Resonance absorption and fluorescence of plane-polarized monoenergetic photons in ^{208}Pb

W. Biesiot and Ph.B. Smith
Laboratorium voor Algemene Natuurkunde, University of Groningen, Groningen, The Netherlands
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Level parameters in ^{208}Pb have been determined by means of the resonance gamma-ray absorption technique and measurement of the azimuthal distribution of the elastic scattering of plane-polarized photons. The radiation was produced in suitably chosen (p,γ) reactions. The 7.1 MeV doublet was found at $E_x = 7063.5 \pm 0.2$ and 7083.3 ± 0.3 keV with ground-state radiation widths of 19.1 ± 1.5 and 9.1 ± 1.3 eV. A unique negative parity assignment could be made to both levels, in agreement with other observations. The 4.84 MeV bound level has an excitation energy $E_x = 4842.2 \pm 0.2$ keV, and is most probably a $J^\pi = 1^+$ level.

NUCLEAR REACTIONS $^{34}S(p,\gamma)^{35}Cl$, ^{208}Pb res. abs., ^{208}Pb res. fluor., $E = 4.8$, 7.1 MeV; measured $\sigma(E,E_\gamma)$. ^{208}Pb deduced levels π, Γ, levels. Enriched lead sample.

I. INTRODUCTION

In a simple shell model picture, two 1^+ states are expected to occur in ^{208}Pb resulting from the 1p-1h configurations $\nu(i_{13/2}{}^{-1},i_{11/2})$ and $\pi(h_{11/2}{}^{-1},h_{9/2})$. These states are expected to mix strongly as they are nearly degenerate in energy. The present state of the relevant shell-model calculations was recently reviewed by Raman.[1] In one such calculation the upper 1^+ state at 7.5 MeV is mainly isovector and carries most of the strength while the lower one at 5.4 MeV is mainly isoscalar and has little strength.[2] The distribution of $M1$ strength between the two states depends critically on the coupling between the neutron 1p-1h and the proton 1p-1h configurations.

Inclusion of other configurations (e.g., 2p-2h) results in the fragmentation of the two states into many components. Several measurements have been carried out to locate this fragmented $M1$ strength.[1]

The technique used here to determine the J^π combination of levels in ^{208}Pb is a new variant of the nuclear resonance fluorescence (NRF) method involving the elastic scattering of plane-polarized photons. A first quantitative test of this technique has been described elsewhere, involving scattering at a known 2^+ level in ^{14}N.[3] As a second step we have applied the method to two long standing problems: the parity of (a) the members of the 7.1 MeV doublet (that is, 7.06 and 7.08 MeV) and (b) the 4.84 MeV level in ^{208}Pb. The experiments and interpretation are discussed in Sec. III. The high-resolution NRF technique used requires precise absolute knowledge of the excitation energy of the level under consideration in order to locate the resonance angle. We have performed several resonance absorption experiments in order to obtain the relevant quantities (including values for the total level width). In Sec. II the techniques used are briefly examined.

II. EXPERIMENTAL TECHNIQUES

A. Resonance absorption

The principle of the method has been described in a number of publications (see, e.g., Ref. 3 for the literature on this subject). The gamma rays were produced by proton-capture reactions on ^{34}S. The proton energy, absorber length, and further details are given in Table I for each measurement. The proton beam was provided by the Groningen 5 MV Van de Graaff accelerator. The setup for the experiments is given schematically in Fig. 1. It was necessary to measure the transmitted intensity with a 115 cm^3 Ge(Li) detector to be able to identify interfering gamma-ray lines. The detector was shielded from radiation arising at diaphragms in the beam line.

TABLE I. Characteristic data concerning the resonance absorption experiments with a ^{208}Pb absorber.

E_x (keV)	E_p (keV)	Absorber[a] length (mm)	Number of series	I_{target} (μA)	Running time (h)
7064	1974	7	28	35	88
7064	2541	7	18	35	68
7084	2541	7	23	35	75
4841	1684	30	36	30	84

[a]Enriched to 98.7% in ^{208}Pb.

The ^{34}S targets were of $^{64}Zn^{34}S$. The double-isotopic compound was chosen in order to reduce the $Zn(p,n)$ production and also high-energy gamma-ray production. In all cases the backing was 0.3 mm tantalum, which was heated in vacuum to incandescence for several minutes, prior to evaporating the target material, in order to reduce the fluorine contamination. A forced flow of demineralized water cooled the rear face of the tantalum backing directly. Under these conditions the ZnS targets are able to withstand beam currents of 35 μA for up to 12 h without significant deterioration (i.e., with a yield drop of less than 10%). The target holder can be shifted in two directions in the plane of the backing disc, making multispot use of the targets possible. A lN_2 cold trap in the last 40 cm of the beam pipe minimizes carbon contamination of the target surface.

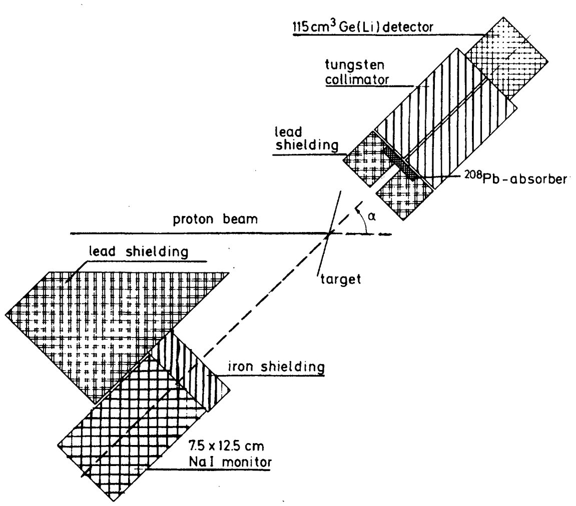

FIG. 1. The experimental configuration of the resonance absorption experiments described in Sec. II A. In the reaction plane the collimator has an aperture of 1°. In the vertical plane the collimator slit has a wider aperture, thus increasing the transmission with little loss in resolving power.

