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Parity Measurements of Nuclear Levels Using a Free-Electron-Laser Generated γ-Ray Beam

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The quality and intensity of γ rays at the High Intensity γ-ray Source are shown to make nuclear resonance fluorescence studies possible at a new level of precision and efficiency. First experiments have been carried out using an intense (10^7 γ/s) beam of 100% linearly polarized, nearly monoenergetic, γ rays on the semimagic nucleus ^{138}Ba. Negative parity quantum numbers have been assigned to 18 dipole excitations of ^{138}Ba between 5.5 MeV and 6.5 MeV from azimuthal γ-intensity asymmetries.

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Nuclear survival rates in hot thermal photon baths (for instance, in supernova explosions) are crucial for our understanding of the process of nucleosynthesis. For many nuclides such survival rates critically depend on photon excitation cross sections to intermediate states with depopulating decay paths [1,2], or on photoparticle evaporation cross sections close to the threshold for (γ, n), (γ, p), or (γ, α) processes [3,4]. Most of the photonuclear reactions have dipole character due to the low momentum transfer of the photon. Understanding the nuclear dipole response, especially near particle emission threshold, is therefore of broad current interest. Moreover, the relatively weak binding of nucleons in excitations close to this threshold makes these excitations sensitive to the theoretically debated coupling to the continuum [5] which is responsible for the formation of exotic phenomena, e.g., halo structures [6]. The development of moderately collective phenomena such as clustering [7], local isospin resonances [8], "pygmy" resonances [9,10], or newly suggested "proton-crust oscillations" [11] are known or expected to play important roles in the near threshold regime. Close to the particle threshold, the nuclear dipole response is far from being understood [12] despite its astrophysical importance and its theoretical potential.

The electromagnetic dipole response ($E1$ and $M1$) can be sensitively studied using real photons as projectiles (cf. [13,14], and references therein). The low momentum transferred by the real photons gives rise to a high selectivity in exciting low-spin states. The combination of this selectivity with high-resolution γ-ray spectroscopy is essential for detailed studies of the fragmentation of the strength of specific dipole modes. The photonuclear reaction is completely electromagnetic at γ energies below the particle emission threshold and hence a wealth of information on the nuclear response can be extracted from photonuclear reactions in a model-independent way.

The purpose of this Letter is to present the results of a recent nuclear resonance fluorescence (NRF) experiment. These initial results demonstrate that the quality and intensity of γ rays at the High Intensity γ-ray Source (HIγS) facility opens up a new generation of photonuclear experiments which can be used to observe the nuclear dipole response at a new level of precision and sensitivity.

Recently it has become possible to resolve the fine structure of the nuclear dipole response below the particle threshold in highly sensitive NRF experiments, e.g., [9,15–17], and references therein. The progress in modern NRF spectroscopy, namely, the availability of high efficiency, composite Ge γ-spectrometers, along with the advent of higher flux γ-ray beams, has led to the rebirth of the classical NRF technique. Despite these achievements, it remains difficult to assign parity quantum numbers to the majority of moderately strong dipole excitations above 4 MeV. However, as was pointed out, e.g., in Ref. [14], parity information is crucial for the interpretation of the observed dipole states.

Parity measurements in NRF experiments require polarization information on one of the γ quanta involved. Either a polarized γ beam must be used in the entrance channel or polarization must be measured in the exit channel. Measuring the polarization of scattered photons using Compton polarimeters has been very successful at energies near and below 3 MeV [14]. However, this technique becomes difficult at excitation energies exceeding 4 MeV because the analyzing power of the Compton scattering process is energy dependent and approaches zero at these energies.

The use of polarized photons in the entrance channel and the measurement of the intensity distribution with respect to the polarization plane of the beam is preferable for parity measurements of nuclear dipole excitations above about 4 MeV: the analyzing power of this process is 100% and independent of the scattered γ-ray energy. Moreover, parity information can be obtained from relatively simple intensity measurements. This approach has suffered up until now from difficulties in producing sufficiently intense polarized γ beams, although it has been possible to measure the parity of a few strong dipole excitations using partially polarized off-axis bremsstrahlung, e.g., [18,19].

A completely polarized γ-ray beam generated by Laser Compton backscattering (LCB) of relativistic electrons presents an alternative to the use of off-axis bremsstrahlung. Indeed, Ohgaki *et al.* measured the parity of a previously known strong $M1$ excitation in ^{208}Pb using a LCB γ-ray beam [20]. However, LCB sources using external lasers have γ-ray fluxes inferior to that of the available unpolarized bremsstrahlung sources. Recently, it was shown that the γ-ray flux in the LCB scheme could be increased by 2 to 4 orders of magnitude by using the high intracavity laser power in a storage ring free electron laser (SR FEL) [21]. The achievable γ flux from SR FEL Compton γ-ray sources is comparable to that from on-axis bremsstrahlung.

