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Published in:
Physical Review C

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
1976

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Smith, PB. (1976). Resonance absorption in the ~ant Mi resonance region of Pb. *Physical Review C*, *13*(5), 2071-2074.

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PHYSICAL REVIEW C VOLUME 13, NUMBER 5 MAY 1976

Resonance absorption in the giant $M1$ resonance region of ^{208}Pb

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(Received 11 November 1975)

A neutron unbound state lying at $E_x = 7685$ keV in ^{208}Pb, purportedly belonging to the giant $M1$ resonance in this element, has been studied in resonance absorption with γ rays from the $E_p = 1354$-keV resonance in the ^{34}S$(p,\gamma)^{35}$Cl reaction. The absorber was 3-cm natural lead. The tungsten collimator subtended a (geometrical) half angle of 0.77° at the target. The absorption dip was fitted with a five-parameter Lorentz curve. The level parameters found are $E_n = 316.0 \pm 0.8$ keV, $\Gamma_t = 1.1^{+0.5}_{-0.3}$ keV, and $\Gamma_{\gamma 0} = 14^{+6}_{-4}$ eV.

[NUCLEAR REACTIONS ^{208}Pb, resonance absorption; $E_x = 7685$ keV; deduced E_n, $\Gamma_{\gamma 0}$, Γ_t.]

Several authors have reported a concentration of $M1$ strength in the region of 7.4–8.2 MeV excitation in ^{208}Pb, in both (γ, n)[1,2,3] and (n, γ)[4] reactions. A giant-resonance structure has been suggested since a large proportion of the available $M1$ strength appears to be exhausted in a limited region.

A study of one of these levels, lying 316 keV above the neutron binding energy of ^{208}Pb, has been made by means of resonance absorption of γ rays[5,6] emitted following proton capture in ^{34}S. The level excited in ^{35}Cl has an excitation energy of 7686.3 keV (corresponding to $E_p = 1354$ keV). The decay has a 72% ground-state branch[7] which has exactly the right energy to excite the state in ^{208}Pb mentioned above. The Q value of the ^{34}S(p, γ) ^{35}Cl reaction has recently been redetermined[8] very accurately to be 6371.6 ± 0.4 keV. Many months of fruitless search had preceded this successful measurement, since previously published Q values differed in some cases considerably from this value. The spread in the published values of the excitation energy in ^{208}Pb is in itself equivalent to a 15° uncertainty in the expected dip position (~207 eV/deg).

Resonance absorption provides an absolute measurement of the strength of a ground-state transition in cases such as this where the measured absorption dip is much broader than the experimental resolution. Although the results of the present measurement are not very precise, they do serve to support the general conclusions of Refs. 1–4.

The experimental setup is shown in Fig. 1. A 3-cm thick natural lead absorber was placed before a 20-cm long tungsten collimator subtending an angle of 1.1° (ignoring penetration of the collimator edges and finite target-spot size) at the target. The γ rays traversing the absorber and the collimator were detected by a 10×10-cm NaI crystal and photomultiplier. The spectrum measured by this detector (summed over the whole experiment) is shown in Fig. 2.

Protons (20 μA) were provided by the Groningen 5 MV Van de Graaff accelerator. The target was 100 μg/cm^2 Zn^{34}S evaporated onto a 0.3-mm thick Ta blank which formed the vacuum wall of the target holder. The background in the gate (see Fig. 2) was determined by measuring the spectrum behind the collimator at a proton energy just below the resonance.

The collimator (with absorber and detector) was rotated about the target in 20 steps of $1\frac{1}{2}$° (corresponding to ~300-eV change in γ-ray energy/step) and the spectra for each position were stored for a fixed number of counts (8000) registered by a 7.5×7.5-cm NaI monitor (Fig. 1) in a window covering the photopeak and the two escape peaks arising from the 7685.4-keV γ ray. The entire experiment was computer controlled, with computerized peak stabilization of the detectors. In one week of continuous measurement 29 series of 20 points were taken. Further, 5 series were made without absorber (the off-resonance transmission through the absorber is 20%). The results of these measurements are shown in Fig. 3. It can be seen from Fig. 1 that for increasing angle the apparent width of the target spot increases, so that the transmission decreases slightly for larger angles. This is the origin of the slope in the base line of Fig. 3.

