

COULOMB EXCITATION OF THE LEAD ISOTOPES WITH α AND ^{16}O BEAMS

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Received 22 June 1971

Abstract: The lead isotopes were Coulomb excited with α -particles of 15 and 18 MeV and ^{16}O ions of 70 and 80 MeV. By measuring the absolute yields of the de-excitation γ -rays very accurately, $B(E\lambda)$ values for the first 2^+ states in ^{204}Pb and ^{206}Pb , the 3^- states in ^{206}Pb and ^{208}Pb and of four states in ^{207}Pb were obtained. The E2 transition strengths to the two first excited states of ^{207}Pb are well described by coupling these states to a quadrupole core excitation of ^{208}Pb . The $B(E3)$ values for the excitation of the $(3^- \otimes p_{\frac{1}{2}}^-)$ doublet show only slight deviations from the weak coupling value, yet the lifetimes of the two states, which were determined with the Doppler-shift attenuation method, are different from model predictions. The M1 transition rate of the $\frac{3}{2}^-$ state to ground as determined from the lifetime of 0.17 ps agrees with the value obtained from the $B(E2)$ and the mixing ratio measurement.

E NUCLEAR REACTIONS $^{204,206,207,208}\text{Pb}(\alpha, \alpha'\gamma)$, $E = 15$ and 18 MeV; $^{206,207,208}\text{Pb} (^{16}\text{O}, ^{16}\text{O}'\gamma)$ $E = 70$ and 80 MeV; measured E_γ , I_γ , Doppler-shift attenuation. $^{204,206,207,208}\text{Pb}$ deduced $B(E\lambda)$, $B(M\lambda)$ and lifetimes. Natural and enriched targets.

1. Introduction

Various investigations have been performed on the electromagnetic properties of single-particle states in odd- A nuclei around ^{208}Pb [refs. ¹⁻⁶]. The deviations of experimentally determined γ -transition rates and nuclear moments from the single-particle shell-model predictions are accounted for by the concept of core polarization. In ^{207}Pb one can investigate transition matrix elements between the $p_{\frac{1}{2}}^-$, $f_{\frac{3}{2}}^-$ and $p_{\frac{3}{2}}^-$ neutron hole states by E2 Coulomb excitation. Neutron pick-up experiments have shown that these levels are good single-particle states ^{7,8}). Coulomb excitation of these states has been carried out by Nathan ¹) and Andreev *et al.* ²) and the experimentally determined transition strengths have been fitted with an effective neutron charge of 0.85 ± 0.2 .

Since the quoted errors of the measured transition strengths are in general too big to allow a severe test of theoretical predictions, a reinvestigation using new tech-

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niques, such as high-resolution Ge(Li) detectors and heavy-ion beams seemed to be useful to us. A high-accuracy experiment would make it possible to decide, whether one effective charge is sufficient to describe all E2 transitions between the neutron hole states or if the core polarization is dependent on l -values or spins of the states involved. Coulomb excitation is especially suited to investigate these questions, because of the unambiguous extraction of reduced transition probabilities from the experimental data.

The Coulomb excitation of single-particle states in ^{209}Bi has been investigated very thoroughly by Broglia *et al.* ⁶⁾ who could explain their results in the framework of the weak coupling model ³¹⁾. The multiplet formed by coupling the $h_{7/2}$ proton to the octupole vibration of ^{208}Pb has also been Coulomb excited ^{6, 9)} and the transition strengths agree well with calculations performed on the basis of the particle-vibration coupling model ^{34, 35)}. A similar octupole vibration multiplet has been observed in inelastic scattering from ^{207}Pb with a cross section comparable to the excitation of the 3^- state in ^{208}Pb [refs. ¹⁰⁻¹⁵⁾]. Using the $(2J+1)$ rule the spins of the doublet could be assigned ¹²⁾ which have been later confirmed in an analogue resonance experiment [ref. ¹⁵⁾].

In this paper we discuss the Coulomb excitation of this doublet and of the first two excited states in ^{207}Pb ; part of this work has been reported recently ^{16, 17)}. Results are also given of an experiment concerning the excitation of the 2^+ states in ^{204}Pb and ^{206}Pb and of the 3^- states in ^{206}Pb and ^{208}Pb which have to be compared to data obtained by inelastic scattering ^{13, 14)}, Coulomb excitation ^{1, 18)} and lifetime measurements ¹⁹⁾.

2. Experimental procedure

The experiments were carried out at the Heidelberg EN and MP Tandem-accelerators with an α -beam of 15 and 18 MeV and ^{16}O ions of 70 and 80 MeV, using thick metallic lead targets which stopped the beam. Natural lead and isotopically enriched targets of ^{206}Pb (97.4 %), ^{207}Pb (92.4 %) and ^{208}Pb (99.5 %) were used.

The γ -rays emitted after Coulomb excitation were detected by a Ge(Li) detector of about 40 cm^3 sensitive volume which was placed at either 0° , 55° or 90° with respect to the beam, and at a distance of 4 cm to the target. At 55° degrees the influence of the γ -ray angular distribution can be neglected, since its anisotropy is due essentially only to a $P_2(\cos\theta)$ term ¹⁷⁾ which vanishes at this angle. A γ -spectrum obtained by bombarding a ^{207}Pb target with an 18 MeV α -beam is shown in fig. 1b. Fig. 2 shows two spectra obtained with an ^{16}O beam of 70 MeV. The two strongest transitions observed are the ground state decay lines of the $\frac{5}{2}^-$ and $\frac{3}{2}^-$ states at 569.7 and 897.5 keV respectively. One notes that the 897.5 keV line is Doppler broadened and its centroid is shifted by about 4 keV which has allowed us to determine the lifetime of this level, as will be discussed below. Besides these two transitions the decay of the $(3^- \otimes p_{3/2})$ doublet at 2.6 MeV is observed, as shown in a partial decay scheme of ^{207}Pb (fig. 3).