The High Intensity γ-ray Source at the Duke Free Electron Laser Laboratory (DFELL) used for this experiment is based on the Duke/OK-4 SR FEL [22]. The wavelength of the FEL photons can be tuned by a simple change of the current in the wigglers, while the lasing range is limited by the reflectivity band of the optical cavity mirrors. The length of the OK-4 FEL optical cavity is equal to one-half of the circumference of the ring. The use of two equally spaced electron bunches in the storage ring provides for a natural head-on collision of the relativistic electrons and the FEL photons. This Compton effect boosts the backscattered photons to high energies in the lab frame. An on-axis collimator selects the resulting beam of semi-mono-energetic γ rays. The tunability of the OK-4 FEL and of the energy of the electron beam in the ring makes the energy of the γ rays tunable over a large range of values.

The HIγS facility has been used to measure the parity quantum numbers of dipole excitations in ^{138}Ba between 5.5 and 6.5 MeV, including the 5.644 MeV level tentatively assigned $J^\pi = 1^{(+)}$ by Herzberg *et al.* [23]. The small Compton scattering asymmetry measured in Ref. [23] was not significant enough to draw a definite conclusion about the parity of that dipole excitation (see Table I below). If its parity were positive, it would have [23] a large excitation strength of $B(M1; 0^+ \rightarrow 1^+) = 2.52(16)\mu_N^2$ which could not be understood by any reasonable current nuclear-structure model. The independent confirmation of the findings by Herzberg *et al.* would be, therefore, of high interest.

The OK-4 FEL was tuned to lase in the red range of the spectrum ($\lambda \sim 670$ nm). The storage ring was operated at four sets of energies between 425 MeV (for 5-MeV γ rays) and 470 MeV (for 6-MeV γ rays). With an 18–20 mA stored beam current, the total γ-beam intensity was measured to be 1.6×10^8 γ rays per second. A 10-cm-thick lead collimator with 2.54 cm aperture formed a semi-mono-energetic γ-ray beam with a FWHM resolution of $\Delta E_\gamma / E_\gamma \sim 3.2\%$ (at electron-beam energy of 425 MeV) and a degree of horizontal linear polarization better than 99.9% [24]. This primary collimator is located in a well-shielded "collimator hut," at the entrance to the γ-ray vault, 60 m downstream from the Compton collision point. The intensity of the beam on target was 0.9×10^7 γ rays per second with about 0.4×10^5 γ rays/(sec keV) at the maximum. The target consisted of 2.14 g/cm^2 $^{\mathrm{nat}}$BaNO$_3$ in a thin-walled plastic cylinder with dimensions of 10 mm (length) and 30 mm (inner diameter). It was surrounded by four coaxial Ge detectors of 60% photopeak efficiency relative to a standard 3 in. × 3 in. NaI detector at 1.33 MeV. These detectors were mounted at polar angles of $\theta = 90°$ and azimuthal angles of $\phi = 0°, 90°, 180°$, and 270° with respect to the (horizontal) polarization plane of the γ beam. The axes of the 78-mm-long detectors with diameters of 68 mm were oriented parallel to the beam at a distance of about 10 cm from it. The γ-ray beam energy was tuned to the desired value by monitoring the energy profile with a large high-purity Ge detector, which is 109-mm long with a diameter of 96 mm and has 123% relative efficiency. This beam monitor was positioned along the beam axis, behind a Pb attenuator and a pinhole collimator, 6 m behind the target position.

The intensity distribution function of a $0^+ \xrightarrow{\vec{\gamma}} 1^{\pi_1} \xrightarrow{\gamma} 0^+$ photon scattering reaction can be derived within the angular correlation formalism [25] and is given by

$$W(\theta, \phi) = 1 + \tfrac{1}{2}\left[P_2(\cos\theta) + \tfrac{1}{2}\pi_1 \cos(2\phi) P_2^{(2)}(\cos\theta)\right], \tag{1}$$

with $P_2^{(2)}$ being the unnormalized associated Legendre polynomial of second order and ϕ being the azimuthal angle of the reaction plane with respect to the polarization plane of the incident γ beam. W becomes zero at $(\theta, \phi) = [90°, \arccos(-\pi_1)/2]$ and, therefore, the analyzing power of the $0^+ \xrightarrow{\vec{\gamma}} 1^{\pi_1} \xrightarrow{\gamma} 0^+$ cascade becomes

$$\begin{aligned} \Sigma &= \frac{W(90°, 0°) - W(90°, 90°)}{W(90°, 0°) + W(90°, 90°)} \\ &= \pi_1 = \begin{cases} +1 & J^\pi = 1^+, \\ & \text{for} \\ -1 & J^\pi = 1^-. \end{cases} \end{aligned} \tag{2}$$

Parities of dipole excitations in a nucleus with a 0^+ ground state can be sensitively measured by observing the resonance scattering distribution with the detectors of our setup.