The data of the measurement with lead absorber was fitted to a straight line multiplied by a transmission factor of Breit-Wigner shape[9]:

$$I(E_i) = (A + BE_i)\exp\left(\frac{-R\Gamma/2\pi}{\frac{1}{4}\Gamma^2 + (E_i - E_0)^2}\right)$$
$$= (A + BE_i)\,T(E_i, E_0, \Gamma, R)\ . \qquad (1)$$

In Eq. (1), Γ is the total width of the level ($\simeq \Gamma_n$),

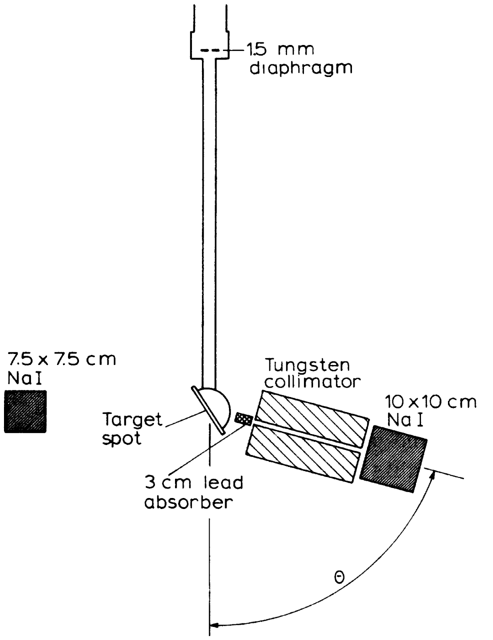

FIG. 1. A schematic view of the experimental setup.

and $R=\frac{1}{4}ng\lambda^2\Gamma_{\gamma 0}$. The parameter R is, to a very good approximation, equal to the area of the absorption dip.[9] The number of atoms $(^{208}\mathrm{Pb})/\mathrm{cm}^2$ in the absorber is given by n; the statistical factor $g=(2J+1)/(2I+1)$, where J is the spin of the excited state and I of the ground state, is 3 in this case.

The five parameters in Eq. (1) were determined by a combination of linear and nonlinear least-

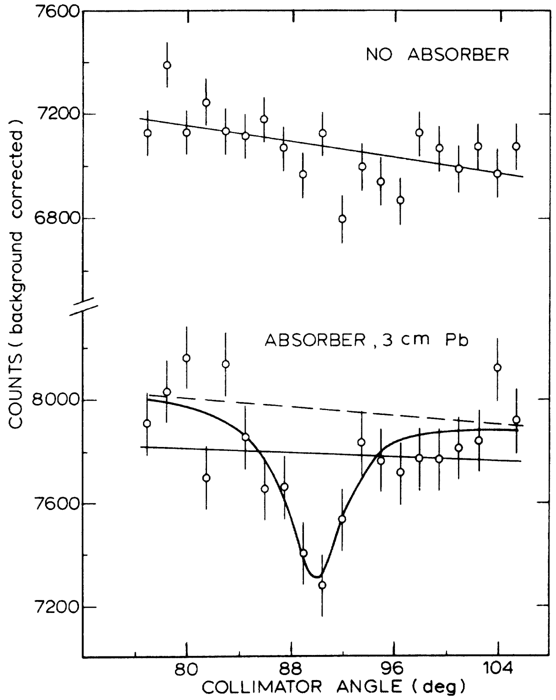

FIG. 3. Measurements, with and without absorber, of the transmitted intensity as a function of angle. The straight-line fit to the measurement without absorber is discussed in the text. In the measurement with absorber the dotted line is the calculated base line for the best fit to the absorption dip ($\chi^2=1.31$). The best straight-line fit to this data (solid line) has a χ^2 of 3.57. The probability that this corresponds to a good fit (Ref. 10) is 4×10^{-7}.