To perform the resonance absorption experiments the absorber-collimator detector system was rotated about the target in 17 steps of 0.25 to 0.75°, corresponding to a 50 to 150 eV change in the gamma-ray energy per step. For each position the detector spectrum was stored after a fixed number of counts registered by a NaI(Tl) monitor. The monitor-target distance, the number of counts, and the monitor window were chosen appropriately for each measurement. As in earlier measurements[3] the monitor was set up so that it rotated at 180° with respect to the collimator. This greatly reduced (angular distribution) tilting of the base line. The entire experiment was computer controlled, with computerized peak stabilization of the gamma-ray detectors. The measurement was split into a number of short runs of 8 − 12 min duration at each angle. The complete angular range was covered many times.

For this work we had a lead block measuring $7 \times 30 \times 40$ mm enriched to 98.7% in ^{208}Pb at our disposition. This was kindly supplied by the Central Bureau for Nuclear Measurements (Joint Research Centre, Commission of the European Communities), Geel, Belgium, on reloan from Oak Ridge National Laboratories.

B. Resonance fluorescence

The general features of this method have been discussed elsewhere[3]; see Fig. 2 for the experimental setup. The partially plane-polarized photons were produced by a suitable chosen (p,γ) reaction. The background in the scattering experiments was determined by measurement at angle α which differed enough from α_r to destroy the energy matching condition, taking the level widths of the emitting compound nucleus and the scattering nucleus into account. The scatterer was a block of enriched lead (see above) of dimensions $7 \times 30 \times 40$ mm. In the azimuthal plane two 7.5×7.5 cm NaI(Tl) detectors

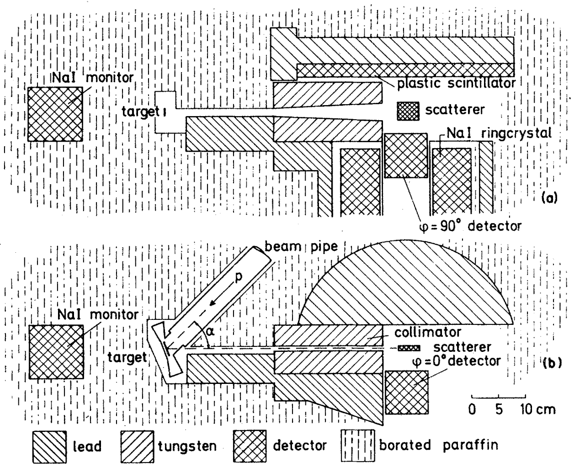

FIG. 2. The experimental setup used for the resonant scattering of monoenergetic plane-polarized photons (a) in elevation and (b) in plan view.

were placed to measure the scattered intensity at $\phi = 0°$ and $\phi = 90°$, ϕ being the angle with respect to the (p,γ) reaction plane. Behind the scatterer a 7.5×12.5 cm NaI(Tl) detector was used to monitor the gamma flux transmitted through the lead.

As the counting rates are extremely low, care had to be taken to reduce the background. Most of the cosmic-ray background was eliminated by means of an active shielding consisting of a 22.5×30 cm NaI(Tl) ring crystal (with a hole of 9 cm diam) and a 30×40 cm plastic scintillator. Direct transmission of gamma rays produced in the target or diaphragms was suppressed to acceptably low levels by passive shielding with lead and tungsten as indicated in Fig. 2. A serious problem is caused by neutrons produced in the target and/or backing material. Several backing materials were tested with respect to neutron and high-energy gamma-ray production and the ability to sustain the heat production caused by the beam spot. Finally, the tantalum discs treated as described in Sec. II A, were selected. Above $E_p = 2.0$ MeV there is nonetheless an appreciable neutron production in this material. It was found necessary to surround the detecting equipment with closely fitted blocks of borated paraffine and at suitably chosen places also with calcium boride as neutron absorber. The beam line was also shielded as much as possible with borated paraffine, so that a 4π neutron shielding of the target was almost achieved. Due to these measures the NaI(Tl) background counting rate was diminished to a level only slightly higher than that measured with the accelerator off. It is practically limited by the imperfect active shielding of the scattering detectors by the anticoincidence scintillator and ring crystal.

III. BOUND LEVELS

A. Calibration of the configuration for resonance fluorescence

As can be seen from Fig. 2 the collimator slit does not show cylindrical symmetry, so that the configuration must be calibrated. Fortunately the $E_p = 1.97$ MeV resonance in $^{34}S(p,\gamma)^{35}Cl$ has been proven[4] to have spin and parity $J^\pi = \frac{1}{2}^-$. It had been shown earlier by Sparks *et al.*[5] that this reaction produces a gamma ray matching the 7.06 MeV level in ^{208}Pb [through a 48% branch to the 1.22 MeV first excited state of ^{35}Cl (Ref. 6)]. Since this gamma ray is unpolarized it is possible to determine the experimental asymmetry of the system directly. We first repeated the resonance absorption study of Sparks *et al.*[5] in order to locate the resonance angle α_r in our configuration.

