Electric and Magnetic Dipole Transitions to Bound States in ^{206}Pb

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Nuclear resonance flourescence measurements with linearly polarized bremsstrahlung were performed to determine parities of bound dipole transitions in ^{206}Pb. A new 1^+ level at 5800 keV was found, which has almost the same strength as the isoscalar $M1$ transition in ^{208}Pb. Twenty-four further dipole states in ^{206}Pb below 7.6 MeV possess negative parity.

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The discovery of the isoscalar magnetic dipole transition to the $E_x = 5846$ keV state in ^{208}Pb,[1,2] which solved an old problem[3] concerning the isoscalar $M1$ strength in this nucleus,[4] has prompted the question of whether this $J^\pi = 1^+$ state survives when the two $3p_{1/2}$ neutrons close to the Fermi surface are removed. The residual ^{206}Pb nucleus has the same proton $\pi|h_{11/2}\rangle$ and neutron $\nu|i_{13/2}\rangle$ configurations as ^{208}Pb, which are the basis for the isoscalar $M1$ transition in ^{208}Pb. This $M1$ transition is explained[5] in a two-state model as a destructive interference of neutron and proton spin-flip excitations:

$$|1^+\rangle = \alpha|\pi h_{11/2}^{-1} h_{9/2}\rangle - \beta|\nu i_{13/2}^{-1} i_{11/2}\rangle, \qquad (1)$$

with $\beta < 0$ and $\alpha^2 + \beta^2 = 1$. The isoscalar nature of the 5846-keV state has been confirmed in a number of reactions that are sensitive to a distinction between isoscalar and isovector modes.[2,5–9]

Very recently, results from a ^{206}Pb$(\gamma_{\rm tag}, \gamma)$ experiment using polarized tagged bremsstrahlung photons were published.[10] The authors claim that they observed a $M1$ strength of $B(\uparrow M1) \approx 19\mu_0^2$ in the energy region between 6.7 and 8.1 MeV, which can account for most of the isovector $M1$ strength expected in the ^{206}Pb nucleus. Furthermore, the energy region of bound states in ^{206}Pb (up to the neutron-emission threshold at 8.1 MeV) has been examined by high-resolution nuclear resonance fluorescence experiments with unpolarized photons, and plenty of dipole transitions could be identified.[11,12] The parities of the individual transitions observed above 4.2 MeV, however, remain unknown.

In this paper we report on a ^{206}Pb$(\gamma_{\rm pol}, \gamma)$ experiment employing linearly polarized bremsstrahlung and high-resolution Ge(Li) detectors. A $J^\pi = 1^+$ level close to the excitation energy of the "model" isoscalar 1^+ state[4] in ^{208}Pb with about the same $M1$ strength was discovered. On the other hand, this ^{206}Pb$(\gamma_{\rm pol}, \gamma)$ measurement demonstrates the electric character of the strongest dipole transitions in the energy region from 4.3 to 7.5 MeV.

Nuclear resonance fluorescence (NRF) with linearly polarized photons is a model-independent method for the determination of parities of multipole radiation. Excitation of magnetic and electric states yields different azimuthal asymmetries of the photon scattering intensities in a $(\gamma_{\rm pol}, \gamma)$ measurement.[13] To determine the character of the dipole transitions in ^{206}Pb, linearly polarized photons from off-axis bremsstrahlung produced in a thin bremsstrahlung target (25 μm Al) were used. The method employed at the University of Giessen 65-MeV electron linear accelerator and the determination of bremsstrahlung polarization are described in more detail by Berg.[14]

Two different types of NRF measurements were carried out on ^{206}Pb: firstly, an angular-distribution measurement with bremsstrahlung of 7 MeV end-point energy to determine spins of states which could not be figured out in the ^{206}Pb(γ, γ') measurement by Chapuran, Vodhanel, and Brussel,[12] and secondly, measurements with linearly polarized bremsstrahlung of 10 and 12 MeV end-point energy to determine the parities of the states excited.

The Pb target was enriched to 88% in ^{206}Pb; the abundances of the remaining isotopes ^{207}Pb and ^{208}Pb were 9% and 3%. A target thickness of 0.4 g/cm^2 was used for the angular-distribution measurement, whereas a somewhat thicker target (0.7 g/cm^2) was necessary for the polarized measurements to obtain sufficient statistics.

