Nuclear resonance fluorescence measurements by quasi-monochromatic linearly polarized photon beams

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Abstract. Low-lying electromagnetic transitions have been studied by the method of nuclear resonance fluorescence (NRF) or nuclear photon scattering. Quasi-monochromatic linearly polarized photon beams from inverse Compton scattering of laser light are used to excite nuclei around shell closure. In this report, the results of NRF measurements on ²⁰⁸⁰Pb are presented. The magnetic dipole resonance below the neutron separation energy is resolved into several individual transitions. The experimental results are compared with theoretical predictions based on self-consistent RPA calculations. A role of the tensor force is discussed.

1. Introduction

The magnetic dipole (M1) response is one of the fundamental low-energy excitations in nuclei. The electromagnetic field couples the spin of the nucleon via the nuclear magnetization current. The M1 response therefore provides direct information on the spin-dependent parts of the nuclear interaction. Since the M1 excitation is primarily of single particle character, individual proton/neutron excitations and their possible interference reflected in isoscalar and isovector M1 modes can be investigated.

The distribution of magnetic dipole strengths in the doubly closed-shell nucleus ²⁰⁸⁰Pb is of particular interest, because of the closed-shell nature both for protons and neutrons. The missing M1 problem for ²⁰⁸⁰Pb has been an intriguing subject of nuclear structure physics [1]. In the independent particle model, the M1 transitions to the lowest two ¹⁺ states are expected as the 1p-1h spin-flip excitations of \[ \pi(h_{11/2}^{-1}, h_{9/2}) \] and \[ \nu(i_{13/2}^{-1}, i_{11/2}) \]. The mixing between these states by the residual proton-neutron interaction yields isoscalar (IS) and isovector (IV) states. A calculation in the Tamm-Dancoff approximation (TDA) predicts the M1 strengths of 1.2 \( \mu_N^2 \) for the IS state and 48 \( \mu_N^2 \) for the IV state [2]. For the latter, a localized M1 resonance has been observed near the neutron threshold in the tagged photon [3] and neutron measurements [4].
Figure 1. Photon scattering spectra observed at the scattering angles of $\theta = \pm 90^\circ$ in the plane parallel (a) and perpendicular (b) to the polarization plane of the LCS photon beam at $E_{\gamma}^{\text{max}} = 7.4$ MeV. In panel (a), $M1$ ($E2$) peaks are marked with filled circles (triangles). The known $E1$ peaks are marked with open circles in panel (b). Peaks attached label "c" and "s" are due to contamination of the $E1$ transitions and the single escape, respectively.

The total $M1$ strength (15.6 $\mu^2_N$, see Ref. [3]) is quenched by about 70% from the above TDA estimate. This quenching invoked many theoretical studies [5]. The core polarization (CP), the meson exchange current (MEC), the isobar excitation ($\Delta-h$), and the higher order configuration mixing (e.g. coupling to the $2p-2h$ states) affect the IV $M1$ strength. The combination of these effects accounts for the quenching to an appreciable extent [1].

The previous tagged photon work reveals the $M1$ strength distribution below the neutron threshold in $^{208}$Pb [3]. However, the limited resolution for the detection of scattered electrons remains the discrete $M1$ structure unresolved. The method of nuclear resonance fluorescence (NRF) employed in the present work is suitable for studies of the nuclear electro-magnetic response below the particle threshold [6]. The availability of quasi-monochromatic, 100% linearly polarized photon beams from the inverse laser-Compton scattering (LCS photons) has considerably increased the experimental sensitivity for detecting fine structure of relatively weak $M1$ transitions in combination with high-resolution $\gamma$-ray spectroscopy [7, 8].

2. Experimental procedure
Photon scattering experiments have been performed at the National Institute of Advanced Industrial Science and Technology (AIST). A quasi-monochromatic, linearly polarized photon beam is generated by the inverse Compton scattering of laser light with relativistic electrons circulating in the storage ring TERAS [9]. A Nd:YVO$_4$ Q-switch laser at wavelength of 1064 nm was operated at a frequency of 20 kHz. The electron energies were selected at 558, 588, 625, and 648 MeV to produce LCS photons with the maximum energy of $E_{\gamma}^{\text{max}} = 5.5, 6.1, 6.9,$ and 7.4 MeV, respectively. The details of the experiment are described in Ref. [10].