Some data concerning the measurement are to be

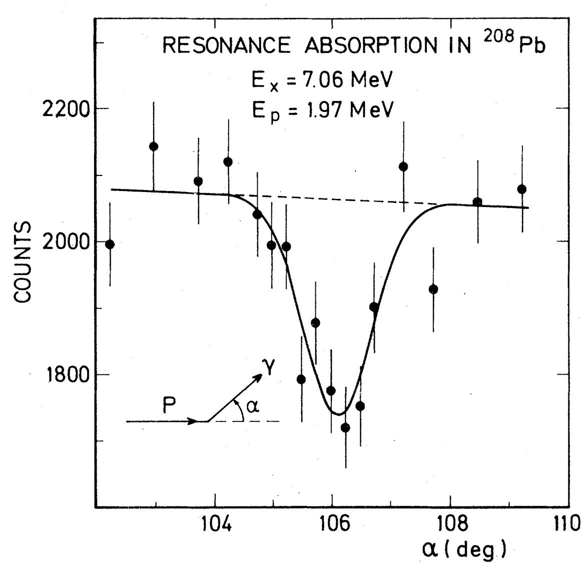

FIG. 3. The transmission curve resulting from the resonance absorption in a 7 mm thick absorber of ^{208}Pb of the ($R \rightarrow 1.22$ MeV) decay gamma of the $E_p = 1.97$ MeV resonance in $^{34}S(p,\gamma)^{35}Cl$. The ordinate is not normalized to unity in the wings, but represents the total number of true counts in a spectrum gate. The solid line is the best fit to the data. The dotted line represents the (linear) background. The value of the normalized χ^2 for the fit is 1.22.

found in Table I. The contents of the 7.06 MeV photopeak and both escape lines in the Ge(Li) spectra were determined and used as input data for a computer code. The results are shown in Fig. 3. The solid curve is the result of fitting the data with a Gaussian instrumental function plus a linear background. The center of the absorption dip occurs at $106.1 \pm 0.5°$. The absorption integral A_α equals 51 ± 10 eV, and the total level width $\Gamma = 17.4 \pm 3.3$ eV. In the analysis we used the value of the spin of this level ($J = 1$) and the ground-state branching ratio ($\Gamma_{\gamma_0}/\Gamma = 1$) as determined by Swann.[7]

The Doppler broadening in the lead absorber at room temperature is less than 4 eV and the related correction to the calculated absorption integral and level width is negligible.

The unshifted energy of the 7.06 MeV gamma rays is known to be $E_\gamma = 7067.1 \pm 0.3$ keV.[4] This leads with $\alpha_r = 106.1°$ to a value of the ^{208}Pb resonance energy: $E_x = 7063.5 \pm 0.3$ keV. Sparks *et al.*[5] found the dip at $105.20 \pm 0.08°$, which deviates 0.9° from our result. As the error specified by Sparks *et al.* results from the fitting process, it does not include systematic errors. The value of the error in the absolute dip center position is difficult to obtain as it depends upon possible misalignment of the beam tube and of the proton beam. A reasonable estimate for our setup is the 0.5° value assigned to the above mentioned result. Assigning a similar systematic error to the measurement of Sparks would be sufficient to reconcile the results within the error margins.

Having determined the resonance angle and the parameters of the scattering level, as described above, the same gamma rays were used to perform a scattering experiment in order to calibrate the asymmetry of the experimental setup (Fig. 2). The off-resonance background was obtained at two angles which differ by 1.8° from α_r, corresponding to an energy difference of 400 eV, enough to prevent resonance scattering. The angular range was covered 104 times, requiring 190 h of running time with a proton beam current of 30 μA. The signal-to-background ratio amounted to 0.3 with a background counting rate in the relevant part of the spectrum of 0.2 counts/min. The spectra of the NaI(Tl) detectors in the azimuthal plane are shown in Fig. 4.

The measured asymmetry can be expressed in the following relation:

$$R_{\exp} = \frac{N_0 - N_{90}}{N_0 + N_{90}} \times 100\% \ , \tag{1}$$

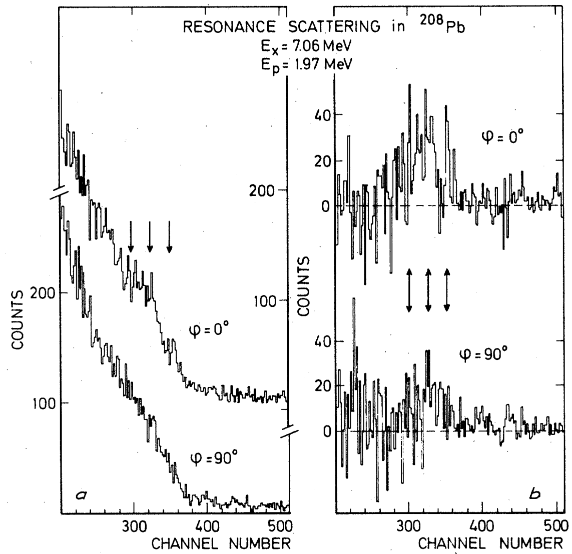

FIG. 4. The relevant part of the NaI spectra produced by unpolarized 7.06 MeV gamma rays resonantly scattered at ^{208}Pb. The uncorrected spectrum on resonance is shown in (a) and the difference between the spectra on and off resonance in (b). The upper spectra are for $\phi = 0°$ and the lower spectra for $\phi = 90°$. The positions of the photopeak and both escape lines are indicated by vertical arrows.

where N_0 and N_{90} denote the true counting rates in the $\phi = 0°$ and the $\phi = 90°$ detector. In the case of this calibration experiment Eq. (1) yields the instrumental asymmetry $R_{\text{cal}} = 18 \pm 11\%$.

Assuming a simple efficiency difference to be the source of the asymmetry and assigning the $\phi = 0°$ detector an efficiency of unity, the efficiency ϵ of the $\phi = 90°$ detector is calculated to be $\epsilon = 0.70 \pm 0.16$. This result is qualitatively not surprising as the shape of the scatterer is such that photons scattered in the direction of the $\phi = 90°$ detector undergo more attentuation due to the transmission through a longer distance in lead than those scattered in the $\phi = 0°$ direction.