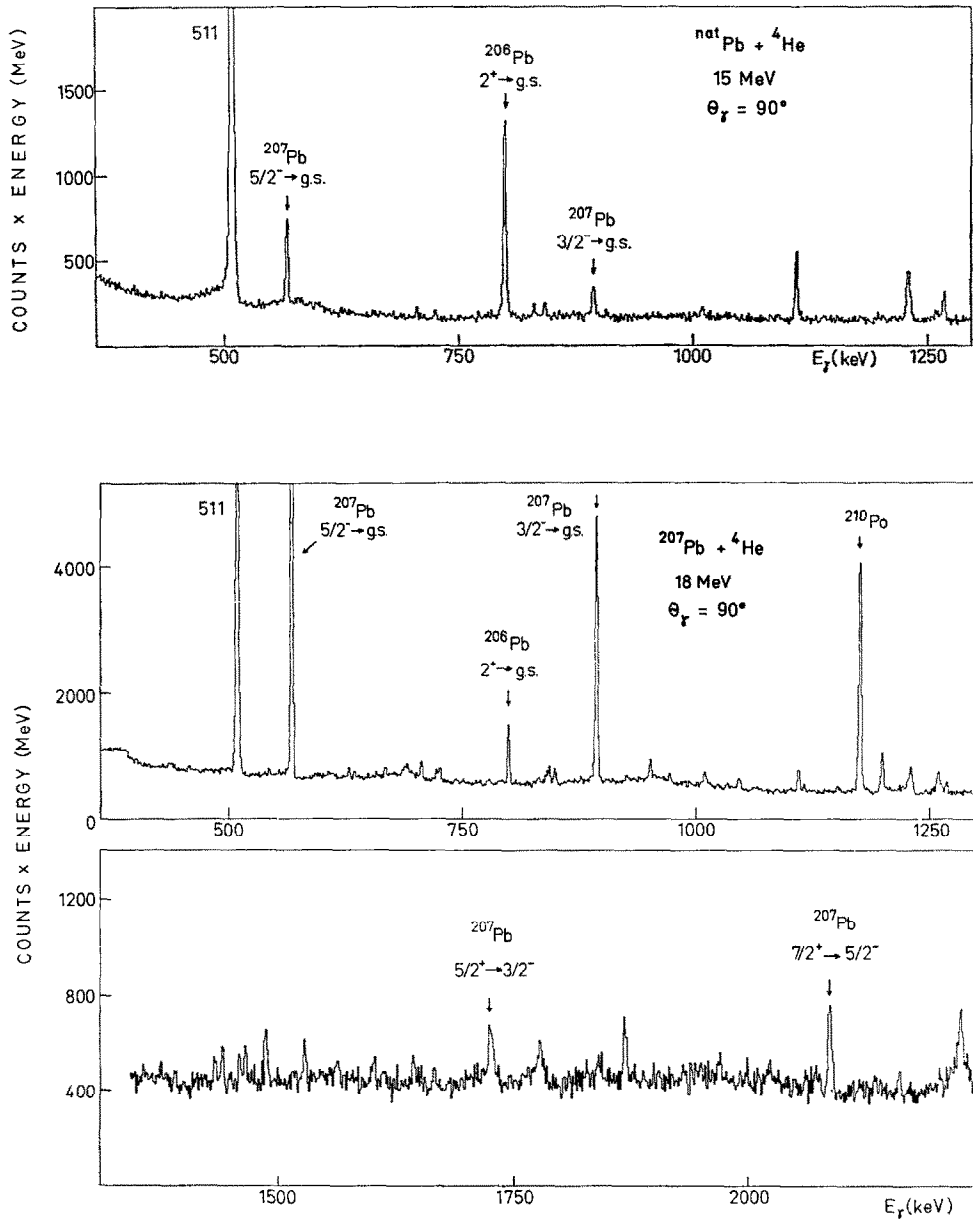


Fig. 1. Gamma-ray spectrum following bombardment of natural lead (a) and ^{207}Pb (b) with 15 and 18 MeV α -particles respectively. The Ge(Li) detector efficiency is roughly taken into account by multiplying the γ -yield by the γ -energy. Lines of Coulomb excitation of ^{207}Pb (and ^{206}Pb contamination) and of the ^{207}Pb (α, n) reaction can be seen.