During the NRF measurements, the polarization of the LCS photon beam was varied into the vertical and horizontal planes in short interval (20 ~ 100 sec) to measure the asymmetry of resonant photon intensities with respect to the polarization plane. The measured asymmetry
Figure 2. Measured asymmetry for the NRF intensities obtained for \( E_1 \) (open circles), \( M_1 \) (filled circles), and \( E_2 \) (triangles) transitions in \(^{208}\text{Pb}\). The polarization sensitivity in this experiment amounts to approximately 0.85 which was obtained from the numerical simulation.

serves to separate \( M_1 \) from the dominant \( E_1 \) transitions. The theoretical analyzing power is defined as

\[
\Sigma = \frac{W(90^\circ, 0^\circ) - W(90^\circ, 90^\circ)}{W(90^\circ, 0^\circ) + W(90^\circ, 90^\circ)},
\]

where \( W(\theta, \phi) \) is the intensity distribution function [11] on the polar angle \( \theta \) and the azimuthal angle \( \phi \) with respect to the polarization plane of the LCS photon beam. For magnetic dipoles or electric quadrupoles (\( E_2 \)), \( \Sigma = +1 \) is expected and for electric dipoles (\( E_1 \)), \( \Sigma = -1 \), under the condition of complete polarization.

The experimental asymmetry is given by \( \epsilon = (N_{\parallel} - N_{\perp})/(N_{\parallel} + N_{\perp}) \) where \( N_{\parallel} \) (\( N_{\perp} \)) represents the efficiency corrected intensities of resonant photons detected with the Ge detectors at the polar angle of \( \theta = \pm 90^\circ \) in the plane parallel (perpendicular) to the polarization plane. The quantity \( q \) denotes the sensitivity of the detection system. For the present case, \( q \) amounts to about 0.85 deduced from the numerical simulation, which deviates from unity because of the finite solid angles of the detectors and spatially extended target. Thus, the parity of observed transitions can be determined from the azimuthal intensity asymmetry.

3. Results

Photon scattering spectra at \( E_\gamma^{\text{max}} = 7.4 \) MeV obtained with the detectors at the different azimuthal angles are shown in Fig. 1. While the known \( E_1 \) lines are obvious in Fig. 1(b), several peaks which are assigned \( M_1 \) are seen in Fig. 1(a). As shown in Fig. 2, the transitions are clearly distinguished depending on their multipolarities. It should be noted that \( E_2 \) transitions are expected to show the asymmetry similar to that of the \( M_1 \) transitions [11]. Therefore, the angular distribution ratio between resonant photon intensities observed at the polar angle of \( \theta = \pm 90^\circ \) and 145° is used to distinguish \( M_1 \) from \( E_2 \) transitions.

Table 1 summarizes the measured values of the excitation energy, spin and parity, the ratio \( \Gamma_\delta^2/\Gamma \) which is proportional to the NRF cross section, and the reduced transition strength for the
Table 1. The excitation energies ($E_x$), the spin and parity ($J^\pi$), the decay-width ratio ($\Gamma_0^2/\Gamma$), and the reduced transition strength $B(\sigma\lambda)$ are given.

| $E_x$ (keV) | $J^\pi$ | $\Gamma_0^2/\Gamma$ (eV) | $B(\sigma\lambda) \uparrow$ (eV) |
|-------------|---------|--------------------------|--------------------------------|
| 4841.5(9)   | 1−      | 4.6(8)                   | 116(21)                        |
| 5292.0(9)   | 1−      | 5.5(9)                   | 106(17)                        |
| 5511.9(9)   | 1−      | 23.0(36)                 | 394(61)                        |
| 5844.3(9)   | 1+      | 1.5(3)                   | 2.0(3)                         |
| 5946.7(9)   | 1−      | 1.1(2)                   | 15(3)                          |
| 6264.4(9)   | 1−      | 4.0(8)                   | 47(9)                          |
| 6315.2(9)   | 1−      | 3.0(7)                   | 35(8)                          |
| 6362.0(9)   | 1−      | 2.0(5)                   | 23(6)                          |
| 6486(1)     | 1−      | 0.31(13)                 | 3.3(14)                        |
| 6720.4(8)   | 1−      | 8.3(13)                  | 78(13)                         |
| 7063.3(8)   | 1−      | 15.9(24)                 | 129(20)                        |

