Parity of Bound Dipole States in ^{208}Pb

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The parities of eleven $J=1$ levels in ^{208}Pb were determined by nuclear resonance fluorescence scattering of linearly polarized photons. A new 1^+ level at $E_x = 5.846$ MeV with $\Gamma_0^2/\Gamma = 1.2 \pm 0.4$ eV was found. This level can probably be identified with the theoretically predicted isoscalar 1^+ state in ^{208}Pb. All other bound dipole states below 7 MeV with $\Gamma_0^2/\Gamma > 1.5$ eV have negative parity. The 1^- assignment to the 4.842-MeV level is of special significance because of previous conflicting results about its parity.

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For more than a decade the location of magnetic dipole ($M1$) strength in ^{208}Pb has been a challenging problem for experimentalists and theorists.[1] This continued interest lies in the fact that from the energies of the $M1$ excitations and their particle-hole structure one expects information about the spin-dependent part of the effective nucleon-nucleon interaction in nuclei. In a simple shell-model picture, two 1^+ states are expected in ^{208}Pb resulting from the one-particle, one-hole (1p-1h) configurations $\nu(i_{13/2}{}^{-1}, i_{11/2})$ and $\pi(h_{11/2}{}^{-1}, h_{9/2})$. Since these states are nearly degenerate in energy they are expected to mix strongly and most of the strength is moved to higher energy.[2] In one calculation[3] the upper 1^+ state at 7.5 MeV is mainly isovector and carries most of the strength $[B(M1)\uparrow = 48\mu_0{}^2]$ while the lower 1^+ state at 5.4 MeV is mainly isoscalar and has little strength $[B(M1)\uparrow = 1.2\mu_0{}^2]$. The distribution of the $M1$ strength between these two states depends critically on the coupling between the neutron 1p-1h and the proton 1p-1h configurations. The inclusion of 2p-2h configurations[4,5] results in the fragmentation of the upper state into many components. However, the properties of the lower level are virtually unchanged because of its very weak coupling to 2p-2h states.[4,6]

The present experimentally established $M1$ strength gives a completely different picture. Original claims, prior to 1977, of finding a large concentration of strengths $[B(M1)\uparrow > 50\mu_0{}^2]$ as expected in the 7.0-8.3-MeV region have been reduced to a total definitive and probable $M1$ strength above 7 MeV of only $\approx 8.5\mu_0{}^2$ each.[1] Therefore, new theoretical concepts have been considered either to shift the isovector state to higher energies[6] or to quench the intrinsic g_s factor in the $M1$ operator.[7]

The experimental results reported in this Letter clarify the situation of the $M1$ strength in the bound-state region of ^{208}Pb. The 4.842-MeV state which has a ground-state radiative width of 5 eV $[B(M1)\uparrow = 11.4\mu_0{}^2]$ was originally classified as 1^+ on the basis of a linear polarization measurement using a Compton polarimeter.[8] This result was afterwards questioned and a 1^- assignment was established.[9] A repetition of the linear polarization measurement,[10] now with an enriched ^{208}Pb target, found an inconsistency with either a pure $E1$ or $M1$ transition and it was concluded that there are two levels (1^+ and 1^-) at 4.842 MeV less than 3 keV apart with Γ_0 values of about 2.5 eV $[B(M1)\uparrow = 5.7\mu_0{}^2]$ each.[10] However, other unpolarized nuclear resonance fluorescence (NRF) experiments did not require such an assumption.[11] Quite recently a NRF experiment involving the elastic scattering of linearly polarized photons from a nuclear reaction found that the level has an excitation energy $E_x = 4842.2 \pm 0.2$ keV with $\Gamma = 4.3^{+3.5}_{-1.4}$ eV and is most probably a 1^+ level.[12] None of the existing calculations can account for such a large $M1$ strength at such a low excitation energy.