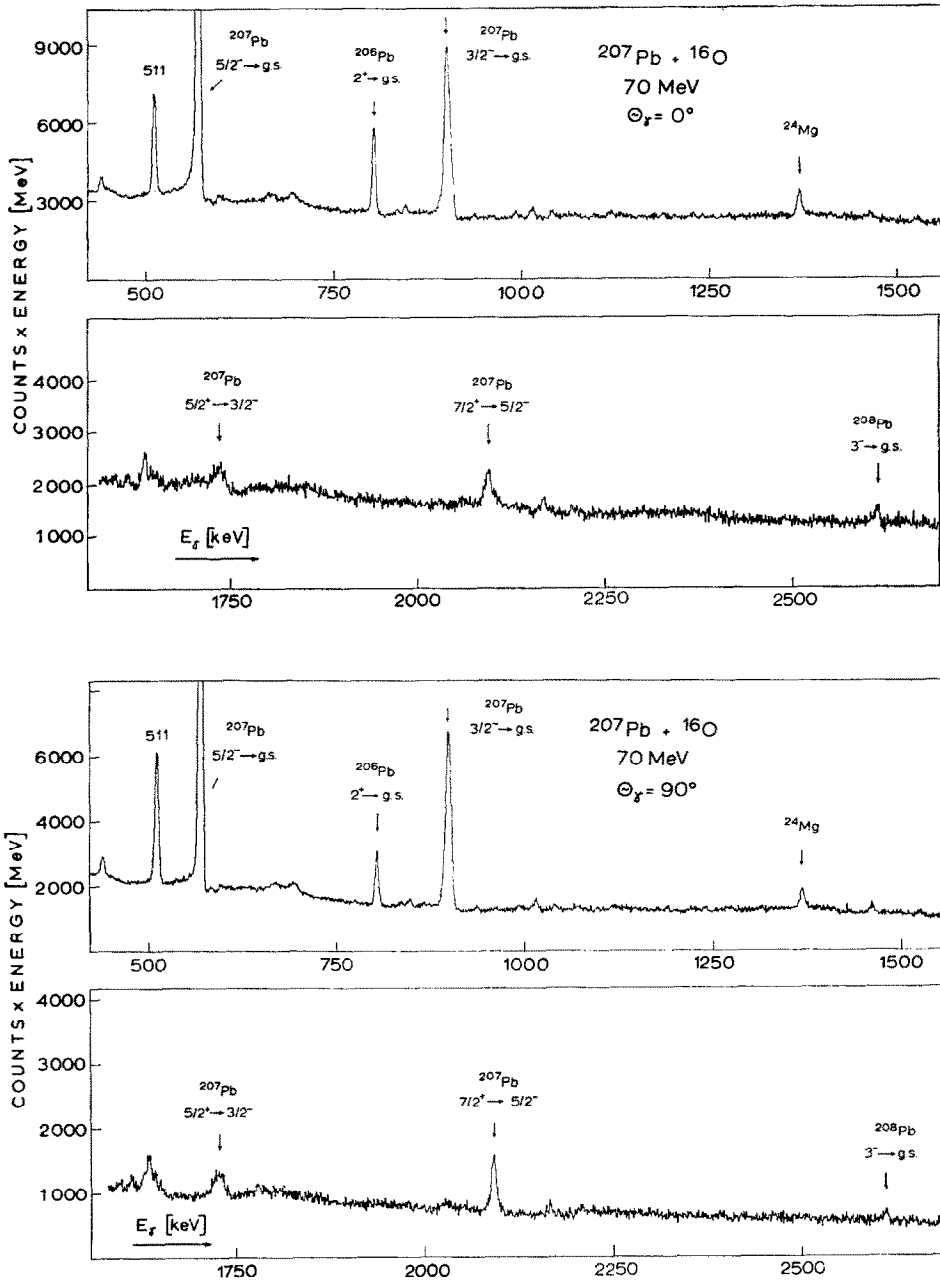


Fig. 2. Gamma-ray spectrum following the Coulomb excitation of ^{207}Pb with 70 MeV ^{16}O ions. The Ge(Li) detector was placed at 0° (a) and 90° (b) with respect to the beam.

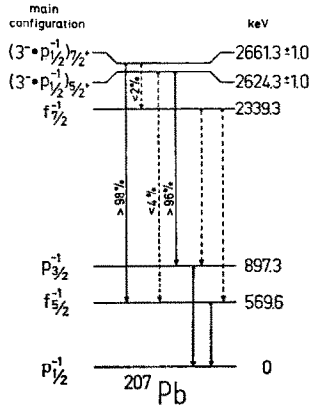


Fig. 3. The partial decay scheme of ^{207}Pb showing the decay of the $(3^- \otimes p_{3/2})$ doublet. Unobserved transitions are shown as dotted lines. Upper limits for their intensities are given in the picture.

The peak belonging to the $\frac{5}{2}^+ \rightarrow \frac{3}{2}^-$ transition is Doppler broadened, but the poor statistics of our spectra only allow a rough lifetime estimate. In our experiment we could detect no Doppler shift for the $\frac{7}{2}^+ \rightarrow \frac{5}{2}^-$ transition which gives a lower limit for the lifetime of the $\frac{7}{2}^+$ level.

An 802 keV γ -ray from the decay of the first excited state of ^{206}Pb , which was in our target as a contamination of about 1 %, can be seen in figs. 1 and 2. The relative ratio of the cross sections for excitations of the 802 keV and 570 keV lines could be determined by using a natural lead target which has a well-known isotopic composition. In the spectra taken with this target the 897 keV line is found to have about double the intensity as compared to the enriched ^{207}Pb target. We believe that this anomaly is due to the excitation of the 899 keV state in ^{204}Pb [refs. ^{1,21})] which has a natural abundance of 1.48 %. By subtraction of the known yield for the 897 keV line from ^{207}Pb the yield of the 899 keV transition in ^{204}Pb has been determined.

