

# CHCRUS

This is the accepted manuscript made available via CHORUS. The article has been published as:

## Polarized photon scattering off $^{52}Cr$ : Determining the parity of J=1 states

Krishichayan, Megha Bhike, W. Tornow, G. Rusev, A. P. Tonchev, N. Tsoneva, and H. Lenske Phys. Rev. C **91**, 044328 — Published 30 April 2015

DOI: 10.1103/PhysRevC.91.044328

### Polarized photon scattering of <sup>52</sup>Cr: determining the parity of J = 1 states

Krishichayan,\* Megha Bhike, and W. Tornow

Department of Physics, Duke University, Durham, NC 27708 and

Triangle Universities Nuclear Laboratory, Durham, NC 27708

G. Rusev

Chemistry Division, Los Alamos National Laboratory, Los Alamos, NM 87545

A.P. Tonchev

Physics Division, Lawrence Livermore National Laboratory, Livermore, CA 94550

N. Tsoneva

Institut für Theoretische Physik, Universität Gießen, Heinrich-Buff-Ring 16, D-35392 Gießen, Germany and

Institute for Nuclear Research and Nuclear Energy, 1784 Sofia, Bulgaria

H. Lenske

Institut für Theoretische Physik, Universität Gießen, Heinrich-Buff-Ring 16, D-35392 Gießen, Germany

The photoresponse of  ${}^{52}$ Cr has been investigated in the energy range of 5.0 - 9.5 MeV using the photon scattering technique at the HI $\gamma$ S facility of TUNL to complement previous work with unpolarized bremsstrahlung photon beams at the Darmstadt linear electron accelerator. The unambiguous parity determinations of the observed J = 1 states provides the basis needed to better understand the structure of the E1 and M1 excitations. Theoretical calculations using the Quasiparticle Phonon Model incorporating self-consistent energy-density functional theory were performed to investigate the fragmentation pattern of the dipole strength below and around the neutron-emission threshold. These results compare very well with the experimental values.

PACS numbers: 21.10. Re, 21.60.Jz, 23.20.Lv, 25.20.Dc, 27.40.+z, 63.20kg

#### I. INTRODUCTION

Much experimental effort has been focused on measuring the low-lying magnetic (M1) and electric (E1) dipole strengths in nuclei across the nuclear landscape [1, 2]. The observation of dipole states provides rich information on the various collective and single-particle nuclear excitation modes, in particular, the pygmy dipole resonance (PDR) and the spin-flip M1 resonance.

The concentration of E1 strength below or in the vicinity of the particle separation energy is commonly known as PDR, because of its weak strength in comparison with the giant dipole resonance (GDR), which dominates the E1 strength in nuclei [3, 4]. The origin of the PDR excitation is interpreted as the vibration of the neutron skin against the inert core of the nucleus, and has been observed experimentally in deformed as well as spherical nuclei in the medium- and high-mass regions [2]. However, not much detailed information on this low-energy E1 excitation is available in the mass ~ 50 region. From the analysis of transition densities, the unique behavior of the PDR mode is revealed, making it distinct from the well-known giant dipole resonance. The existence of the PDR mode near the neutron threshold has also important astrophysical implications. For example, reaction rates of  $(\gamma, \mathbf{n})$  and  $(\mathbf{n}, \gamma)$  reactions in explosive nucleosynthesis of certain neutron deficient heavy nuclei may be significantly enhanced by the PDR [5]. Furthermore, for very neutron-rich exotic nuclei, the PDR is an important topic of study at the new generation of radioactive ion-beam facilities.

The M1 spin-flip resonance is another mode of dipole excitations involving nucleons that undergo a spinchange and others that do not change their spin. This resonance is expected to appear typically around 8 MeV [1, 6]. This mode is considered to split up into two parts: an isoscalar and an isovector, respectively, at the lowerand higher-side of the excitation energy. One of the famous examples for such a resonance is the observation of M1 spin-flip excitation in <sup>48</sup>Ca (N = 28), where the M1 strength is essentially concentrated in a single strong transition [7, 8]. The observation of the M1 mode of

<sup>\*</sup> krishi@tunl.duke.edu & krishichayan@gmail.com

dipole excitation at the N = 28 shell gap provides a particularly intriguing example where the interplay of proton and neutron degrees of freedom can be explored in great detail [9, 10]. When moving from the doubly-closed shell <sup>48</sup>Ca nucleus (Z = 20, N = 28), the open proton  $1f_{7/2}$ shell makes the M1 strength more complex and fragmentation emerges. Nuclei in the vicinity of the closed N = Z = 28 shell are an another favorable region for observing a spin-flip M1 resonance, and according to the independent-particle model [11], a strong spin-flip M1transition in these nuclei can be interpreted in terms of both proton and neutron  $1f_{7/2}1f_{5/2}$  particle-hole excitations. The present nucleus <sup>52</sup>Cr lies in this region and differs from the doubly magic nucleus <sup>56</sup>Ni by four nucleons, having 4 fewer protons, i.e.,  $\pi 1f_{7/2}^{-4} \otimes \nu 1f_{7/2}$ .

The recent investigation [12] of the low-lying dipole structure in  ${}^{52}$ Cr yielded information on several dipole excitations in this fp-shell nucleus using unpolarized bremsstrahlung and the Nuclear Resonance Fluorescence (NRF) technique. However, because it is very difficult to obtain parity information with unpolarized bremsstrahlung beams, the lack of parity assignments hampers a reliable interpretation of the observed J =1 states in  ${}^{52}$ Cr. In order to quantify the occurrence of electric (E1) and magnetic (M1) dipole excitations in  ${}^{52}$ Cr, the unambiguous parity determination is very crucial and indeed much needed.

