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Determination of Maximum Safe Bombarding Energies and B(E3) Values in Reorientation Experiments with ^{204}Pb, ^{206}Pb and ^{208}Pb

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Abstract

Data are presented which display the onset of Coulomb–nuclear interference in the inelastic scattering of ^{4}He, ^{12}C and ^{16}O projectiles from ^{204}Pb and ^{206}Pb. These results have been used to determine maximum safe bombarding energies in a recent reorientation effect determination of the quadrupole moments of the first 2^{+} states in these nuclei. Similar data are also presented for the excitation by ^{16}O projectiles of the first 3^{-} states in ^{204}Pb, ^{206}Pb and ^{208}Pb. The results are used to determine $B(\mathrm{E3}; 0^{+}\rightarrow 3^{-})$ values for the first 3^{-} states of ^{204}Pb and ^{206}Pb; these are found to be remarkably similar to each other and to the corresponding value for the first 3^{-} state in ^{208}Pb.

Introduction

In a recent publication Spear *et al.* (1978) have shown that the maximum safe bombarding energy for any given experiment involving the reorientation effect in Coulomb excitation should always be determined by direct measurement rather than by calculation from some universal formula involving only the masses and charges of the interacting nuclei. Motivated by such considerations, we present herein data which display the onset of Coulomb–nuclear interference in the inelastic scattering of ^{4}He, ^{12}C and ^{16}O projectiles from ^{204}Pb and ^{206}Pb. These results have been used by Joye *et al.* (1978) to determine maximum safe bombarding energies in a reorientation effect determination of the static quadrupole moments of the first 2^{+} states of these nuclei. We also present new results concerning the determination of the safe energy for excitation of the first 3^{-} state in ^{208}Pb with ^{16}O projectiles; these results are pertinent to the choice of bombarding energies made by Joye *et al.* (1977) to determine the quadrupole moment of this state. The data for excitation of the first 3^{-} states in ^{204}Pb and ^{206}Pb are used to extract B(E3) values for the transitions involved.

Experimental Procedure and Analysis

For each projectile–target combination, spectra were obtained for a range of bombarding energies using an annular surface-barrier detector at a mean laboratory scattering angle of 171·6°. Experimental details have been given previously (Esat *et al.* 1976; Joye *et al.* 1977, 1978). Some representative spectra are shown in Figs 1–3.

The areas of elastic and inelastic peaks were extracted from each spectrum to obtain the experimental excitation probability R_{exp} defined by

$$R_{\mathrm{exp}} = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{\mathrm{inel}}^{\mathrm{lab}} \Big/ \left\{\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{\mathrm{inel}}^{\mathrm{lab}} + \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{\mathrm{el}}^{\mathrm{lab}}\right\}.$$

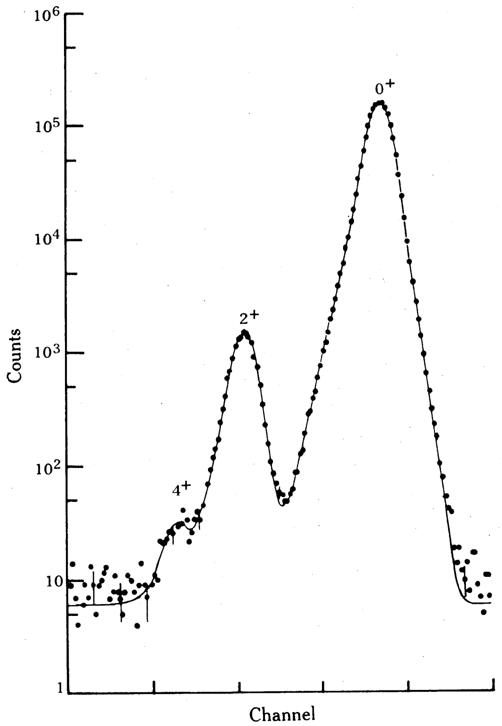

Fig. 1. Spectrum of 60 MeV ^{16}O projectiles backscattered from ^{204}Pb, at a laboratory angle of 171·6°. The curve is a fit to the spectrum, obtained as described by Esat *et al.* (1976) and Joye *et al.* (1977). The peaks correspond to elastic scattering (0^+) and to inelastic scattering to the first 2^+ and 4^+ states of ^{204}Pb.