Two Ge(Li) detectors were placed at an angle of $\theta = 90°$ and two at $\theta = 127°$ for the angular-distribution measurement. The ratio of cross sections $R = W(90°)/W(127°)$ for elastic photon scattering on a nucleus with ground-state spin $J^\pi = 0^+$ is 0.79 and 2.28 for dipole and quadrupole radiation, respectively. Part of a ^{206}Pb(γ, γ) spectrum measured with 7-MeV bremsstrahlung at a scattering angle of $\theta = 127°$ is depicted in Fig. 1. An excellent peak-to-background ratio could be obtained in the ^{206}Pb(γ, γ) spectra in spite of the high density of dipole levels in ^{206}Pb. The aforementioned ratio of (γ, γ) cross sections R for the states at 4604, 5472, 5800, and 5817 keV, whose spins were unknown, is 0.91 ± 0.33, 0.66 ± 0.35, 0.77 ± 0.19, and 0.51 ± 0.45, respectively, giving evidence that dipole states were excited. For the other transitions we

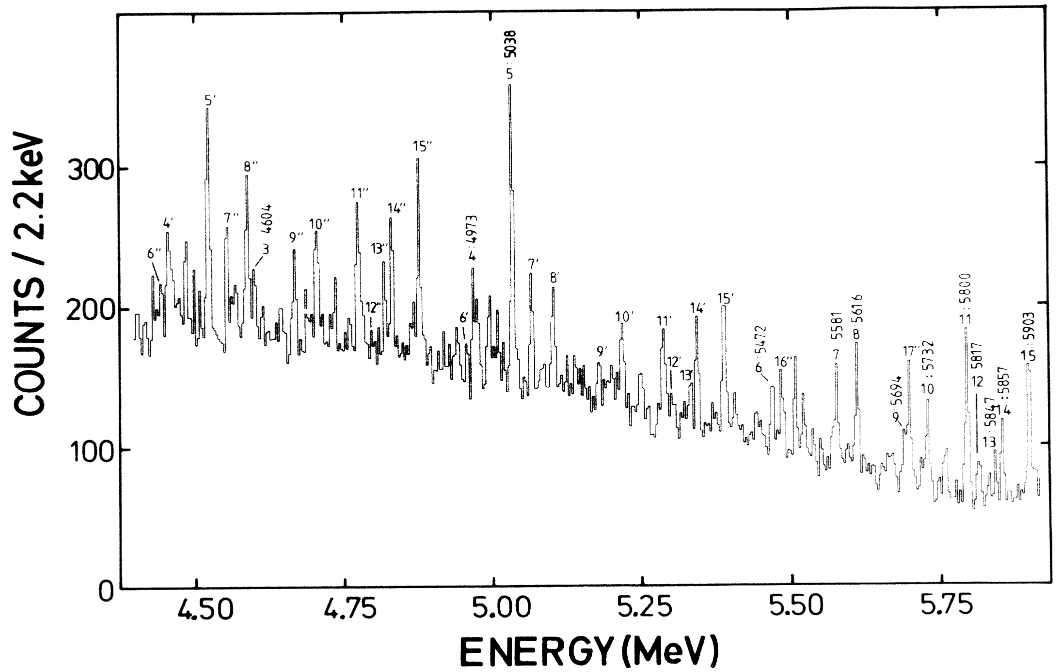

FIG. 1. Part of a $^{206}Pb(\gamma, \gamma)$ spectrum measured with 7-MeV bremsstrahlung at a scattering angle of 127°.

are in complete agreement with the $^{206}Pb(\gamma, \gamma)$ results published by Chapuran, Vodhanel, and Brussel.[12] The only quadrupole transition occurred to a state at 4116 keV; the measured ratio amounted to $R = 2.25 \pm 0.20$ in full accordance with the expected value.

For the parity determination the four Ge(Li) detectors were placed around the beam line at azimuthal angles of $\phi = 0°$, 90°, 180°, and 270° relative to the polarization plane of the linearly polarized bremsstrahlung beam.