In the spectra obtained with a natural lead target the decay of the 3^- states in ^{206}Pb and ^{208}Pb has also been observed. For a better yield determination we also repeated this experiment using enriched targets. In ^{206}Pb the only observed decay branch of the 3^- state is the transition to the 2^+ state at 802 keV which is clearly Doppler broadened.

3. Determination of the $B(E\lambda)$ values

The energy and efficiency calibration of the experimental set-up in these experiments was carried out using calibrated γ -ray sources [†] placed on the spot of the target, and correcting the data for dead-time losses of the electronics. The energy resolution was about 2.5 keV for a 1 MeV γ -line allowing a measurement of γ -ray energies with an accuracy of about 0.3 keV. Spectra obtained with an α -beam were used for this

[†] Obtained from the International Atomic Energy Agency.

purpose, since in this case there is less Doppler broadening of the γ -lines. The whole target chamber together with part of the beam tube were electrically insulated allowing an accurate beam-charge measurement. Absolute thick target yields have been measured with this set-up to an accuracy of about 5 %. Using the quantum mechanical

TABLE 1
 $B(E\lambda)$ values as obtained from Coulomb excitation of the lead isotopes

A	$j_1 \rightarrow j_2$	E_2 (keV)	λ	$B(E\lambda, j_1 \rightarrow j_2)$ [$e^2 \cdot b^2$]		
				this work	other exp.	ref.
204	$0^+ \rightarrow 2^+$	899.0 ± 0.3	E2	0.146 ± 0.015	0.22 ± 0.08	¹⁾
206	$0^+ \rightarrow 2^+$	803.3 ± 0.3	E2	0.103 ± 0.008	0.091 ± 0.006	¹⁹⁾
	$0^+ \rightarrow 3^-$	2545.3 ± 1.0	E3	0.66 ± 0.07	0.64 ± 0.04	¹⁴⁾
207	$\frac{1}{2}^- \rightarrow \frac{3}{2}^-$	569.7 ± 0.3	E2	0.0210 ± 0.0015	0.0213 ± 0.0009	⁴⁾
	$\frac{1}{2}^- \rightarrow \frac{3}{2}^-$	897.5 ± 0.3	E2	0.0124 ± 0.0010	$\left\{ \begin{array}{l} 0.016 \pm 0.008 \\ 0.015 \pm 0.006 \end{array} \right.$	¹⁾
	$\frac{1}{2}^- \rightarrow \frac{5}{2}^+$	2624.5 ± 1.0	E3	0.19 ± 0.02		²⁾
	$\frac{1}{2}^- \rightarrow \frac{7}{2}^+$	2551.4 ± 1.0	E3	0.26 ± 0.03	sum = 0.67 ± 0.04	¹⁴⁾
208	$0^+ \rightarrow 3^-$	2614.8	E3	0.60 ± 0.07	$\left\{ \begin{array}{l} 0.72 \pm 0.04 \\ 0.58 \pm 0.04 \end{array} \right.$	¹⁴⁾
	$0^+ \rightarrow 2^+$	4080	E2	not observed		0.30 ± 0.02

TABLE 2
 $B(E\lambda)$ values in ^{207}Pb from excitation with α and ^{16}O ions of different energies

Beam ion	$B(E\lambda)$ [$e^2 \cdot b^2$]		
	$\frac{1}{2}^- \rightarrow \frac{3}{2}^-$	$\frac{1}{2}^- \rightarrow \frac{5}{2}^+$	$\frac{1}{2}^- \rightarrow \frac{7}{2}^+$
α (15 MeV)	0.0121 ± 0.0012		
α (18 MeV)	0.0126 ± 0.0015	0.21 ± 0.03	0.29 ± 0.05
^{16}O (70 MeV)	0.0126 ± 0.0013	0.20 ± 0.03	0.26 ± 0.04
^{16}O (80 MeV)	0.0124 ± 0.0017	0.17 ± 0.04	0.22 ± 0.05
Mean value	0.0124 ± 0.0010	0.19 ± 0.02	0.26 ± 0.03

The values are normalized to $B(E2, \frac{1}{2}^- \rightarrow \frac{3}{2}^-) = 0.0210 \pm 0.0015 e^2 \cdot b^2$.

first-order Coulomb excitation formalism²²⁾ and empirical energy-loss data^{23,24)} $B(E\lambda)$ values were extracted from the experimentally measured γ -yields, after correcting the data for the feeding from higher levels and for conversion²¹⁾. The results are given in table 1.

Since the $\frac{5}{2}^-$ state in ^{207}Pb and the 2^+ state in ^{206}Pb decay only via E2 radiation to the ground states, the mean lifetime of these states can be calculated from the measured $B(E2)$ values and the known conversion coefficients²¹⁾. The values obtained by us in this way agree with direct lifetime measurements^{4,19)} within the errors, as shown in table 1. From table 2 the good agreement of relative $B(E\lambda)$ values deduced from measurements with α -particles and ^{16}O ions at several incident energies can be

seen, supporting the assumption that no systematic errors have been made in the analysis of the data. Similar agreement between the data from bombardment with α - and ^{16}O beams of the same energies as used by us has been reported for the Coulomb excitation on ^{208}Pb [ref. ¹⁸] and ^{209}Bi [refs. ^{6, 9}].