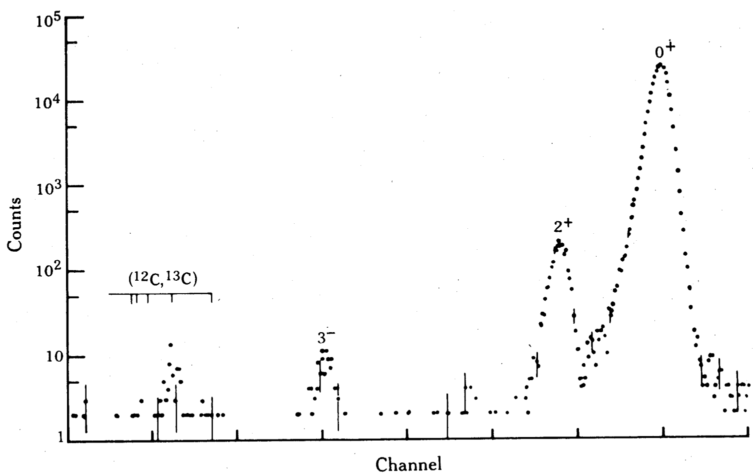

Fig. 2. Spectrum of 52 MeV ^{12}C projectiles backscattered from ^{206}Pb, at 171·6°. The peaks correspond to elastic scattering (0^+) and to inelastic scattering to the first 2^+ and 3^- states of ^{206}Pb. Single-nucleon transfer peaks are also indicated, including those for the reaction $^{206}Pb(^{12}C, ^{13}C)^{205}Pb$.

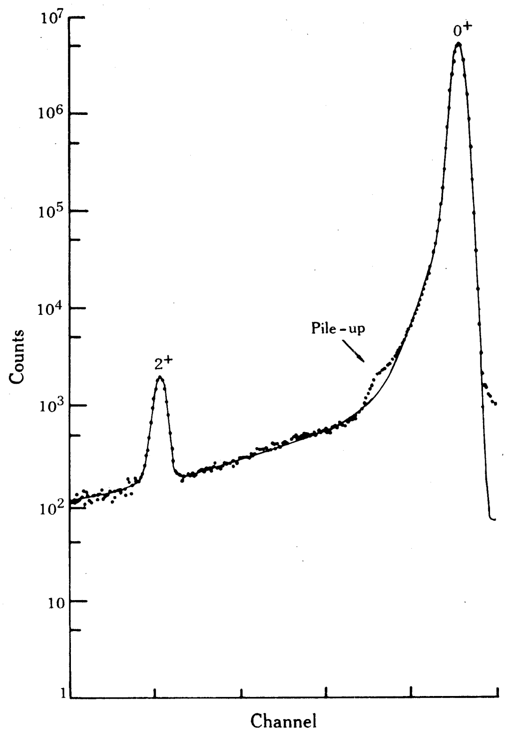

Fig. 3. Spectrum of 13·8 MeV ^{4}He projectiles backscattered from ^{206}Pb, at 171·6°. The curve is a fit to the spectrum, obtained as described by Esat *et al.* (1976) and Joye *et al.* (1977). The peaks correspond to elastic scattering (0^+) and to inelastic scattering to the first 2^+ excited state of ^{206}Pb. The feature labelled 'Pile-up' is due to pulse pile-up arising from projectiles scattered from ^{27}Al and ^{16}O in the target.

The effect of Coulomb–nuclear interference is manifested by deviation of R_{exp} from the excitation probability R_{comp} calculated assuming a pure Coulomb interaction; this calculation is performed using the de Boer–Winther program and known matrix elements (Joye *et al.* 1977, 1978). The double ratio R_{exp}/R_{comp} is then plotted as a function of laboratory bombarding energy E and of the distance of closest approach S between the nuclear surfaces in a head-on collision (assuming a nuclear radius parameter $r_0 = 1{\cdot}25$ fm).