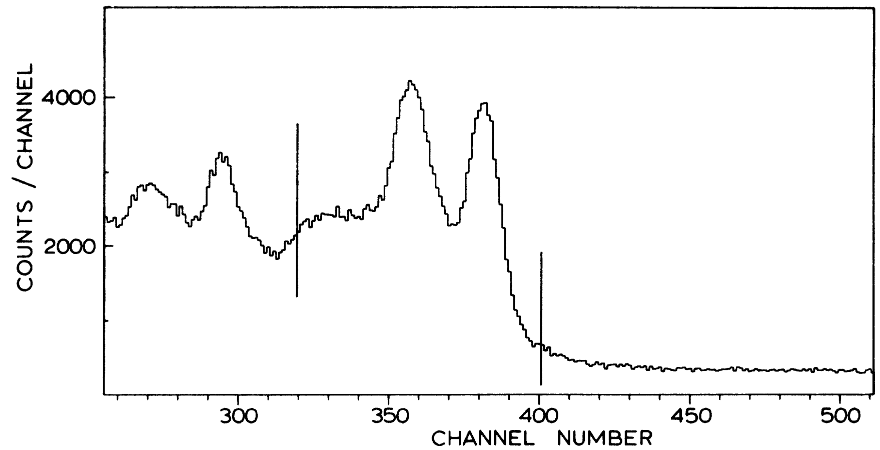

FIG. 2. The sum of the spectra measured during the entire experiment in the 10×10-cm NaI detector behind the collimator. The region between the vertical lines, corrected for background by means of a measurement with the proton energy just below the 1354-keV resonance, was used for the data of Fig. 3.

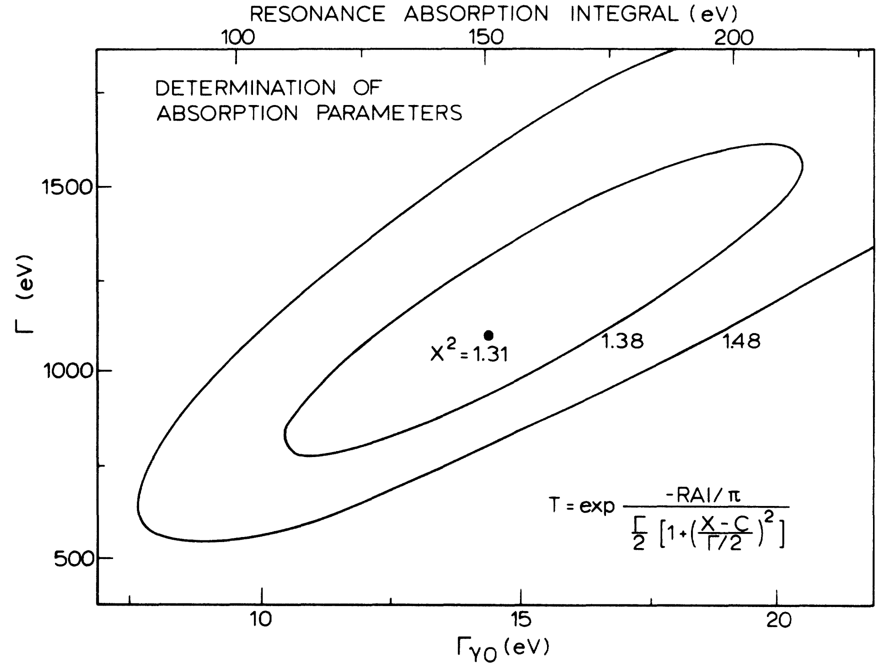

FIG. 4. A contour plot of Q^2 for values of Γ and R. As explained in the text, each point corresponds to the optimum value of A, B, and E_0, and as such represents the overall goodness of fit.

squares fitting. The center of the dip E_0 was quickly found to be very well determined and to show little correlation with other parameters, so further discussion of E_0 will be left out of the following description of the fitting procedure. The nonlinear parameters Γ and R were varied in a grid search. For each point in the grid the measured points $M(E_i)$ were divided by $T(E_i, E_0, \Gamma, R)$. The points obtained in this way, $M'(E_i)$, were fitted by a standard linear least-squares procedure to a straight line, giving A, B, and Q^2. The advantage of this procedure is that A and B become functions of Γ and R so that the results of the analysis can be given by one contour plot of Q^2 (Fig. 4). The standard deviation is taken to be $Q^2 = \chi^2 + 1/\nu = 1.38$ (ν is the number of degrees of freedom, 15 in this case).