B. Measurements on the 7.1 MeV doublet

The decay of the $E_p = 2.54$ MeV resonance in the ^{34}S$(p,\gamma)^{35}$Cl reaction exhibits a 63% branch to the 1.76 MeV bound level, thereby producing a 7.07 MeV gamma ray.[6] The reaction kinematics are such that both members of the 7.1 MeV doublet in ^{208}Pb can be excited with this (p,γ) reaction.

1. Resonance absorption

The 7.06 MeV member of the doublet was reached at $\alpha_r = 130.4 \pm 0.5°$ and the 7.08 MeV member at $47.0 \pm 0.5°$. The relevant experimental data of the resonance absorption measurements are summarized in Table I. The contents of the 7.1 MeV photopeak and both escape lines in the Ge(Li) spectra were determined. In order to increase the accuracy of the determination of the level parameters a broad gate covering all three peaks was set on the spectra, and several corrections were applied to the results obtained in this way. The resulting transmission vs angle curves are shown in Figs. 5 and 6. The parameters obtained from this fit differ less than the error band from the results of the fit to the contents of the three spectral lines alone. The absorption integral A_α equals 57 ± 5 eV, and $\Gamma = 19.5 \pm 1.7$ eV for the 7.06 MeV level; for the 7.08 MeV level these data are 26 ± 4 and 9.1 ± 1.3 eV, respectively. In the analysis we used $J = 1$ and $\Gamma_{\gamma_0}/\Gamma = 1$. The unshifted energy of the 7.1 MeV photons is $E_\gamma = 7073.3 \pm 0.2$ keV.[4] With $\alpha_r = 130.4°$, the energy of the 7.06 MeV ^{208}Pb level is calculated to be $E_x = 7063.5 \pm 0.3$ keV, in excellent agreement with the (independent) result obtained with the 1.97 MeV resonance. For the 7.08 MeV level one obtains with $\alpha_r = 47.0°$, $E_x = 7083.3 \pm 0.3$ keV.

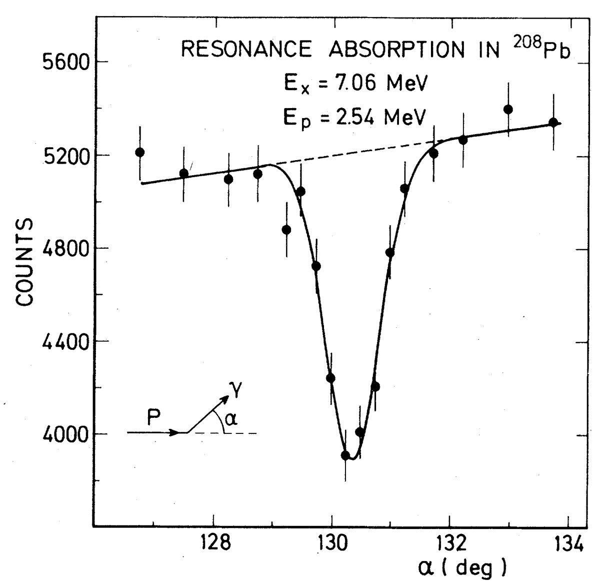

FIG. 5. The transmission curve resulting from the resonance absorption in a 7 mm thick absorber of ^{208}Pb of the 7.06 MeV ($R \rightarrow 1.76$ MeV) decay gamma of the $E_p = 2.54$ MeV resonance in ^{34}S$(p,\gamma)^{35}$Cl. The ordinate represents the total number of true counts in a spectrum gate. The solid and dotted lines have the same meaning as those described in Fig. 3. The value of the normalized χ^2 for the fit is 0.65.

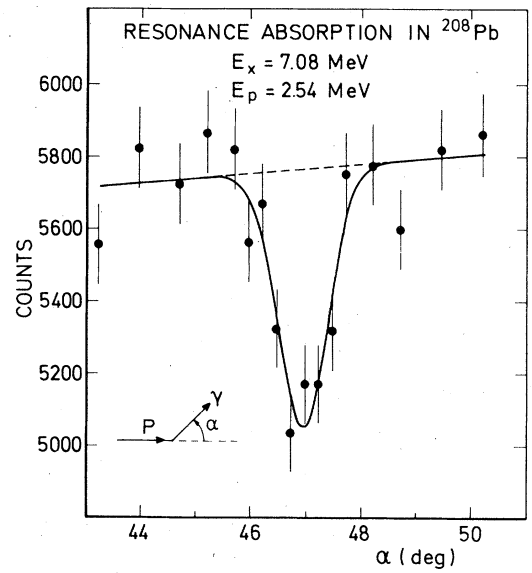

FIG. 6. The transmission curve resulting from the resonance absorption in a 7 mm thick absorber of ^{208}Pb of the 7.08 MeV ($R \rightarrow 1.76$ MeV) decay gamma of the $E_p = 2.54$ MeV resonance in ^{34}S$(p,\gamma)^{35}$Cl. The layout is the same as described under Fig. 3. The value of the normalized χ^2 for the fit is 1.18.

2. Resonance scattering

The spin-parity combination of the $E_p = 2.54$ MeV resonance has been determined to be $\frac{7}{2}^-$.[4] The polarization $\mathscr{P}$ of the photons resulting from the $\frac{7}{2}^- \rightarrow \frac{5}{2}^+$ transition ($R \rightarrow 1.76$ in ^{35}Cl) depends strongly on the mixing parameter δ and the angle α_r as is illustrated in Fig. 7. With $\arctan\delta \simeq -4°$ as determined from an angular distribution measurement[4] and $\alpha_r \simeq 130°$ (or 50°) it follows that $\mathscr{P} = 0.37$. From formulas given in Ref. 3 we derive that

$$R_{\text{theor}} = -3\mathscr{P}(-)^{\Pi}Q_2/(4 - Q_2) \qquad (2)$$

for a $0 \rightarrow 1 \rightarrow 0$ transition. For electric multipoles Π is 0 and for magnetic multipoles Π is 1. The dipole attenuation factor for cylindrical counters with the source on the axis is given by Q_2. Although our geometry is not cylindrical (see Fig. 2) Eq. (2) serves adequately to interpret the results since in fact only the sign must be determined.