Results and Discussion

The results for excitation of the first excited 2^+ states are shown in Fig. 4*a* for ^{204}Pb ($E_x = 0{\cdot}899$ MeV) and in Fig. 4*b* for ^{206}Pb ($E_x = 0{\cdot}803$ MeV). In both cases ^{4}He, ^{12}C and ^{16}O projectiles were used. The ^{16}O data have been published previously by Spear *et al.* (1978) in another context, but are shown again here for the sake of completeness. The curves show fits to the data (for $S \geqslant 3$ fm) of the function $A + B\exp\{C(S{-}D)\}$. This function, and the fitting parameters A, B, C and D, have no fundamental significance but the fits provide a convenient guide to the eye and are useful for systematic comparisons among the various sets of data. The arrows on the diagrams indicate the maximum bombarding energies used by Joye *et al.* (1978) for data analysed to determine quadrupole moments Q_{2^+}. It is evident that in each case the energies used are safe to the extent required by the accuracy of the data.

In Fig. 5*a* we show results for excitation by ^{16}O projectiles of the first 3^- state in ^{208}Pb at $E_x = 2{\cdot}615$ MeV. These results represent an extension of those presented by Joye *et al.* (1977) in connection with their determination of the quadrupole

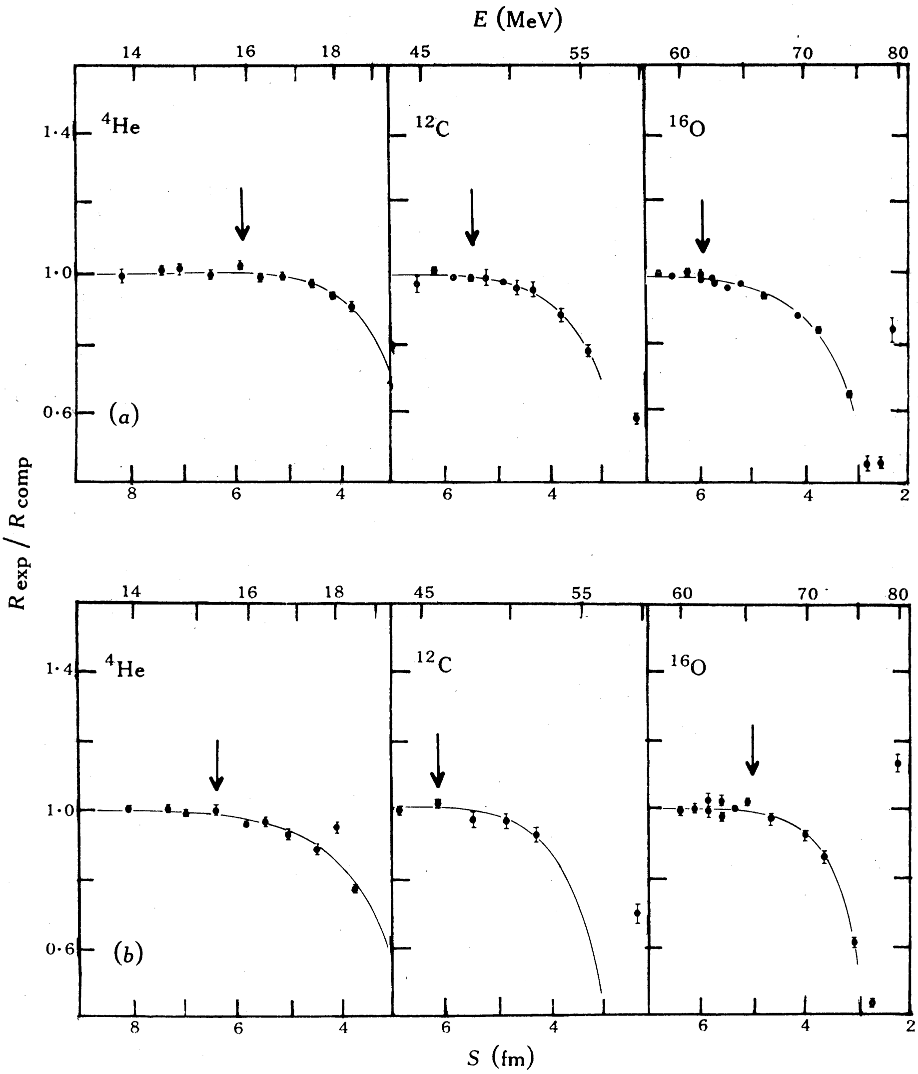

Fig. 4. Plots of the double ratio $R_{\mathrm{exp}}/R_{\mathrm{comp}}$ for excitation by ^{4}He, ^{12}C and ^{16}O projectiles of the first 2^+ states in (*a*) ^{204}Pb and (*b*) ^{206}Pb. The data are plotted as a function of laboratory bombarding energy E and distance of closest approach S. The curves are fits to the data obtained as described in the text. The significance of the arrows is explained in the text.