This method of fitting makes equal use of all measured points, and ensures that all correlation errors are exposed in the final contour plot. It should be noted that parametrization in terms of width and depth of the dip leads to larger correlation errors than in our method in which width and area are the parameters. A second advantage is that the physically significant result $\Gamma_{\gamma 0}$ is obtained directly from R.

It is a remarkable coincidence that the center of the dip falls at $(90.0 \pm 1.0)^0$, taking both statistical and instrumental errors into account. The straight-line fit to the data taken with no absorber shown in Fig. 3 has a χ^2 value, for $\nu = 18$, of 1.64. The probability[10] that χ^2 is this large or larger is 0.04. This is rather small, but not small enough to provide serious evidence for an instrumental effect. It should be mentioned, however, that there has been as yet no measurement of the angular distribution of the γ ray used. A small correction to the base line may have to be made when this angular distribution is measured.

Taking the extreme values of Γ and $\Gamma_{\gamma 0}$ on the $Q^2 = 1.38$ contour of Fig. 4 as limits of error, we find

$$\Gamma_{\gamma 0} = 14^{+6}_{-4} \text{ eV} \quad \text{and} \quad \Gamma = 1.1^{+0.5}_{-0.3} \text{ keV} .$$

The only reported value of Γ is that of Allen and Macklin.[4] They give $\Gamma = 930$ eV, in agreement with the above value. The present value for $\Gamma_{\gamma 0}$ is larger than all other measured values, as can be seen in Table I. It should be noted that errors are only stated in Ref. 3, where an additional 20% error is surmised for possible instrumental effects.

If full credence is given to all of the $J^\pi = 1^+$ assignments made in Refs. 1–3, the present work suggests that more than 100% of the expected $M1$ strength is exhausted in this region of ^{208}Pb excitation. Further discussion of this point does not seem to be fruitful until smaller error limits are achieved and model-independent J^π assignments are made. It should also be mentioned that

TABLE I. Comparison of the results for $\Gamma_{\gamma 0}$ with published values.

Authors and Refs.	$\Gamma_{\gamma 0}$ (eV)
Bowman *et al.* (Ref. 1)	6.7
Toohey and Jackson (Ref. 2)	10.2
Allen and Macklin (Ref. 4)	8.5
Haacke and McNeill (Ref. 3)	7.0 ± 1.1
Present work	14^{+6}_{-4}

too little attention has been paid to the calculation of expected $M1$ strength and the various mechanisms which may be responsible for this strength.

The excitation energy E_0, as mentioned above, is extremely accurately determined in this experiment. Combining this error (corresponding to 200 eV) with the error in the Q value and the proton bombarding energy we find an over-all uncertainty of 0.5 keV in E_0. Correcting for recoil losses in ^{35}Cl and ^{208}Pb we find that the level in ^{208}Pb has an excitation energy of $E_x = 7685.3 \pm 0.5$ keV. This corresponds to an energy of 317.5 keV above the neutron binding energy[11] (7367.7 ± 0.6 keV). The deduced neutron energy in the (γ, n) reaction is then 316.0 ± 0.8 keV. Values of 318, 315, and 316 keV are reported in Refs. 1–3, respectively. The neutron bombarding energy in the (n, γ) reaction calculated using the present result is 319.1 ± 0.8 keV. In Ref. 4 the value of E_n reported is 317.8 keV. The agreement among all reported values is seen to be satisfactory.

The author wishes to acknowledge the indispensable help of W. G. F. Jansens, Dr. H. Gruppelaar, and A. S. Keverling Buisman in the preparatory stages of this experiment, and of his colleagues in the Van de Graaff accelerator group for assistance during the measurement.

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