4. Lifetime measurements using the Doppler-shift attenuation method (DSAM)

As mentioned in sect. 2, the $\frac{3}{2}^- - \frac{1}{2}^-$ 897 keV γ -transition is broadened and shifted by the Doppler effect in the spectra obtained with an ^{16}O beam. This allows the determination of the lifetime of the $\frac{3}{2}^-$ state with the Doppler-shift attenuation method. The lineshape and centroid shift observed at 0° with ^{16}O beams of 70 and 80 MeV were fitted with a program ²⁵) employing the Lindhardt-Scharff-Schiøtt ²⁶) stopping theory and the scattering formalism due to Blaugrund ²⁷). This program calculates a theoretical line shape as a function of the lifetime of the decaying state and folds into this the shape of an unbroadened line. By comparison with the experimental data a χ^2 is calculated. The following effects had to be taken into account in this calculation of the line shape:

(i) The slowing down of the beam in the target to an energy of about 40 MeV had to be considered, for which energy the contribution to the total Coulomb excitation yield is less than 1 %.

(ii) The angular distribution of the scattered ^{16}O ions was calculated using ref. ¹⁹). Since the γ -ray angular distribution is rather flat ¹⁷) the neglect of the particle- γ correlation does not introduce a large error.

(iii) Instead of the Blaugrund approximation for $\langle v \cos \theta \rangle$ a different procedure for averaging the projected ion velocity was employed which has been described recently ²⁵).

(iv) The stopping power parameters were changed by $\pm 20\%$ to investigate the dependence of the extracted lifetime on these parameters. The quoted absolute error for the lifetime is mainly due to ambiguities in the stopping power of the lead ions recoiling into the lead target.

The best fit was obtained with a mean lifetime of 0.17 ± 0.05 ps, the corresponding theoretical line shape is shown in fig. 4. The state in question decays via M1 and E2 radiation to the ground state. The mixing ratio has been measured by analysing the γ -ray angular distribution following excitation with α -particles of 14.4 MeV with Coulomb excitation formulae ²²), as described in another paper ¹⁷). From this mixing ratio, the $B(\text{E}2)$ value, and conversion coefficients ²¹) a lifetime of 0.21 ± 0.04 ps is found which agrees with the above value within the errors. This demonstrates that the Doppler-shift attenuation method can yield quite accurate results in this mass region.

We also have applied the quoted method to the $\frac{5}{2}^+ - \frac{3}{2}^-$ γ -decay in ^{207}Pb and to the $3^- - 2^+$ γ -decay in ^{206}Pb which were observed following Coulomb excitation with ^{16}O ions of 80 MeV. Values for the lifetimes obtained from the fit are given in table 3.

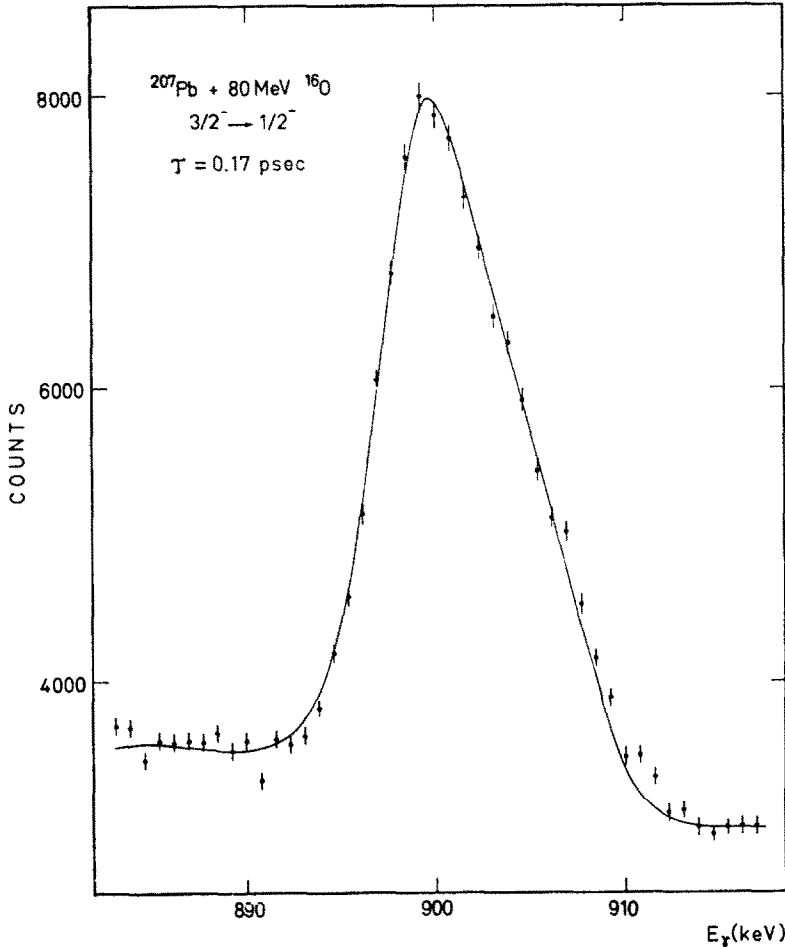


Fig. 4. Part of the spectrum of γ -rays following excitation of ^{207}Pb with 80 MeV ^{16}O ions, showing the shape of the $\frac{3}{2}^- \rightarrow \frac{1}{2}^-$ line as observed at 0° with respect to the beam. The drawn line is the best fit obtained from the Doppler-shift attenuation calculations.