The clear polarization effect in a (γ_{pol}, γ) study, namely, that $E1$ radiation is emitted predominantly perpendicular to the polarization plane and, on the other hand, $M1$ radiation parallel to it, was demonstrated by Berg *et al.*[15] The combined results from the $^{206}Pb(\gamma_{pol}, \gamma)$ studies with polarized bremsstrahlung of 10 and 12 MeV end-point energy are plotted in Fig. 2. The photon scattering asymmetries

$$\Sigma = (N_\perp - N_\parallel)/(N_\perp + N_\parallel) \qquad (2)$$

calculated from the number of γ rays $(N_\perp)$ scattered perpendicular to the average E vector of the incoming linearly polarized photon beam versus the number of photons $(N_\parallel)$ scattered parallel to the polarization plane are depicted in Fig. 2, with their statistical error bars. Systematic errors were avoided by recording of the photon scattering spectra perpendicular and parallel to the polarization plane simultaneously and by periodic turning of the plane of polarization around an angle of $\phi = 90°$. The latter can be achieved by deflection of the electron beam in horizontal and vertical directions a short distance in front of the bremsstrahlung target.

From Fig. 2 it is evident that the bulk of the dipole transitions to bound states in ^{206}Pb are due to $E1$ excitations. The measured asymmetry to the known $J^\pi = 2^+$ state is, as expected, negative, proving that a positive state has been excited. A summary of the results from the angular-distribution measurement and the experiments with linearly polarized photons is given in Table I.

The only dipole transition which has an obvious positive parity [negative asymmetry according to Eq. (2)] is to a state at 5800 ± 1 keV. The measured asym-

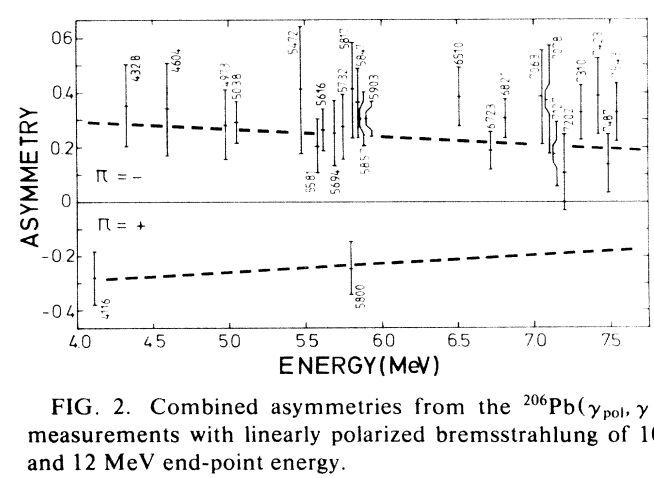

FIG. 2. Combined asymmetries from the $^{206}Pb(\gamma_{pol}, \gamma)$ measurements with linearly polarized bremsstrahlung of 10 and 12 MeV end-point energy.

TABLE I. Results from the $^{206}Pb(\gamma_{pol}, \gamma)$ experiments with polarized photons. Values of Γ_0^2/Γ are from a NRF measurement with unpolarized bremsstrahlung by Chapuran, Vodhanel, and Brussel (Ref. 12). Parentheses indicate tentative assignments.

Energy (keV)	J^{π}	Γ_0^2/Γ [a] (eV)
4116 ± 1	2^+	0.58 ± 0.15
4328 ± 1	1^-	0.48 ± 0.11
4604 ± 2	1^-	0.58 ± 0.16
4973 ± 1	1^-	0.95 ± 0.23
5083 ± 1	1^-	2.6 ± 0.4
5472 ± 2	$1^{(-)}$	0.7 ± 0.2
5581 ± 1	1^-	1.7 ± 0.3
5616 ± 1	1^-	1.8 ± 0.4
5694 ± 2	1^-	0.8 ± 0.2
5732 ± 1	1^-	1.3 ± 0.3
5800 ± 1	1^+	1.1 ± 0.3
5817 ± 3	1^-	0.5 ± 0.2
5847 ± 2	1^-	1.1 ± 0.2
5857 ± 1	1^-	2.0 ± 0.4
5903 ± 1	1^-	3.0 ± 0.6
6510 ± 1	1^-	1.9 ± 0.4
6723 ± 1	1^-	3.4 ± 0.6
6821 ± 1	1^-	4.7 ± 0.9
7063 ± 2	$1^{(-)}$	2.5 ± 0.6
7078 ± 4 [b]	$1^{(-)}$ [c]	0.9 ± 0.3
7127 ± 2 [b]	(1^-)	1.0 ± 0.2
7202 ± 4 [b]	$1^{(-)}$ [c]	1.8 ± 0.4
7310 [b]	1^- [c]	3.7 ± 0.9
7423 ± 4 [b]	1^- [c]	1.6 ± 0.4
7487 ± 4 [b]	(1^-)	1.7 ± 0.4
7543 ± 2 [b]	1^- [c]	2.3 ± 0.6

[a]From Ref. 12.
[b]Energies above 7070 keV were adopted from Ref. 12.
[c]Spins from Ref. 12.

metry of $\Sigma = -25 \pm 10$ together with the aforementioned result from the angular-distribution measurement proves the discovery of a magnetic dipole transition in ^{206}Pb. The asymmetry of the 5800-keV transition is almost exactly the value that we expect from a measurement of the bremsstrahlung polarization with the help of a $^2H(\gamma_{pol}, p)$ polarization monitor[14] (dashed lines in Fig. 2).