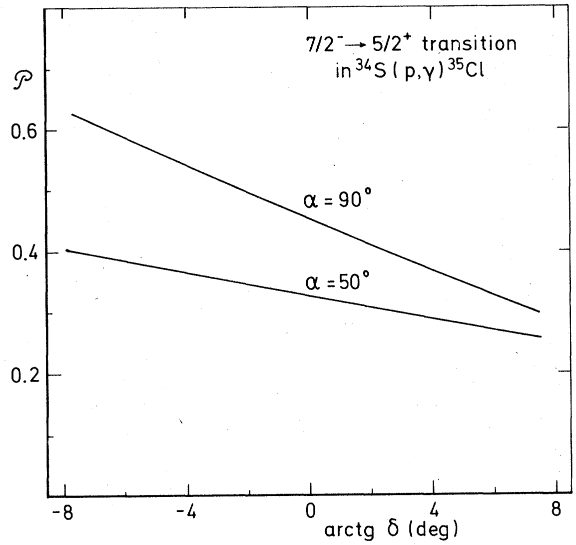

FIG. 7. The polarization $\mathscr{P}$ of a $\frac{7}{2}^- \to \frac{5}{2}^+$ transition in $^{34}S(p,\gamma)^{35}Cl$ as function of the mixing parameter δ for two values of α. Only a limited range of arctan δ values is shown.

Assuming $Q_2 = 1$ Eq. (2) gives $R_{\text{theor}} = \pm 37\%$, where the plus sign holds for an $M1$ resonance and the negative sign for an $E1$ resonance. A Q_2 value of 0.72 (the lowest possible value corresponding to the "any interaction" assumption) yields an attenuation of R_{theor} to $\pm 25\%$.

These partially polarized photons were scattered at the 7.06 and 7.08 MeV resonances in ^{208}Pb in the setup shown in Fig. 2. The off-resonance background was obtained at two angles, 2° away from α_r, corresponding to an energy difference of 400 eV. The angular range was covered 59 times requiring 64 h of running time with a 30 μA proton beam for the 7.06 MeV resonance, and 124 times in 121 h for the 7.08 MeV level. Due to improved neutron shielding the background counting rate in the relevant part of the spectrum increased only to 0.3 counts/min in the case of the 7.06 MeV measurement, compared to the 0.2 counts/min found in the calibration experiment, despite the fact that the neutron production at $E_p = 2.5$ MeV is much higher than at 2.0 MeV. As the $E_p = 2.54$ MeV resonance is stronger than the $E_p = 1.97$ MeV resonance, the photon flux was higher and the signal-to-background ratio remained ~ 0.3. In the case of the 7.08 MeV level the same signal-to-background ratio was achieved, despite the fact that the resonance scattering is weaker there. This was possible because at $\alpha = 47°$ better neutron shielding could be applied than at 130°.

Analysis of the results yields a value of $R_{\text{exp}} = -32 \pm 21\%$ for the 7.06 MeV level and $-19 \pm 17\%$ for the 7.08 MeV resonance. Correction for the instrumental asymmetry (see Sec. III A) is made by the following relation

$$R_{\text{corr}} = \frac{R_{\text{exp}} - R_{\text{cal}}}{1 - R_{\text{exp}} R_{\text{cal}}} . \tag{3}$$

This results with $R_{\text{cal}} = 18 \pm 11\%$ in $R_{\text{corr}}(7.06) = -47 \pm 22\%$ and $R_{\text{corr}}(7.08) = -36 \pm 18\%$. Comparing this with the theoretical range it can be uniquely concluded that the spin-parity combination of the doublet is 1^-.

C. Measurements on the 4.84 MeV level

1. *Resonance absorption*

A 4.84 MeV gamma ray results from a 17% branch to the 3.16 MeV level in the decay of the $E_p = 1.68$ MeV resonance[8] in $^{34}S(p,\gamma)^{35}Cl$. From the reaction kinematics it can be calculated that the available Doppler shift amounts to maximal ± 8.3 keV. This implies a dispersion of only 150 eV/deg. In this situation it is quite difficult to locate the resonance absorption dip of the 4.84 MeV ^{208}Pb level, as the absolute energy of both levels was not known better than to 1 keV. In Ref. 9 the excitation energy of the ^{208}Pb level is specified in terms of a calibration with lines resulting from Fe$(n,n'\gamma)$. We have performed a corresponding experiment in which the Fe(n,γ) lines were measured simultaneously with the decay of the $E_p = 1.68$ MeV resonance in $^{34}S(p,\gamma)^{35}Cl$. With the same calibration data set as in Ref. 9 a rather limited angular range could be predicted within which α_r had to lie.

A resonance absorption experiment was performed in this angular range as specified in Table I. The analysis of the data was difficult because of the complexity of the decay of the ^{35}Cl resonance. The results are shown in Fig. 8. Only limited statistical accuracy could be reached due to the weak branching to the 3.16 MeV ^{35}Cl level, but it is considered sufficient for localization of the ^{208}Pb level. The solid line is the result of fitting the data with a Gaussian instrumental function plus a linear background. The dotted line is discussed in Sec. III E. The center of the dip occurred at $82.7 \pm 0.5°$, and the energy of the ^{208}Pb level is calculated to be $E_x = 4842.2 \pm 0.2$ keV based upon Ref. 4 for the unshifted energy of the $(R \to 3.16)$ ^{35}Cl transition.