TABLE 3
Mean lifetimes measured by the Doppler-shift attenuation method

A	j_2	E_2 (keV)	Mean lifetime τ (ps)		
			this work	other exp.	ref.
206	3^-	2645.3	0.4 ± 0.2		
207	$\frac{3}{2}^-$	897.5	0.17 ± 0.05	0.21 ± 0.04	¹⁷⁾
	$\frac{5}{2}^+$	2624.5	0.25 ± 0.20		
	$\frac{7}{2}^+$	2661.4	$\tau > 0.6$	$\tau < 6.0$	^{a)}

^{a)} From branching ratio as measured in this work.

The quoted errors are mainly due to the bad statistics of our spectra. The fact that the $\frac{7}{2}^+ - \frac{5}{2}^-$ transition is not broadened allows us to set a lower limit of 0.6 psec for the mean lifetime of the $\frac{7}{2}^+$ member of the doublet since the stopping time is about 1.2 psec [ref. ²⁶]. An upper limit of 6 psec is given by the fact that the ground state decay branch of that state has not been observed and the ground state transition rate is known from the Coulomb excitation yield (cf. table 3).

5. Weak coupling calculations

As shown by Bohr and Mottelson ³⁰) and de-Shalit ³¹) core-polarisation effects in E2 matrix elements can be explained by admixtures of a collective quadrupole core excitation. Values of $B(E2)$ in the odd Tl isotopes have been calculated in this way ³¹⁻³³). The quadrupole excitation of ²⁰⁸Pb was first used in such a calculation by Broglia *et al.* ⁶) to explain E2 transition rates in ²⁰⁹Bi.

Core-excitation weak coupling multiplets in the Pb region have been discussed previously from a theoretical point of view in a number of papers by Hamamoto ³⁵) and by Stein and Auerbach ³⁶). In ²⁰⁷Pb the $(3^- \otimes p_{\frac{3}{2}}^{-1})$ and $(2^+ \otimes p_{\frac{3}{2}}^{-1})$ doublets have been investigated experimentally ^{11, 12}) and other multiplets in this nucleus have been tentatively assigned ^{15, 20}). The single-particle states, the core-coupled multiplets and their mixing can be described by the Hamiltonian (1) which is composed of a shell-model term, a term describing the vibration, and a coupling term ³³⁻³⁵)

$$H = H^{s.m.} + H^{vib} + H^{coup1}, \quad (1a)$$

with

$$H^{coup1} = -r \frac{dV}{dr} \sum_{\lambda, \mu} (\alpha_{\lambda}^{\mu} Y_{\lambda}^{\mu})_0. \quad (1b)$$

The matrix elements of the coupling Hamiltonian between a single-particle state j_2 and the core-coupled state $(j_1 \lambda) j_2$ is given by:

$$\begin{aligned} \langle (j_1 \lambda) j_2 | H^{coup1} | j_2 \rangle &= (-)^{j_2 - j_1 + \frac{1}{2}(l_2 - l_1 + \lambda)} \frac{\sqrt{4\pi}}{3ZeR^{\lambda}} \\ &\times \langle j_2 \frac{1}{2} \lambda 0 | j_1 \frac{1}{2} \rangle \langle j_1 \left| -r \frac{dV}{dr} \right| j_2 \rangle \langle \lambda || \mathcal{M}(E\lambda) || 0 \rangle, \end{aligned} \quad (2)$$

$\langle \lambda || \mathcal{M}(E\lambda) || 0 \rangle$ is the reduced matrix element for the $E\lambda$ transition in the core. The reduced matrix elements and spherical harmonics are defined in ref. ²⁸).

To investigate the effect of core-excitation admixtures on the E2 transition matrix elements we did some calculations using formula (2). The matrix element $\langle j_1 | -r \frac{dV}{dr} | j_2 \rangle$ was calculated in a Saxon-Woods potential ²⁹). To fix the core parameters we calculated the E2 transition rate between the $s_{\frac{1}{2}}$ and $d_{\frac{3}{2}}$ single-particle states in ²⁰⁹Pb in dependence of the quadrupole transition strength in ²⁰⁸Pb, assuming that this strength is concentrated in the 2^+ state at 4.08 MeV. By comparing the calculated

and the experimental³⁾ transition rate in ^{209}Pb the core strength $\langle \lambda || \mathcal{M}(E\lambda) || 0 \rangle$ was found to be $0.82 \pm 0.02 e \cdot b$. From electron scattering¹⁴⁾ on ^{208}Pb a value of $0.55 \pm 0.02 e \cdot b$ is derived. This discrepancy indicates that there is further quadrupole strength in ^{208}Pb at higher energies, which has not yet been found experimentally (cf. table 1).

TABLE 4

Wave functions of the three lowest states in ^{207}Pb as obtained from the weak coupling calculation taking into account the collective 2^+ state of ^{208}Pb

E	J^π	$p_{\frac{1}{2}}$	$f_{\frac{1}{2}}$	$p_{\frac{3}{2}}$	$2^+ \otimes p_{\frac{1}{2}}$	$2^+ \otimes f_{\frac{1}{2}}$	$2^+ \otimes p_{\frac{3}{2}}$	$2^+ \otimes f_{\frac{3}{2}}$	$2^+ \otimes h_{\frac{3}{2}}$
0	$\frac{1}{2}^-$	(0.98)	0	0	0	-0.16	-0.13	0	0
570	$\frac{5}{2}^-$	0	(0.98)	0	-0.13	-0.12	-0.05	-0.03	-0.08
898	$\frac{3}{2}^-$	0	0	(0.97)	0.14	0.07	-0.11	-0.13	0

Upper limits for the amplitudes of the main configurations as got from normalization are given in brackets.