moment Q_{3^-} of the 3^- state. Joye *et al.* chose in their analysis to ignore data obtained at energies greater than 60 MeV, the energy indicated by the arrow in Fig. 5*a*. The new data confirm that interference effects are significant above 60 MeV. Indeed, it would be interesting to obtain quadrupole moment data at even lower energies than those used by Joye *et al.*; if nuclear interference is significant at ^{16}O bombarding energies of 60 MeV and less, then the result of Joye *et al.* overestimates the magnitude of Q_{3^-}, and correspondingly the true value of Q_{3^-} will be closer to the theoretical predictions.

We also show (in Figs 5*b* and 5*c*) data for ^{16}O excitation of the first 3^- states in ^{204}Pb ($E_x = 2\cdot634$ MeV) and ^{206}Pb ($E_x = 2\cdot648$ MeV). The values of Q_{3^-} are not known for ^{204}Pb and ^{206}Pb, and were assumed to be zero when calculating R_{comp} for these nuclei. It is noteworthy that the three sets of data shown in Fig. 5 are remarkably similar to each other, which suggests that possible excitations of the 3^- states in ^{204}Pb and ^{206}Pb via the low-lying 2^+ states which are present in these nuclei (but not in ^{208}Pb) do not significantly change the energy dependence of R_{exp}/R_{comp}. This suggestion is supported by calculations made with the de Boer–Winther Coulomb excitation program; for example, it is found that, for 60 MeV ^{16}O ions backscattered from ^{206}Pb, effects involving the first excited 2^+ state contribute less than 0·25% to the observed excitation probability of the 3^- state (assuming that $B(\mathrm{E2}; 0^+ \to 2^+) = 0{\cdot}10\ e^2\,\mathrm{b}^2$ (Joye *et al.* 1978) and $B(\mathrm{E1}; 3^- \to 2^+) = 8\times10^{-6}\ e^2\,\mathrm{b}$ (deduced from the lifetime measurement of Häusser *et al.* 1972)).

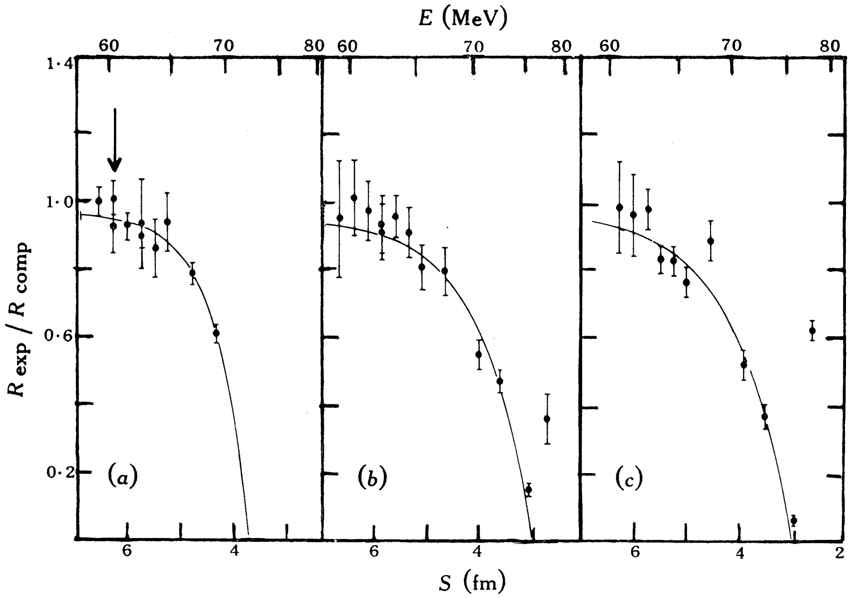

Fig. 5. Plots of the double ratio R_{exp}/R_{comp} for excitation by ^{16}O projectiles of the first 3^- state in (*a*) ^{208}Pb, (*b*) ^{204}Pb and (*c*) ^{206}Pb. The data are plotted as a function of laboratory energy E and distance of closest approach S. The curves are fits to the data obtained as described in the text. The significance of the arrow in (*a*) is explained in the text.