The mean energies of the γ beams were chosen to be close to 5.6, 6.0, and 6.3 MeV. Figure 1 shows the raw spectra obtained at the beam energy $\overline{E}_\gamma = 5.62$ MeV with (a) the detectors in the polarization plane and (b) perpendicular to the polarization plane. γ-ray lines were clearly visible only in the spectra obtained perpendicular to the polarization plane. A rotation of our spectrometer by an azimuthal angle of $\Delta\phi = 90°$ around the beam axis did not change that result. The spectral shape of the $\overline{E}_\gamma = 5.62$ MeV photon beam is displayed in Fig. 1(a). This result was obtained by comparing the observed NRF intensities to the previously determined cross sections [23], and can be well described by a Gaussian function as shown in Fig. 1(a).

Experimental relative photon scattering intensities, $I(\|)$ and $I(\perp)$, were determined by consistently fitting peak areas and local background in the spectra obtained in the polarization plane and perpendicular to it, respectively, and by correcting for the relative detection efficiencies. These were determined by the use of a ^{226}Ra source mounted at the target position.

Experimental asymmetries $\epsilon = [I(\|) - I(\perp)]/[I(\|) + I(\perp)] \equiv q\Sigma$ measured in ^{138}Ba are shown in Fig. 2 and summarized in Table I. The quantity q denotes the sensitivity of our spectrometer. The results of the previous asymmetry measurements using a Compton polarimeter are also shown here. The advantage of the present method is obvious: the analyzing power of NRF on a target with ground state spin $J_0 = 0$ using a linearly polarized γ-ray beam is maximum ($\Sigma = \pm 1$) and can be obtained by observing γ singles' intensities while small coincidence asymmetries must be measured in Compton polarimetry. As a result of finite geometry the sensitivity, q, of our setup is smaller than 100%. In fact, a numerical simulation taking into account the geometry of our setup yielded a sensitivity of $q = 0.83(1)$, in good agreement with the observed asymmetries given in Table I. For the purpose of making parity assignments, corrections are unnecessary and have not been applied. In addition, a ^{32}S target of thickness 3.32 g/cm^2 was used to observe a known $M1$ transition at 8.13 MeV, establishing the detector array sensitivity to the positive parity of a $J = 1$ level. This data point is also included in Fig. 2 and Table I. All measured asymmetries in ^{138}Ba are clearly negative, consistent with $E1$ excitations, and exclude $M1$ assignments. For the 5.644 MeV level, previously assigned to be a $1^{(+)}$ state [23], we can exclude positive parity by more than 40 standard deviations. In obtaining this result, the target was exposed to the $\overline{E}_\gamma = 5.62$ MeV beam for ~8 h in total.

To summarize, we have measured relative NRF intensities off a natural BaNO$_3$ target at a polar angle $\theta = 90°$ and at azimuthal angles of $\phi = 0°$ and 90° around a completely polarized γ beam produced by laser Compton

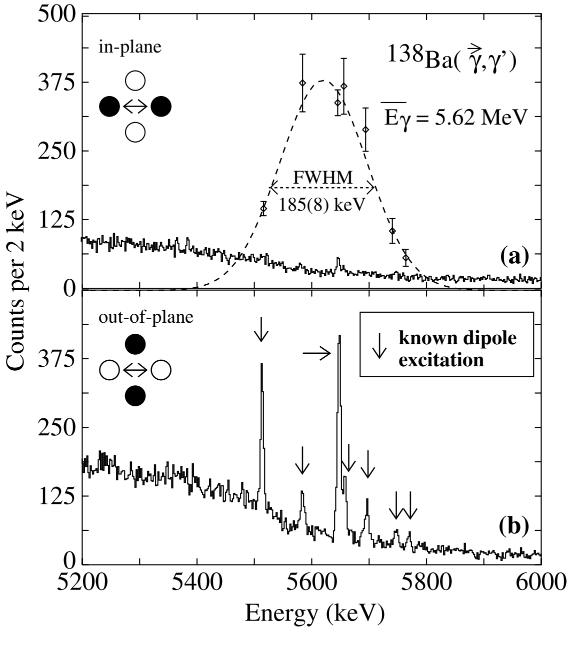

FIG. 1. Photon scattering spectra obtained using a BaNO$_3$ target with detectors at $\theta = 90°$ (a) in the polarization plane of the incident γ beam, and (b) perpendicular to that plane. The arrows mark the known [23] dipole excitations of ^{138}Ba. The dashed curve in (a) is a Gaussian with FWHM = 185(8) keV obtained from an error-weighted least-squares fit to the seven data points for the γ-beam intensity, plotted in arbitrary units.

