	90	6·1	7·63±0·63	0·279±0·023

In Table 3 the values of $P_{exp}(2^+)$ are listed. The data are not sufficiently precise to provide useful values for $B(E2;0^+\to2^+)$ and Q_{2^+} simultaneously. In order to compare the results from different angles, energies and projectiles, the $B(E2;0^+\to2^+)$ values derived from each point assuming $Q_{2^+} = 0$ are included in Table 3. The agreement between the ^{12}C data and the ^{16}O data is excellent with the weighted averages of the $B(E2;0^+\to2^+)$ values being $0·276\pm0·009\ e^2 b^2$ and $0·274\pm0·010\ e^2 b^2$ respectively. The agreement for the different values of s is also good indicating that nuclear interference effects are negligible. The weighted average of all the $B(E2;0^+\to2^+)$ values is $0·275\pm0·007\ e^2 b^2$. This is in disagreement with corresponding values derived from the most recent (e, e′) work: $0·329\pm0·016\ e^2 b^2$ (Heisenberg 1981) and $0·318\pm0·016\ e^2 b^2$ (Heisenberg *et al.* 1982). This conflict between (e, e′) results and the present work can be resolved if a large negative static quadrupole moment Q_{2^+} is assumed for the 2^+ state. A least-squares fit to the values of $P_{exp}(2^+)$ and the most recent electron scattering result gives $Q_{2^+} = -0·7\pm0·3\ e$b. Sources of uncertainty such as interference effects from other states of ^{208}Pb and the GDR effect are negligible compared with the quoted error.

5. Discussion

The results obtained for Coulomb excitation of the 4·086 MeV (2^+) state of ^{208}Pb suggest that either electron scattering work for this state is in error in producing a $B(E2;0^+\to2^+)$ value which is too large by about 15%, or that the 2^+ state has a substantial negative quadrupole moment. The latter possibility is intriguing because the measured values of Q_{2^+} for ^{204}Pb and ^{206}Pb are $+0·23\pm0·09\ e$b and $+0·05\pm0·09\ e$b respectively (Joye *et al.* 1978), and a theoretical calculation by Ring and Speth (1974) gives $Q_{2^+}(^{208}Pb) = +0·09\ e$b. The value for $Q_{2^+}(^{208}Pb)$ of $-0·7\pm0·3\ e$b is close to the rotational model value of $|Q_{2^+}| = 0·5\ e$b. Clearly more experimental work is required to determine unambiguously if the 2^+ state has a relatively large negative quadrupole moment.

For $B(E3;0^+\rightarrow3^-)$ the present result of $0\cdot611\pm0\cdot012\ e^2\,b^3$ is in excellent agreement with the recent work of Goutte *et al.* (1980) who analysed various (e, e′) data, and included in their fitting procedure the weighted average of previous Coulomb

Table 4. Experimental and calculated values for $Q_{3^-}(^{208}Pb)$

Abbreviations: GCM, generator coordinate method; PVC, particle vibration coupling; TDA, Tamm–Dancoff approximation; FFS, finite Fermi systems; RPA, random phase approximation

Q_{3^-} (*e* b)	Method	Reference
$-1\cdot3\ \pm0\cdot6$	Exp.	Barnett and Phillips (1969)
$-1\cdot1\ \pm0\cdot4$	Exp.	Barnett *et al.* (1973)
$-0\cdot26\pm0\cdot32$	Exp.	Joye *et al.* (1977)
$-0\cdot34\pm0\cdot15$	Exp.	Present work
$-0\cdot09$	RPA	Blomqvist (1970)
$-0\cdot20$	PVC	Hamamoto (1970)
$-0\cdot12$	RPA	Sorensen (1971)
$-0\cdot06$	TDA	True *et al.* (1971)
$-0\cdot17$	FFS	Speth (1973)
$-0\cdot10$	PVC	Bohr and Mottelson (1975)
$-0\cdot13$	PVC	Hamamoto (1977)
$-0\cdot10$	GCM	Deji and Pao (1983)