To clarify this conflicting situation we performed an accurate measurement of the parities of the bound $J=1$ levels in ^{208}Pb which are excited by NRF scattering using linearly polarized bremsstrahlung. Our results show that the 4.842-MeV state has $J^\pi = 1^-$ and a width of $\Gamma_0^2/\Gamma = 4.7 \pm 0.9$ eV. We furthermore present evidence for a new 1^+ level at $E_x = 5.846$ MeV with $\Gamma_0^2/\Gamma = 1.2 \pm 0.4$ eV. This level can probably be identified with the theoretically predicted isoscalar 1^+ state in ^{208}Pb. In addition we show that all other bound dipole states below 7 MeV with $\Gamma_0^2/\Gamma > 1.5$ eV have negative parity.

Two experiments were performed. In the first with 10-MeV linearly polarized bremsstrahlung

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the parities of states excited were deduced from the azimuthal asymmetry of the elastically scattered photons. The second measurement was done with unpolarized bremsstrahlung of 7 MeV maximum energy to determine the multipolarities of the transitions observed.

For the first experiment linearly polarized photons from off-axis bremsstrahlung produced by 10-MeV electrons bombarding a 25-μm Al foil were selected by a narrow collimator. A ^{2}H(γ_{pol}, p) polarimeter measured and monitored continuously the photon polarization and photon intensity. The azimuthal asymmetry of photons scattered by a 1.1-g/cm^2 enriched ^{208}Pb target (86.5% ^{208}Pb) was observed with four Ge(Li) detectors arranged symmetrically around the photon beam at a scattering angle $\theta = 90°$ and at azimuthal angles $\Phi = 0°$, 90°, 180°, and 270°. Data were taken by switching permanently the polarization direction after a certain number of counts had been accumulated in the ^{2}H(γ_{pol}, p) monitor to cancel experimental asymmetries.

A summary of the results of the polarization measurement is shown in the upper part of Fig. 1. In the lower part of Fig. 1 the values of $\Gamma_0^2/(\Gamma E^2)$ for levels observed in unpolarized NRF scattering experiments[11,13] are shown as vertical bars together with the low-resolution (tagged photon) measurement of the average elastic-scattering cross section $\sigma_{\gamma\gamma}$.[14] For a spin $J = 0$ target and elastic scattering of linearly polarized photons through an isolated dipole or quadrupole state, the analyzing power at $\theta = 90°$ is unity. Therefore, the magnitude of the observed asymmetry is equal to the polarization of the incoming photons and the sign of the asymmetry gives directly the parity of the intermediate state. The band of two solid lines in the upper part of Fig. 1 shows the photon polarization; i.e., the expected asymmetry of a γ transition at $\theta = 90°$ (upper part for negative parity, lower part for positive parity) as measured simultaneously with the aforementioned ^{2}H(γ_{pol}, p) reaction. It was extrapolated below the 6-MeV detection threshold of the polarimeter by dashed lines using the known energy dependence of the photon polarization.[15] The width of these lines gives the statistical accuracy of the ^{2}H(γ_{pol}, p) measurement. The error bars (one standard deviation) show the measured asymmetries for the strongest transitions.

For the 4.842-MeV level we obtain an asymmetry of 33.9% ± 8.1%. This overlaps with the expected asymmetry of 28% for an electric dipole transition and is more than seven standard deviations away from the value expected for a magnetic dipole transition. Therefore, we conclude