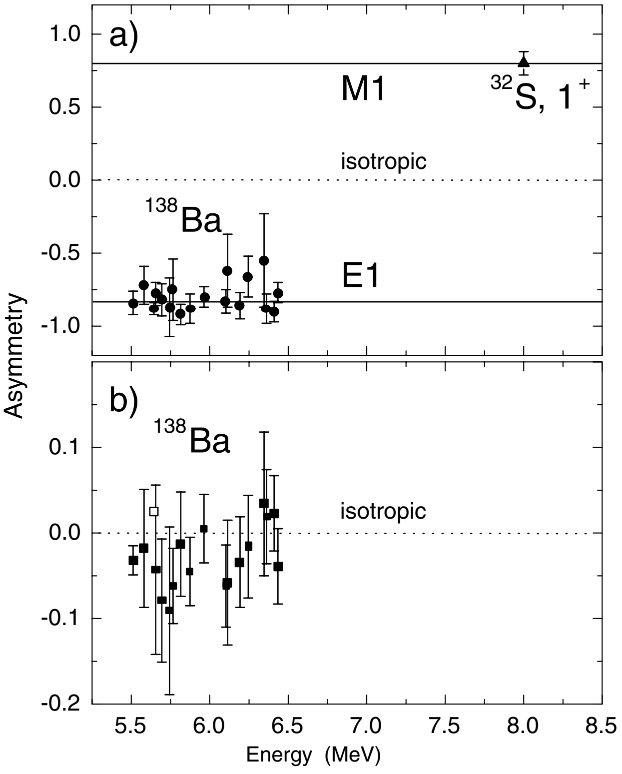

FIG. 2. Measured NRF intensity asymmetries obtained from this experiment on ^{138}Ba (a) and coincidence asymmetries from previous [23] Compton polarimetry (b). Note the different scales in parts (a) and (b). The solid lines in part (a) indicate the expected values of the asymmetry (± 0.83) obtained from the simulation. The open symbol in (b) indicates the result for the 5.644 MeV level which was assigned $1^{(+)}$ in Ref. [23]. The triangle represents the NRF intensity asymmetry of the 8.13 MeV $1^+ \rightarrow 0_1^+$ transition in ^{32}S measured with our setup.

TABLE I. Measured resonance scattering asymmetries and parity quantum number assignments for $J = 1$ states of ^{138}Ba.

E_x (MeV)	ϵ		J^π ($\hbar$)	
	Ref. [23]	This work	This work	Ref. [23]
5.511	−0.032(17)	−0.84(8)	1^-	1^-
5.581	−0.018(69)	−0.72(13)	1^-	1
5.644	0.025(30)	−0.88(4)	1^-	$1^{(+)}$
5.655	−0.043(99)	−0.78(8)	1^-	1
5.694	−0.079(72)	−0.82(11)	1^-	$1^{(-)}$
5.743	−0.091(98)	−0.87(20)	1^-	1
5.766	−0.062(44)	−0.75(21)	1^-	$1^{(-)}$
5.815	−0.013(61)	−0.92(7)	1^-	1
5.874	−0.045(40)	−0.88(10)	1^-	$1^{(-)}$
5.963	0.005(40)	−0.80(7)	1^-	1
6.103	−0.062(48)	−0.83(8)	1^-	$1^{(-)}$
6.114	−0.058(73)	−0.62(25)	1^-	1
6.193	−0.034(53)	−0.86(9)	1^-	1
6.245	−0.016(60)	−0.66(14)	1^-	1
6.346	0.034(84)	−0.55(32)	1^-	1
6.362	0.019(55)	−0.88(10)	1^-	1
6.410	0.023(44)	−0.90(7)	1^-	1
6.434	−0.039(44)	−0.77(7)	1^-	1
8.13[a]	···	0.80(8)	1^+	···

[a] Known $J^\pi = 1^+$ state of ^{32}S.

backscattering of intracavity FEL photons at the HIγS facility. The energy spread of ~180 keV (FWHM at $\overline{E}_\gamma = 5.62$ MeV) and the intensity of 10^7 γ/s on target with no other beam components present, made it possible to measure NRF intensity asymmetries of 18 dipole excitations of ^{138}Ba in just hours of beam time. All intensity asymmetries observed were negative and consistent with an $E1$ character for the dipole excitations. Negative parity quantum numbers could be assigned to 18 known $J = 1$ levels in ^{138}Ba. The previously proposed strong $M1$ excitation in ^{138}Ba does not exist. The HIγS facility has advanced the method of NRF, especially as a means for making parity assignments, to a level of precision and sensitivity which was previously unknown.

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Note added.—While this manuscript was under review, H. Ohgaki [26] presented evidence to us that his group has independently found negative parity for the levels at 5511 and 5644 keV, however, with much smaller statistical significance.

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