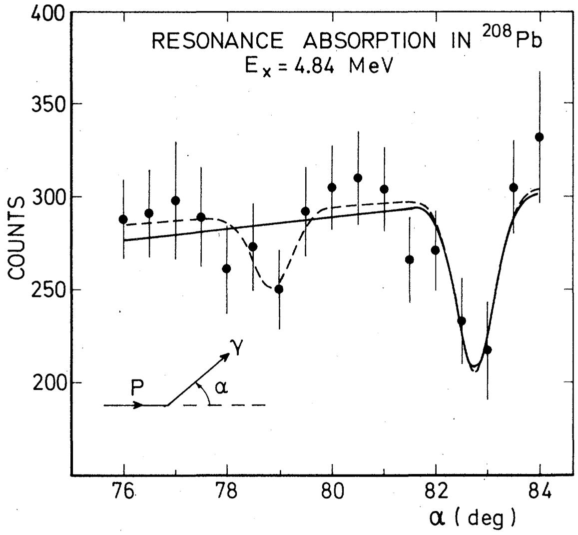

FIG. 8. The transmission curve resulting from the resonance absorption in a 30 mm thick absorber of ^{208}Pb of the 4.84 MeV ($R \rightarrow 3.16$ MeV) decay gamma of the $E_p = 1.68$ MeV resonance in ^{34}S$(p,\gamma)^{35}$Cl. The ordinate represents the total number of true counts in a spectrum gate. The solid line is the best fit to the data. The dotted line represents a fit of two closely spaced resonances in ^{208}Pb to the data. The value of the normalized χ^2 for the first fit is 0.79 and for the second fit 0.53.

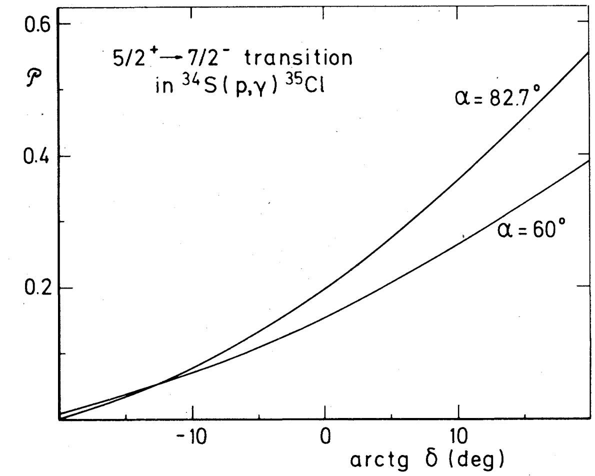

FIG. 9. The polarization of a $\frac{5}{2}^+ \rightarrow \frac{7}{2}^-$ transition in ^{34}S$(p,\gamma)^{35}$Cl as a function of the mixing parameter δ for several values of α. Only a limited range of arctan δ values is shown.

The absorption integral A_α and the total width Γ are found with large errors: $A_\alpha = 41^{+33}_{-13}$ eV and $\Gamma = 4.3^{+3.5}_{-1.4}$ eV. In the analysis we used the value of the spin of this level ($J = 1$) and of the ground-state branching ratio ($\Gamma_{\gamma_0}/\Gamma = 1$) as determined by Swann.[10]

2. *Resonance scattering*

The spin-parity combination of the $E_p = 1.68$ MeV resonance in ^{34}S$(p,\gamma)^{35}$Cl has been determined to be $\frac{5}{2}^+$.[4] The dependence of the polarization $\mathscr{P}$ of the photons resulting from the $\frac{5}{2}^+ \rightarrow \frac{7}{2}^-$ transition ($R \rightarrow 1.76$) in ^{35}Cl on the mixing parameter δ and the angle α_r is illustrated in Fig. 9. From an angular distribution study we have found arctan $\delta \simeq 2°$.[4] For $\alpha_r \simeq 83°$ it follows from Fig. 9 that $\mathscr{P} = 0.23$, so that (for $Q_2 = 1$)$R_{\text{theor}} = \pm 23\%$, with the plus sign for $M1$ and the minus sign for $E1$ transitions [see Eq. (2)]. These partially polarized photons were scattered at the 4.84 MeV bound level in ^{208}Pb in a setup that differed only slightly from the one shown in Fig. 2. The off-resonance background was obtained at two angles 2.7° away from α_r, corresponding to a 400 eV energy difference. The angular range was covered 136 times in 122 h of running time with a 30 μA proton beam. Although the neutron production is rather low at this bombarding energy, the background in the relevant part of the spectrum was considerably higher than at 7.1 MeV. The signal-to-background ratio was consequently low: ≤ 0.2.

Analysis of the results yields a value of $R_{\text{exp}} = 89 \pm 39\%$, and with Eq. (3): $R_{\text{corr}}(4.84) = 85 \pm 54\%$. Comparing this with the theoretical range it can only be concluded that the value corresponding to a 1^- assignment differs two standard deviations from the experimental result, making a 1^- assignment unlikely but not impossible. Most probably this level has an $M1$ character. Improved shielding of the detectors in the azimuthal plane is a prerequisite for narrowing the error bars of R_{exp}.

D. Discussion of the 7.1 MeV doublet

Measurements concerning the 7.1 MeV doublet in ^{208}Pb cover two decades. Several reactions have been studied: ^{208}Pb(γ,γ) [Refs. 5,7,11–14(a)], ^{206}Pb(t,p), (Refs. 15,16) and ^{208}Pb$(p,p'\gamma)$ (Refs. 17–21). In some of the ^{208}Pb(γ,γ) experiments[5,7,22,23] the use of Ge(Li) detectors led to high precision in the results. The excitation energies have been determined by Sparks *et al.*[5] with a quoted error of 0.5 keV based upon a calibration with Fe(n,γ) lines. Our results are in a traceable manner based upon the accepted set of gamma rays from the decay of ^{56}Co as described in Ref. 4 and the preceding sections. The discrepancy of about 1 keV with the work of Sparks *et al.* must be attributed to this difference in calibration energies used.