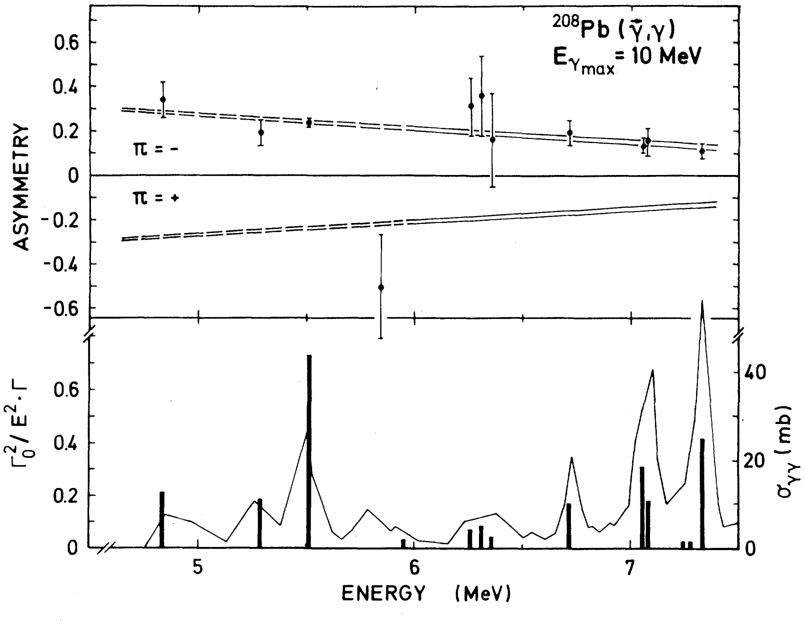

FIG. 1. A summary of the measured asymmetries for the observed γ-ray transitions is shown in the upper part. The solid and dashed lines represent the expected asymmetries for transitions with negative ($\pi = -$) and positive ($\pi = +$) parity. For comparison, in the lower part, the values $(1/E^2)\Gamma_0^2/\Gamma$ for transitions observed in unpolarized NRF scattering are drawn as vertical bars (left scale) together with the average elastic photon scattering cross section (right scale).

that the 4.842-MeV state has $J^{\pi}=1^{-}$ and we find no indication of a close-lying 1^{+} state.[10]

The assignment of 1^{-} to the levels at 6.263, 6.312, and 6.363 MeV is the first parity assignment that has been made for these levels. For the weaker states at 5.948 and 7.243 MeV and for the known 1^{+} state at 7.278 MeV the large error bars prevented a definite parity assignment. Our assignment of 1^{-} to the other stronger levels agrees with previous assignments.[12,16]

As mentioned before a transition with positive parity (measured asymmetry -0.5 ± 0.23) was discovered at 5.846 MeV ±1 keV. Parts of two Ge(Li) spectra in the 5-MeV region are compared in Fig. 2 to demonstrate the polarization effect. In the upper spectrum, where the electric vectors of the incoming photons were perpendicular to the scattering plane, transitions with negative parity are enhanced. While in the upper spectrum ($\varphi=90°$) the double escape peak of the 5.846-MeV excitation is almost absent, it is clearly visible in the lower spectrum where the photon polarization was in the scattering plane ($\varphi=0°$), indicating positive parity.

The spin of the 5.846-MeV state was determined in the separate experiment with 7-MeV beam end-point energy from the relative yields at 90° and 127°. The theoretical 90°-to-127° cross-section ratios for dipole and quadrupole scattering from a spin-0 nucleus averaged over the detector solid angle are 0.74 and 2.21. For the 5.846-MeV transition we measured a ratio of 0.71 ± 0.12 and for the other dipole transitions to 1^{-} levels we obtain 0.73 ± 0.01. For the known 2^{+} level at 4.085 MeV the measured value was 2.01 ± 0.22.

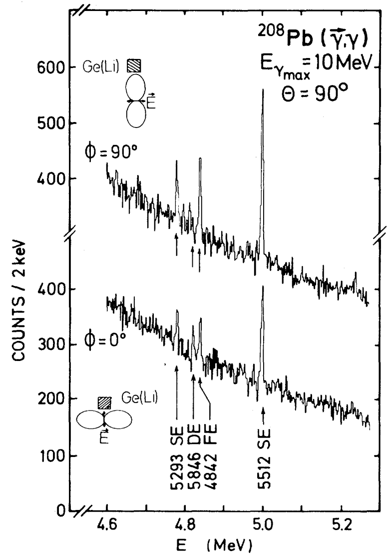

FIG. 2. Part of ^{208}Pb(γ_{pol}, γ) spectra in the 5-MeV region. In the upper part the electric vector $\vec{E}$ of the incoming photons was perpendicular and in the lower part parallel to the scattering plane as shown in the inset.