The ground-state decay width of the 5800-keV transition has been determined by Chapuran, Vodhanel, and Brussel.[12] Decay branches of the 5800-keV level to other states were observed neither in Ref. 12 nor in this work.

The ground-state decay width of $\Gamma_0 = 1.1 \pm 0.3$ eV of the 5800-keV state[12] in ^{206}Pb (on the assumption $\Gamma_0/\Gamma = 1$) is very close to the value of $\Gamma_0 = 1.2 \pm 0.4$ eV for the isoscalar $M1$ transition in ^{208}Pb. The energies of the two $M1$ excitations in the two Pb isotopes differ by only 46 keV. Therefore, we assume that an analogous isoscalar $M1$ transition has been discovered in ^{206}Pb, an assumption which has to be proved of course by experiments which are able to distinguish between isoscalar and isovector excitations.

We will turn now to the higher-excitation-energy region, where a total $M1$ strength of $\sum B(\uparrow M1) = (19 \pm 2)\mu_0^2$ has been deduced from the $^{206}Pb(\gamma_{pol,tag}, \gamma)$ experiment with tagged photons.[10] In the energy region between 7.1 and 7.4 MeV, where the $M1$ strength distribution reaches its maximum of $B(\uparrow M1) = 2.5\mu_0^2$, a total strength of about $\sum B(\uparrow M1) = 10\mu_0^2$ is calculated from the data of Ref. 10. While the photon scattering asymmetries from the tagged photons and this NRF experiment are in agreement that the energy region from 6.5 to 7 MeV is governed by strong $E1$ transitions, no strong $E1$ transitions or strong individual $M1$ transition could be identified above 7 MeV in this work. No definite comparison between transitions from the nuclear resonance fluorescence experiment and those from the tagged-photon scattering measurement can be made because of the high level density and the modest energy resolution which can be obtained in tagging experiments. However, some remarks seem to be appropriate: The strongest transition from NRF in the region where the $M1$ strength in Ref. 10 reaches its maximum is at 7310 keV. If this transition would be due to a $M1$ excitation, a $B(\uparrow M1)$ value of $2.5\mu_0^2$ would be calculated from the ground-state decay width in Table I. This $B(\uparrow M1)$ value would be exactly coincident with the maximum value of the $M1$ distribution in Ref. 10. However, the asymmetry plot in Fig. 2 shows that the 7310-keV state is due to an electric dipole excitation. Two further transitions at 7202 and 7423 keV, which are close, but which carry only about half the dipole strength each, seem to be $E1$ excitations too. Since no further strong individual transitions occur in the NRF spectra in this excitation energy region, $M1$ strength must be highly fragmented here to produce the observed asymmetries in the tagged-photon experiment.[10] We believe, however, that the energy region from 7 to 8 meV in ^{206}Pb should be reexamined with the high sensitivity achievable in modern NRF experiments before drawing final conclusions about $M1$ strength in ^{206}Pb. It turned out from this experiment that the strongest transitions below the neutron-emission threshold are clearly due to electric excitations.

In summary, the NRF experiment with linearly polarized bremsstrahlung has revealed a $J^{\pi}=1^{+}$ state at 5800 keV in ^{206}Pb with a reduced transition probability of $(1.5\pm0.4)\mu_0^2$, if $\Gamma_0/\Gamma=1$ is assumed.[12] The excitation energy and strength suggest that it is an analogous transition to the isoscalar $M1$ transition in ^{208}Pb. The parity determination of 24 further transitions in ^{206}Pb showed that dipole strength in the energy region up to the neutron threshold is dominated by electric excitations. If a total $M1$ strength of $\sum g\Gamma_0^2(M1)/\Gamma=47.7$ eV exists in the excitation interval $6.7\leq E_{\gamma}\leq 8.1$ MeV (Ref. 10) then it must be strongly fragmented.

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