We found the coupling matrix elements (2) to be between 0.2 and 0.6 MeV in our case, depending on the l -values involved. From these matrix elements we have calculated the admixtures of the core-coupled states into the single-particle states. Because of the smallness of the coupling matrix elements compared to the phonon energy of 4 MeV these calculations were carried out in perturbation theory. The resulting wave functions for the three lowest states of ^{207}Pb are given in table 4.

The amplitudes of the configurations based on the 2^+ vibration are listed. The amplitudes of the main configurations are given in brackets to point out that they were only got by normalization not taking other admixtures into account. Especially the 1^+ core excitations which are responsible for the polarization effects in the magnetic moments and M1 transition rates, have been shown to be of importance⁴⁰⁾. It also has to be stressed that the weak coupling model as used here does not include anti-symmetrization which can change the results slightly. Anyhow, the given numbers are not in disagreement with the neutron pick-up results^{7,8)}, since spectroscopic factors obtained from this kind of reaction have got a systematic error of about 20%. Recent calculations^{41,42)} on the amount of single-particle strength in the low-lying states of ^{207}Pb give values similar to those quoted by us.

6. Discussion

The low-lying states of ^{207}Pb have been shown to be good shell-model states by pick-up reactions^{7,8)} which show no deviations from the single-particle model. Electromagnetic transition rates between these states, however, cannot be explained in that framework because of the effect of core polarization. In order to obtain a quantitative estimate for this effect one can introduce the concept of effective charges by comparing observed reduced matrix elements with single-particle values²⁸⁾.

TABLE 5
Experimental and theoretical decay matrix elements in ^{207}Pb

$J_1 \rightarrow J_2$	E (keV)	λ	experiment (this work)	single particle ^{b)}	Matrix element ME ^{a)}			theory	ref.
					Weisskopf estimate	weak coupling calculation ^{c)}			
$\frac{5}{2}^- \rightarrow \frac{1}{2}^-$	569.7	E2	0.042 ± 0.003	$0.050 e_{\text{eff}}^2(\text{E2})$	0.044	0.040 ± 0.003	0.041	³⁷⁾	
$\frac{3}{2}^- \rightarrow \frac{1}{2}^-$	897.5	E2	0.025 ± 0.002	$0.045 e_{\text{eff}}^2(\text{E2})$	0.029	0.030 ± 0.002	0.026	³⁷⁾	
		M1	1.85 ± 0.33	4.62	7.16		$\begin{cases} 2.40 \\ 2.72 \end{cases}$	³⁸⁾ ³⁹⁾	
$\frac{5}{2}^+ \rightarrow \frac{1}{2}^-$	2624.5	E3	0.38 ± 0.04		0.016	0.50 ± 0.04	0.55	³⁵⁾	
$\frac{3}{2}^- \rightarrow \frac{3}{2}^-$	1727.0	(E1)	$(3 \pm 1) \times 10^{-5}$		0.14		$4.1 \times 10^{-3} e_{\text{eff}}^2(\text{E1})$	³⁵⁾	
$\frac{3}{2}^+ \rightarrow \frac{1}{2}^-$	2661.4	E3	0.52 ± 0.06		0.021	0.67 ± 0.05	0.69	³⁵⁾	
$\frac{5}{2}^- \rightarrow \frac{3}{2}^-$	2091.7	(E1)	$10^{-6} < \text{ME} < 10^{-5}$		0.18		$4.8 \times 10^{-3} e_{\text{eff}}^2(\text{E1})$	³³⁾	

^{a)} Matrix element $\text{ME} = |\langle J_1 || \mathcal{M}_\lambda || J_2 \rangle|^2 = (2J_1 + 1)B(E, M\lambda, J_1 \rightarrow J_2) [e^2 \cdot b^\lambda]$ or $[\mu_n^2 b^\lambda - 1]$.

^{b)} The calculations have been carried out with Saxon-Woods potential parameters from ref. ²⁹⁾.

^{c)} The calculational method is given in the text. The error of these values is due to core parameter errors.

Decay branches not quoted are not observed; their intensity is less than 5% of the observed ones.
Note added in proof: A recent calculation ⁴⁶⁾ of the $\frac{3}{2}^- \rightarrow \frac{1}{2}^-$ M1 transition rate gives a ME of $2.06 \mu_n^2$ which agrees with our experimental value.

We have used shell-model matrix elements calculated in a Saxon-Woods potential with standard potential parameters²⁹). The results of this calculation are given in table 5 together with our experimental values. The effective charges obtained from these values are 0.93 ± 0.03 and 0.75 ± 0.08 for the E2 transitions between the $f_{7/2}$ and $p_{3/2}$ neutron hole states respectively and the ground state. The difference between these numbers which is three standard deviations shows that the core-polarization effect is state dependent. The effective neutron charge from the $s_{3/2}$ - $d_{3/2}$ transition in ^{209}Pb has been measured to be 0.42 ± 0.01 whereas proton polarization charges have been found to be between 0.4 and 1 for single-particle^{1, 6)} and multi-particle states^{43, 44)}.