The neutron threshold energy up to 8.7 MeV in the previous work [4]. Consequently, the summed 0 strength between 6.7 and 7.4 MeV amounts to $\Sigma \Gamma N = 17.9 \mu_N^2$. This is larger than the previous tagged photon data of $\Sigma \Gamma N = 16.0 \mu_N^2$ (If the 7335 keV line is $M1$, $\Sigma B(M1) \uparrow = 16.0 \mu_N^2$ (If the 7335 keV line is $M1$, $\Sigma B(M1) \uparrow = 16.0 \mu_N^2$). Consequently, the summed $M1$ strength between 7.1 and 8.7 MeV amounts to $\Sigma B(M1) \uparrow = 17.9 \mu_N^2$.

4. Discussion

The $M1$ strength in $^{208}$Pb has been a focal point of theoretical studies. The CP, MEC, and $\Delta-h$ effects give significant contribution to the $M1$ strength at low energy [5]. These effects cause a modification of the bare $M1$ operator, i.e., $T^{br}(M1) = \sum_{\ell=p,n} (g_{\ell,r}\ell_\tau + g_{s,r}s_\tau)$. Thus, the

observed dipole excitations. Here, $\Gamma$ and $\Gamma_0$ are the total radiative width and ground state decay width of excited states. The ratio $\Gamma_0^2/\Gamma$ is obtained by normalizing each transition strength to the values of the 7063 and 7083 keV $E1$ transitions taken from Ref. [12]. The strength for the known $E1$ and the 5844 keV $M1$ transitions is obtained in good agreement with the values from the previous photon scattering experiments [12, 13, 14]. On the contrary, larger strength than that of the previous experiment [15] for the $M1$ excitations between 7.17 and 7.28 MeV (i.e., 7178, 7210, 7246, and 7281 keV transitions) is observed. This is possibly due to doublet nature of $\gamma$ line at 7332 keV (used for the intensity normalization), described below. In addition, a 7300 keV transition previously reported as $E2$ [15] is now reassigned $M1$ based on the angular distribution data. Two $M1$ transitions of 7322 and 7347 keV are observed for the first time. The azimuthal asymmetry data in Fig. 2 show a smaller absolute value for the 7332 keV transition than expected sensitivity $q$. This implies presence of a positive parity state ($1^+ \ or \ 2^+$) near the 7332 keV $1^-$ state. By careful inspection of the photon scattering spectra, a 7335 keV transition is confirmed. Because of the dominant 7332 keV $E1$ line, it is hard to determine dipole or quadrupole nature for this transition from the angular distribution data.

From the present NRF measurements, seven $1^+$ states, possibly eight, were identified in excitation energies between 7.1 and 7.4 MeV. The total $M1$ strength in this energy region is obtained as $\Sigma \Gamma_0^2/\Gamma = 13.6(21)$ eV corresponding to $\Sigma B(M1) \uparrow = 9.2(14) \mu_N^2$. Assuming that the 7335 keV transition is of $M1$ character, $\Sigma \Gamma_0^2/\Gamma$ and corresponding $\Sigma B(M1) \uparrow$ value are 16.4(25) eV and 11.1(17) $\mu_N^2$. This is larger than the previous tagged photon data of $\Sigma B(M1) \uparrow = 8.8^{+1.0}_{-0.8} \mu_N^2$ between 6.7 and 7.4 MeV. The $M1$ strength of $\Sigma B(M1) \uparrow = 6.8 \mu_N^2$ has been observed above the neutron threshold energy up to 8.7 MeV in the previous work [4]. Consequently, the summed $M1$ strength between 7.1 and 8.7 MeV amounts to $\Sigma B(M1) \uparrow = 16.0 \mu_N^2$ (If the 7335 keV line is $M1$, $\Sigma B(M1) \uparrow = 17.9 \mu_N^2$).
Table 2. Comparison of the low-lying $M1$ strength distribution in $^{208}$Pb calculated using the effective $M1$ operator as shown in eq. (2). The single particle excitations ($\hat{v}_{\text{res}} = 0$), the RPA results without the residual tensor force ($\hat{v}_{\text{res}} = \hat{v}_{\text{sc}} - \hat{v}_{\text{TN}}$), and the fully self-consistent RPA results ($\hat{v}_{\text{res}} = \hat{v}_{\text{sc}}$) are presented. The experimental $M1$ strengths obtained assuming that the $7335$ keV transition is $M1$ are also shown.