Table 5. Energy splittings of $^{209}Bi(h_{9/2}\otimes3^-)$ septuplet

State	Energy shift (MeV) relative to energy of ^{208}Pb 3^- state			
J^π	Exp.	$Q_{3^-}=0$	$Q_{3^-}=-0\cdot34$	$Q_{3^-}=-1\cdot1\ e$b
$\frac{3}{2}^+$	$-0\cdot121$	$-0\cdot190$	$-0\cdot364$	$-0\cdot753$
$\frac{5}{2}^+$	$+0\cdot003$	$+0\cdot007$	$+0\cdot102$	$+0\cdot314$
$\frac{7}{2}^+$	$-0\cdot030$	$-0\cdot006$	$-0\cdot012$	$-0\cdot027$
$\frac{9}{2}^+$	$-0\cdot030$	$-0\cdot089$	$-0\cdot159$	$-0\cdot315$
$\frac{11}{2}^+$	$-0\cdot050$	$-0\cdot031$	$+0\cdot073$	$+0\cdot307$
$\frac{13}{2}^+$	$-0\cdot015$	$-0\cdot063$	$-0\cdot126$	$-0\cdot268$
$\frac{15}{2}^+$	$+0\cdot129$	$+0\cdot156$	$+0\cdot061$	$-0\cdot151$

Table 6. Energies of a two octupole phonon quartet in ^{208}Pb

State	E_x (MeV)	
J^π	$Q_{3^-}=-0\cdot34\ e$b	$Q_{3^-}=-1\cdot1\ e$b
0^+	$4\cdot96$	$2\cdot46$
6^+	$5\cdot12$	$4\cdot08$
2^+	$5\cdot15$	$4\cdot35$
4^+	$5\cdot36$	$6\cdot55$

excitation measurements, to obtain a value of $0\cdot612\pm0\cdot013\ e^2\,b^3$. Most other determinations of $B(E3;0^+\rightarrow3^-)$ are by inelastic hadron scattering and are strongly model dependent. Some of these are listed in Table 1.

In Table 4 the experimental and calculated values for Q_{3^-} are listed. As mentioned above the data of Barnett and Phillips (1969) and Barnett *et al.* (1973) probably suffer from nuclear interference. The present result is consistent with that of Joye *et al.* (1977) but is more accurate and is inconsistent with $Q_{3^-} = 0$. The theoretical calculations of Q_{3^-} are smaller in magnitude than the present result by about one to two standard deviations. However, the work of Guidetti *et al.* (1975) shows that the present results for $B(\mathrm{E3}; 0^+ \to 3^-)$ and Q_{3^-} can in principle be accommodated within the framework of the TDA, if particle–hole excitations up to $3\hbar\omega$ are included, or within the framework of the RPA.

The present results for Q_{3^-} can be used to estimate the energy splittings of the $(h_{9/2} \otimes 3^-)$ septuplet of ^{209}Bi and the $(3^- \otimes 3^-)$ quartet of ^{208}Pb using coupling constants and energy shifts calculated by Bohr and Mottelson (1975) and Hamamoto (1977). These are listed in Tables 5 and 6. Clearly the energies of the ^{209}Bi septuplet are better reproduced by the present value of Q_{3^-} than by the old value of $-1\cdot1\ e$b. A value of $Q_{3^-} = 0$ would give an even better fit, but given the uncertainties involved in the calculation (Bohr and Mottelson 1975; Hamamoto 1977), the present value of Q_{3^-} implies separations within the ^{209}Bi septuplet which do not seem to be inconsistent with experiment. The 0^+ member of a two octupole phonon quartet in ^{208}Pb would be expected to lie at an excitation energy of $4\cdot96^{+0\cdot19}_{-0\cdot28}$ MeV if $Q_{3^-} = -0\cdot34 \pm 0\cdot15\ e$b. The lowest known 0^+ excited state of ^{208}Pb is at $4\cdot859$ MeV but, as pointed out by Mariscotti *et al.* (1983), this is generally believed to be a two neutron pairing vibration. However, these authors have recently produced tentative evidence for a 0^+ state at $4\cdot905$ MeV having some of the characteristics expected for a two octupole phonon vibration.

In conclusion, the present result of $Q_{3^-} = -0\cdot34 \pm 0\cdot15\ e$b is somewhat larger in magnitude than theoretical predictions, but does not imply improbable consequences for theoretical interpretations of energy levels in ^{208}Pb or ^{209}Bi and can in principle be accommodated within standard nuclear theories.

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