In the weak coupling model the effective charges are attributed to admixtures of core excitation into the states involved. The admixtures in the initial and final state lead to two contributions to the E2 transition rate which add up coherently. Since we are discussing neutron states, no single-particle term is added, because the core-polarization effect is treated by admixing core-excited states, i.e. we use effective neutron charges equal to zero. The reduced matrix elements calculated with the weak coupling wave functions given in table 4 are listed in table 5 together with the experimental values. An agreement of the experimental values with the calculated ones within the experimental errors is found. A very satisfying aspect of this agreement is that the core transition strength as derived from ^{209}Pb gives the right results also in ^{207}Pb .

In the last column of table 5 matrix elements calculated with the Migdal theory^{37, 38} are given. Although this theory does not use experimental core parameters, the agreement in the case of E2 transitions is extremely good; for the M1 transition the theoretical value is less than two standard deviations away from the experimental value. Another theoretical M1 transition rate published very recently³⁹⁾ shows a similar deviation from experiment.

In the case of the octupole vibration doublet in ^{207}Pb , the admixtures have been shown by Hamamoto³⁵⁾ to be about 5%. Therefore, the reduced E3 matrix elements to the ground state which has got 98% of the $p_{3/2}$ hole amplitude, are predicted by the weak coupling model to be 0.93 of the matrix element in ^{208}Pb .

If one takes $0.66 \pm 0.04 e^2 \cdot b^3$ as the $B(E3)$ value of the core, which is a mean of different values from the literature^{13, 14, 18)} (cf. table 1), the theoretical values are bigger than the experimental ones by more than two standard deviations, as shown in table 5. This can be, however, due to admixtures of other core states which we have not taken into account.

The decay of the doublet is observed to populate mainly the $\frac{5}{2}^-$ and $\frac{3}{2}^-$ states, as shown in fig. 3. One can assume this decay to be mainly an E1 decay. Such E1 transitions cannot occur between the main configurations of initial and final states, they have to be due to admixtures in at least one of them. In our model we predict an E1 transition of the $(3^- \otimes p_{3/2})$ doublet to the $(2^+ \otimes p_{3/2})$ components of the final states. Since the matrix element $\langle 2^+ || \mathcal{M}(E1) || 3^- \rangle$ in ^{208}Pb is not known, one cannot calculate this decay rate absolutely. In this context it should be remarked that the

3^- state of ^{206}Pb mainly decays to the first excited 2^+ state with an E1 transition rate comparable to the E1 decay rates in ^{207}Pb . A further contribution to the E1 transition strength can arise from an admixture in the doublet states. The configuration relevant for the E1 transition is the dipole giant resonance coupled to the low-lying states. We did not calculate mixing with this configuration, but found out that the transitions $\frac{7}{2}^+ \rightarrow \frac{5}{2}^-$ and $\frac{5}{2}^+ \rightarrow \frac{3}{2}^-$ are favoured by vector algebra compared to $\frac{7}{2}^+ \rightarrow \frac{7}{2}^-$ and $\frac{5}{2}^+ \rightarrow \frac{5}{2}^-$ where spin flips are involved. Experimentally the "spin-flip transitions" have not been observed. Until now no explanation has been found for the experimental fact that the $\frac{5}{2}^+$ state decays faster than the $\frac{7}{2}^+$ member of the doublet, which has got a 20 % higher decay energy.

Recently Hamamoto³⁵⁾ has calculated the admixtures of high-lying single-particle states in the doublet. These admixtures of about 1 % were assumed to be responsible for the decay of the doublet, their decay was described by an effective charge for E1 transitions. Taking our data one gets values between 0.005 and 0.03 for the square of the effective charge for the $\frac{5}{2}^+ \rightarrow \frac{3}{2}^-$ transition and between 0.0002 and 0.002 in the case of the $\frac{7}{2}^+ \rightarrow \frac{5}{2}^-$ transition. As there is no obvious reason for the discrepancy the problem stays open for further investigations. The square of the proton effective E1 charge was found to be 0.05 from three transitions⁴⁵⁾ in ^{209}Bi .

7. Conclusion

We have shown that Coulomb excitation allows us to determine electric transition rates to a very high accuracy. By the use of different beams and bombarding energies a check of the consistency of the experimental method and theoretical assumptions has been obtained. The comparison between transition rates measured from Coulomb excitation cross section and those deduced from direct lifetime measurements shows very good agreement. Furthermore, the ^{207}Pb $\frac{3}{2}^-$ state lifetime, as deduced from the Doppler-shift attenuation method and, independently, from $B(E2)$ and a mixing ratio measurement, agree very well. This fact can be regarded as a confirmation of the validity of the used stopping theory in this mass region, and encourages further lineshape studies in heavy nuclei.

The agreement between the experimental $B(E2)$ values and those calculated with the weak coupling model show that the electromagnetic properties of the single-particle states around ^{208}Pb seem to be determined by the collective parameters of the core. These parameters are a measure of the shell closure around ^{208}Pb . In the case of the octupole vibration doublet in ^{207}Pb the Coulomb excitation probabilities are consistent with the weak coupling model, whereas the lifetimes of the two states cannot be understood without further assumptions.

The authors wish to thank Dr. G. Schrieder for giving them his Doppler-shift attenuation program and helping them with the calculations.

Two of us (J.W.H. and H.J.K.) acknowledge Prof. W. Gentner and Prof. U. Schmidt-Rohr for inviting them to work in the Max-Planck-Institut at Heidelberg.

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