Several studies have yielded information regarding the level widths involved[5,7,22–26]; the relevant values are summarized in Table II. The studies reported in Refs. 7, 14(b), 23, and 24 yield Γ_0 values which are a factor of 2 higher than the other values listed in Table II, although the relative strength of the members of the doublet is in agreement with all other observations mentioned in Table II. If the possibility of the existence of many small and closely spaced levels is ruled out (as is indicated by the negative results of the work described in Ref. 26 where a 1.5 eV sensitivity in Γ_0^2/Γ is reported for levels in this region), one has to conclude that the reported high Γ_0 values are based upon a data analysis with incomplete background correction or faulty spectrum normalization.

Figure 10 shows that our values for Γ are comparatively insensitive to Γ_0/Γ for high values of the branching ratio. As almost all reported Γ_0/Γ are ≥ 0.8, the residual uncertainty in the branching ratio does not seriously affect the value of Γ as obtained in our experiments.

The spins of the members of the 7.1 MeV doublet have been determined by gamma-ray angular distribution measurements to be 1.[7,18,22,26] Regarding the parity of the 7.08 MeV level several measurements involving particle reactions have led to the same result: $J^\pi = 1^-$.[21,27] For this assignment DWBA calculations were used, which although convincing, contain model-dependent assumptions. In the work of Freedman *et al.*[20] the directional correlation between particles inelastically scattered from ^{208}Pb and ground-state gamma-ray decays was measured. Such a directional correlation can be used to determine the spin-parity combination of a level. The in-plane/out-of-plane yield ratio is expected to be less than 1 for 1^- states, greater than 1 for 2^+ states, and equal to 1 for 1^+ states. For the 7.08 MeV level a ratio of 0.72 ± 0.18 was found, leading to $J^\pi(7.08 \text{ MeV}) = 1^-$. With a ratio of 1.22 ± 0.28 for the 7.06 MeV level, they considered it a good candidate for $J^\pi = 1^+$. In a subsequent measurement[21] the angular distribution of this state in inelastic proton scattering was determined. This distribution is consistent with $J^\pi = 1^+$, although the spectrum is too featureless to make the assignment unambiguously. These results conflict with other observations: An inelastic electron scattering experiment[28] yielded results that do not confirm a 1^+ assignment but are consistent with 1^-, and in the work of Horen *et al.*[27] the (d,p) stripping pattern to both ^{208}Pb levels is strikingly similar as regards both magnitude and shape, which suggests that they are formed by identical l transfers and hence have the same (negative) parity. A similar result is reached by Nathan *et al.*[29] by measuring the azimuthal dependence in the elastic scattering of plane-polarized gamma rays resulting from bremsstrahlung. As the "tagged photon" technique was used with a NaI(Tl) detector (with an overall energy resolution of 40 keV), the members of the doublet were not resolved. The measured asym-

TABLE II. Comparison of measured level width and branching ratio for the members of the 7.1 MeV doublet in ^{208}Pb.

	Γ_0^2/Γ(7.06 MeV) (eV)	Γ_0^2/Γ(7.08 MeV) (eV)	Γ_0/Γ (7.06 MeV)	Γ_0/Γ (7.08 MeV)
This work	17.4 ± 3.3	9.1 ± 1.3		
	19.5 ± 1.7			
Sparks *et al.* (Ref. 5)	18 ± 3			
Chapuran *et al.* (Ref. 26)	15.7 ± 2.6	8.8 ± 1.5	$0.98^{+0.02}_{-0.07}$	1.0
Laszewski and Axel (Ref. 25)	25.9 ± 2.1			
Knowles *et al.* [Ref. 14(b)]	24 ± 3	15 ± 3		
Swann (Ref. 7)	31 ± 3	17 ± 2	0.8 – 1.0	0.8 – 1.0
Scholz *et al.* (Ref. 22)		16^{+6}_{-4}	0.62	0.62
Yeh and Lancman (Ref. 23)	29 ± 3	16 ± 3	$0.9^{+0.1}_{-0.4}$	$0.8^{+0.2}_{-0.3}$
Coope *et al.* (Ref. 24)	29 ± 10	14 ± 5		

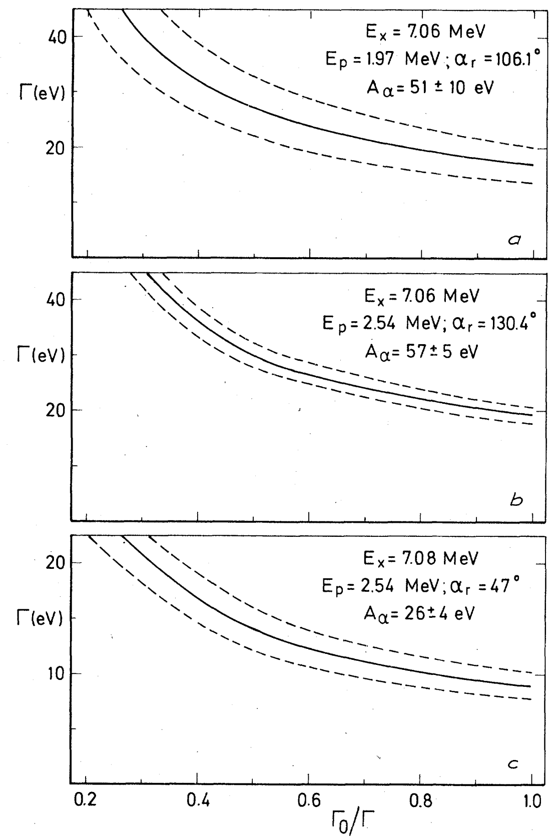

FIG. 10. The total level width calculated from the resonance absorption measurements as function of the ground-state branching ratio for the measurements shown in Figs. 5, 6, and 8. The dotted lines indicate the error band introduced by the uncertainty in A_α. The upper part shows the curve calculated from the experiment involving the 7.06 MeV level and the $E_p = 1.97$ MeV resonance, the middle part the results of the 7.06 MeV level reached with the $E_p = 2.54$ MeV resonance, while the lower part represents the results concerning the 7.08 MeV level reached with the $E_p = 2.54$ MeV resonance [all in $^{34}S(p,\gamma)^{35}Cl$].