| $\hat{v}_{\text{res}}$ | $E_x$(MeV) | $B(M1)^{(\mu_2^2N)}$ | $E_x$(MeV) | $B(M1)^{(\mu_2^2N)}$ |
|------------------------|------------|----------------------|------------|----------------------|
| none                   | 6.1        | 12.7                 | 8.3        | 14.3                 |
| $\hat{v}_{\text{sc}} - \hat{v}_{\text{TN}}$ | 6.9        | 4.7                  | $\sim$9.9  | 16.4                 |
| $\hat{v}_{\text{sc}}$ | 5.9        | 2.4                  | $\sim$9.6  | 19.4                 |
| exp.                   | 5.85       | 2.0                  | 7.1–8.7    | 17.9                 |

effective $M1$ operator is written as

$$T_{\text{eff}}(M1) = \sum_{\tau=p,n} \{(g_{\ell,\tau} + \delta g_{\ell,\tau})\ell_{\tau} + (g_{s,\tau} + \delta g_{s,\tau})s_{\tau} + \delta g_{p,\tau}[Y_2s]^{(1)}_{\tau}\}. \quad (2)$$

Here, the $\delta g$ values represent the contribution from the effects of MEC, $\Delta-h$, and $2p-2h$ configuration mixing. These are taken from Table 29 in Ref. [5]. The $M1$ strength distribution calculated for the single particle excitations, the Random Phase Approximation (RPA) response without the residual tensor force and the fully self-consistent RPA response with the M3Y-P5 interaction [16] are summarized in Table 2. The unperturbed single particle excitations are obtained at $6.1$ MeV for $\pi(h_{11/2}^{-1}, h_{9/2})$ and at $8.3$ MeV for $\nu(i_{13/2}^{-1}, i_{11/2})$. Due to the residual proton-neutron interaction, the lower-energy $M1$ transition has relatively large contribution of the IS component [17], while the higher-lying strength is dominated by the IV component. Although the higher-lying $M1$ strength is rather concentrated into a single $1^+$ state in the RPA results, the coupling to the $2p-2h$ states accounts for the fragmentation [18, 19].

The importance of the tensor force to reproduce the observed $M1$ strength distribution is obvious as seen in Table 2. The tensor force tends to enhance the mixing of the $\pi$ and $\nu$ $1^+$ states, suppressing the IV contribution to the lower-energy $1^+$ state, although significant interference between the IS and IV components remains [20]. This leads to the reduction (enhancement) of the $M1$ strength for the lower-energy (higher-energy) $1^+$ states. In addition, the attractive interference of the tensor force on the IS channel well accounts for the position of the lower-energy $1^+$ state. Finally, it is noted that the tensor force has little influence on the total (IS+IV) $M1$ strength below $11$ MeV.

5. Conclusion

Photon scattering experiments on $^{208}$Pb have been carried out using quasi-monochromatic linearly polarized photon beams. From the high-resolution $\gamma$-ray spectroscopic measurement, at least seven, possibly eight, $1^+$ states were identified at excitation energies between 7.1 and 7.4 MeV. The fully self-consistent RPA calculation with the semi-realistic interaction well describes the low-energy $M1$ strength distribution for the IS and IV $1^+$ states. It is important to include the tensor force in the HF+RPA calculations for investigating nuclear magnetic properties.

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