If we assume that $Q_{3^-} = 0$ for ^{204}Pb and ^{206}Pb, the present data for ^{16}O projectiles, when taken in conjunction with similar but statistically poorer data for ^{4}He and ^{12}C (Joye 1977), yield $B(\mathrm{E3}; 0^+ \to 3^-) = 0{\cdot}61 \pm 0{\cdot}04$ and $0{\cdot}60 \pm 0{\cdot}04\ e^2\,\mathrm{b}^3$ for ^{204}Pb and ^{206}Pb respectively. If $Q_{3^-} = -0{\cdot}42\ e\,\mathrm{b}$ (the value obtained for ^{208}Pb by Joye *et al.* 1977), then the value of $B(\mathrm{E3})$ is increased by about $0{\cdot}05\ e^2\,\mathrm{b}^3$ for both ^{204}Pb and ^{206}Pb, giving results remarkably similar to the value $B(\mathrm{E3}; 0^+ \to 3^-) = 0{\cdot}665 \pm 0{\cdot}035\ e^2\,\mathrm{b}^3$ obtained for ^{208}Pb (Joye *et al.* 1977). The present result for $B(\mathrm{E3})$ in ^{206}Pb is in good agreement with previous results of $0{\cdot}66 \pm 0{\cdot}07\ e^2\,\mathrm{b}^3$ by Grosse *et al.* (1971) and $0{\cdot}64 \pm 0{\cdot}04\ e^2\,\mathrm{b}^3$ by Ziegler and Peterson (1968); it is in less satisfactory agreement with the value of $0{\cdot}50 \pm 0{\cdot}03\ e^2\,\mathrm{b}^3$ reported by Häusser *et al.* (1972). We know of no previous $B(\mathrm{E3})$ determination for ^{204}Pb.

Conclusions

The results presented here demonstrate that the bombarding energies used by Joye *et al.* (1978) in their determination of Q_{2^+} for ^{204}Pb and ^{206}Pb were indeed 'safe', and in addition they lend some support to the selection of ^{16}O bombarding energies made by Joye *et al.* (1977) in their determination of Q_{3^-} in ^{208}Pb. The implications of the ^{16}O data for the general problem of safe energy determinations have been discussed elsewhere (Spear *et al.* 1978). The similarity between the properties of the first 3^- states in ^{204}Pb, ^{206}Pb and ^{208}Pb (that is, excitation energies and B(E3; $0^+ \rightarrow 3^-$) values) suggests that they have a common generic origin; it would therefore be interesting to locate and study the first 3^- states of other even–even nuclei in this mass region.

References

Esat, M. T., Kean, D. C., Spear, R. H., and Baxter, A. M. (1976). *Nucl. Phys.* A **274**, 237.
Grosse, E., *et al.* (1971). *Nucl. Phys.* A **174**, 525.
Häusser, O., Khanna, F. C., and Ward, D. (1972). *Nucl. Phys.* A **194**, 113.
Joye, A. M. R. (1977). Ph.D. Thesis, Australian National University.
Joye, A. M. R., Baxter, A. M., Fewell, M. P., Kean, D. C., and Spear, R. H. (1977). *Phys. Rev. Lett.* **38**, 807.
Joye, A. M. R., Baxter, A. M., Hinds, S., Kean, D. C., and Spear, R. H. (1978). *Phys. Lett.* B **72**, 307.
Spear, R. H., *et al.* (1978). *Phys. Lett.* B **76**, 559.
Ziegler, J. T., and Peterson, G. A. (1968). *Phys. Rev.* **165**, 1337.

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