metry could, however, only be explained with a $J^\pi = 1^-$ assumption for both levels, although a small amount of $M1$ strength is compatible with their results. Our measurements on both levels confirm the $J^\pi = 1^-$ assignments unambiguously.

E. Discussion of the 4.84 MeV level

Using the ^{207}Pb(d,p) reaction several authors have obtained a value for the excitation energy of the 4.84 MeV level with an accuracy of ~ 5 keV.[30–32] Also in the ^{208}Pb(p,p') reaction the bound level is rather strongly excited[17,19,33] and the energy has been determined to be 4841 ± 2 keV. Excitation with bremsstrahlung photons has confirmed this value[24,26] and this is also the case with the ^{208}Pb$(n,n'\gamma)$ experiment of Coope *et al.*[9] already mentioned in Sec. III D and leading to $E_x = 4841.7 \pm 0.5$ keV based upon the Fe(n,γ) data set of Stelts and Chrien.[34] Our result, $E_x = 4842.2 \pm 0.2$ keV is in a traceable manner based upon the accepted set of gamma rays from the decay of ^{56}Co as described in Ref. 4 and Sec. III D, and is in close agreement with the value given in Ref. 9.

Several studies have yielded information regarding the level width and branching ratio[10,14b,24–26] and the results are summarized together with our work in Table III. The Γ values are in good agreement with each other as is also the case for the branching ratios obtained (a high value for Γ_0/Γ is also supported by the work of Earle *et al.*[31]). Our results fit well in this data set.

From gamma-ray angular-distribution measurements it follows that the spin of the ^{208}Pb level is 1,[9,10,26] an assignment also supported by the work described in Ref. 31. Concerning the parity assignment conflicting information exists. In 1974

TABLE III. Comparison of measured level width and branching ratio of the 4.84 MeV level in ^{208}Pb.

	Γ_0^2/Γ (eV)	Γ_0/Γ
This work	$4.3^{+3.5}_{-1.4}$	
Swann (Ref. 10)	5.1 ± 0.8	1
Knowles *et al.* (Ref. 14b)	6 ± 2	
Coope *et al.* (Ref. 24)	6.3 ± 2.2	
Laszewski and Axel (Ref. 25)	6.9 ± 1.4	
Chapuran *et al.* (Ref. 26)	5.0 ± 0.8	$0.85^{+0.13}_{-0.09}$
Earle *et al.* (Ref. 31)		1.0

Swann[10] reported a 1^+ assignment based upon a linear polarization measurement. This result was questioned by Del Vecchio *et al.*[35] who measured a strong excitation in inelastic α scattering of a level at 4841 ± 5 keV which would imply that a natural parity state was involved. In a subsequent experiment Del Vecchio *et al.*[36] measured a nearly 100% decay to the ground state by level excitation in inelastic α scattering. This limits J^π to 1^- or 2^+. Observation of the directional correlation between α particles inelastically scattered from ^{208}Pb and ground-state gamma-ray decays (measured as the in-plane/out-of-plane yield ratio) leads to the conclusion that the 2^+ assignment is excluded. The yield ratio obtained is consistent with 1^-. The same technique was used by Freedman *et al.*[20] in the $^{208}\mathrm{Pb}(p,p'\gamma)$ reaction. Their results were consistent with 1^- although a 1^+ assignment could not be ruled out.

In 1977 Swann repeated the linear polarization measurement with an enriched ^{208}Pb target.[37] His results were inconsistent with either a pure $E1$ or $M1$ transition. The discrepancy with his 1974 result is explained by possible problems in the estimation of the background. The overall results for the 4.84 MeV level are ambiguous and as a possible cause Swann has suggested the assumption of two closely spaced levels of approximately equal widths. Comparison of a self-absorption measurement with the scattering results supports this conclusion.[37] Considering the high-resolution (p,p') study of Wagner *et al.*[19] such a doublet must have a spacing of less than 3 keV, thus remaining unresolved in most experiments.

The resonance absorption experiment described in Sec. III D covers an energy range of 1.2 keV. A spacing of ± 3 keV would require a coverage of a 44° wide angular range which is practically impossible for a resonance absorption measurement with a low photon flux (p,γ) reaction such as the $E_p = 1.68$ MeV resonance in $^{34}\mathrm{S}(p,\gamma)^{35}\mathrm{Cl}$. Our Γ value is $4.3^{+3.5}_{-1.4}$ eV, thereby favoring a single level of 5 eV strength, although the possibility of excitation of only one partner of a postulated doublet is not completely excluded. The resonance absorption spectrum shown in Fig. 8 exhibits several low-lying points at 79°. Although a dip is not statistically significant in this region, the spectrum has been fitted with a doublet; the dotted line in Fig. 8 shows the resulting transmission curve.

The influence of the presence of the "dip" at 79° on our main results is negligible. The statistical accuracy is not sufficient to determine beyond doubt the existence of this "dip." Further experiments are necessary in order to clarify this situation.

The results of the resonance fluorescence experiment at the level excited at $\alpha_r = 82.7°$ have been described in Sec. III D and favor a 1^+ assignment, although a 1^- possibility is not excluded.

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