The weak transition at 5.846 MeV occurred in each spectrum from the four Ge(Li) diodes. Since the 5.846-MeV γ rays were detected also with 7-MeV bremsstrahlung end-point energy, it is obvious that these have to be due to ground-state transitions, because the first excited state in ^{208}Pb is at 2.6 MeV. The 5.846-MeV γ rays cannot stem from ^{206}Pb which was, to a level of 12.5%, contained in our target and where a dipole level at the same energy with $\Gamma_0^2/\Gamma=1.1\pm0.2$ eV is known.[11] A level in ^{206}Pb would have to be 10 eV strong to show up with comparable strength in the spectra. No strong level at this energy is known in ^{207}Pb,[11] which was at a level of 1% in our target. Therefore, these measurements show that there is a state with positive parity in ^{208}Pb at 5.846 MeV excitation energy.

The average elastic photon scattering cross section from low-resolution tagged-photon measurements,[14] which is displayed in the lower part of Fig. 1, shows a bump around 5.85 MeV with a total strength of $\Gamma_0^2=4.4\pm1.1$ eV.[14] We obtain $\Gamma_0^2/\Gamma=1.2\pm0.4$ eV for the 5.846-MeV state. There still may be some other weaker ($\Gamma_0^2/\Gamma<0.7$ eV) levels at this energy.

We conclude that there is a 1^{+} state at 5.846 MeV in ^{208}Pb with a reduced transition probability $B(M1)\uparrow=(1.6\pm0.5)\mu_0^2$ if $\Gamma_0/\Gamma=1$ is assumed. The energy of this 1^{+} state is slightly higher and it is 30% stronger than the theoretical predictions[3] for the isoscalar 1^{+} state in ^{208}Pb.

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Experimental Evidence for the Competition between Resonantly Enhanced Multiphoton Ionization and Third-Harmonic Generation in Xenon

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Competition between third-harmonic generation and multiphoton ionization in xenon is confirmed in a direct experiment using counterpropagating circularly polarized laser beams to suppress third-harmonic emission. Three-photon resonantly enhanced multiphoton ionization through the 6*s* and 6*s*′ levels in xenon, previously reported to disappear at pressures above a few Torr, gives rise to sharp intense ionization signals under these conditions.

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With the advent of high-power lasers, gas-phase multiphoton excitation has been extensively studied in recent years. In particular, xenon atoms have been investigated by three-photon excited fluorescence and resonantly enhanced multiphoton ionization (MPI). In these studies, the signal due to the three-photon allowed $^1S_0$-$5p^5(^2P_{3/2}{}^o)6s$ transition was observed to be strongly pressure dependent. The disappearance of fluorescence signal[1] from the 6*s* level above 8 mTorr was ascribed to radiation trapping, while Aron and Johnson[2] have reported the complete absence of any MPI signal due to this transition, and attributed the anomalous pressure effects to xenon dimers. In that MPI study,[2] 4*f* four-photon atomic resonances were observed in the wavelength region of the expected three-photon 6*s* resonance. Compton *et al.*[3] reported that under collision-free conditions, three-photon resonantly enhanced MPI signals through the 6*s* level dominate the ionization spectrum of xenon. More recently, Miller *et al.*[4,5] have shown that the strong 6*s* and 6*s*′ ionization signal shifts to the blue (in excess of the ac Stark effect) and disappears as pressure is increased above a few Torr. This is accompanied by the production of intense third-harmonic radiation, and it is suggested that third-harmonic generation (THG) and MPI are competitive processes. In a theoretical model, Payne, Garrett, and Baker[6] have attributed the loss of right-angle fluorescence and ionization signals to resonantly enhanced THG following a coherent, collective excitation of an ensemble of xenon atoms. A competition between the third-harmonic field and the laser field (or the one-photon Rabi frequency and the three-photon Rabi frequency) produces these effects.[7] Coherent loss mechanisms are generally excluded in rate equation models of MPI. In this work we report the first direct experimental evidence that xenon MPI through the 6*s* and 6*s*′ levels is quenched by THG. This is accomplished by observing xenon MPI under conditions for which THG is forbidden.

To achieve an unambiguous experiment in which three-photon resonantly enhanced MPI through the 6*s* and 6*s*′ intermediate states is allowed but THG is forbidden, it is necessary to consider the selection rules for MPI and THG with respect to excitation laser polarization. The polarization constraints on THG arise from angular momen-