The aim of the present work is to perform unambiguous parity assignments of the dipole excitations in  ${}^{52}$ Cr, which is achieved in measurements of azimuthal asymmetries of NRF  $\gamma$ -rays using a 100% linearly polarized and quasi-monochromatic photon beam. The experimental data are explained in detail using a microscopic theoretical approach based on Energy-Density-Functional (EDF) theory and the Quasiparticle-Phonon Model (QPM) [13, 14].

#### II. EXPERIMENTS

The current measurements were performed at the High Intensity  $\gamma$ -ray Source (HI $\gamma$ S) facility of the Triangle Universities Nuclear Laboratory (TUNL) [15]. The HI $\gamma$ S facility produces a nearly monoenergetic, 100% linearly polarized (in the horizontal plane) photon beam through Compton backscattering of free-electron-laser photons with relativistic electrons stored in a storage ring. The photon beam was collimated by a lead collimator of length 30.5 cm with a cylindrical hole of 1.27 cm diameter before passing through the target. This collimation results in an energy spread of the photon beam of 3%(FWHM). The scattered  $\gamma$ -rays from the natural Cr target of mass 6.48 g (natural abundance of  ${}^{52}$ Cr is 83.789%) were measured with an array of four HPGe detectors, each of 60% relative efficiency, positioned around the Cr target at  $(\theta, \phi) = (90^{\circ}, 0^{\circ}), (90^{\circ}, 90^{\circ}), (135^{\circ}, 45^{\circ}),$  and  $(135^\circ, 135^\circ)$  where  $\theta$  is the polar scattering angle and  $\phi$ is the azimuthal angle between the polarization plane of the beam and the direction of the scattered  $\gamma$ -ray. The detectors were located at 10 cm from the center of the target. A 123% efficient (relative to a standard  $3'' \times 3''$  NaI detector) co-axial HPGe detector was placed downstream of the target position in order to measure the beam-energy distribution. During beam profile measurements, the beam was attenuated by a series of copper absorbers mounted upstream. An overview of the typical detector setup for parity measurements can be found in Ref. [16].

In its most general form [17, 18], the measured azimuthal asymmetry of the scattered photons is given by

$$\epsilon = \frac{A_h - A_v}{A_h + A_v} = P_{\gamma} \Sigma, \tag{1}$$

where  $A_h$  and  $A_v$  are the corresponding efficiency corrected count rates observed for the  $\gamma$  rays by detectors positioned horizontally and vertically to the scattering plane.  $P_{\gamma}$  is the polarization of the photon beam, which is assumed to be 1 for all energies at the HI $\gamma$ S facility. Therefore, the count-rate asymmetry  $\epsilon$  will be equal to +1 for a  $J_1^{\pi} = 1^+$  state decaying by an M1 emission to the ground state, and -1 for a  $J_1^{\pi} = 1^-$  state decaying by an E1 emission to the ground state. Experimental observations will deviate slightly from this, as the expressions given for  $\epsilon$  do not account for the finite solid angles of the detectors, and statistical uncertainties in the data.

#### **III. DATA ANALYSIS AND RESULTS**

The dipole excitation strength distribution in  ${}^{52}Cr$  has recently been measured with unpolarized bremsstrahlung up to  $\sim 10$  MeV at the S-DALINAC facility [12]. In addition to the previously known dipole states, Pai et al., have added fourteen new dipole states in their investigation with much improved decay-characteristic values [12]. For some of these states, parity assignments were available from earlier measurements [19–22]. Because of the incomplete parity information, only limited conclusions could be drawn in this recent work [12]. For parity assignments of all the observed dipole states reported in Ref. [12] for  ${}^{52}Cr$ , we used linearly polarized photon beams at energies of 5.21, 5.56, 6.40, 6.50, 7.00, 7.08, 7.19, 7.40, 7.51, 7.74, 7.89, 8.02, 8.11, 8.20, 8.75, 8.95, 9.15, 9.25, 9.36, and 9.45 MeV and a natural Cr target. The identification of the dipole states was done by using the previous unpolarized  $(\gamma, \gamma')$  measurements [12]. Surprisingly, in our present work, we have not observed the dipole states at  $E_x = 5213.7$  and 5526.0 keV, as seen in the previous work. The intensity reported by Pai et al. for the gamma-ray transitions from these states is about half of that found for the  $E_{\gamma} = 5098.6$ keV transition [12]. We have observed the 5098.6 keV  $\gamma$ ray transition with good statistics and based on intensity arguments, we should have seen the  $\gamma$ -ray transitions of energies 5213.4 and 5525.7 keV in our spectra. Based on

our non-observation, we argue that these transitions are either inelastic or due to contaminants in the target.

Figures 1 and 2 show parts of the photon-scattering spectra of the detectors parallel to the polarization plane of the HI $\gamma$ S photon beam and perpendicular to it at incident photon energies of 7.89 and 9.15 MeV, respectively. From these figures it is clear that the transitions of energies 7864.5, 9139.4, and 9211.0 keV are of M1 nature, whereas the transitions of energies 7731.3, 7896.8, and 9235.7 keV are of E1 character. Figure 3 depicts the



FIG. 1. NRF  $(\gamma, \gamma')$  spectra from <sup>52</sup>Cr recorded in the parallel (a) and perpendicular detector (b) using a polarized photon beam of energy 7.89 MeV. Transitions in the parallel/perpendicular detector are of M1/E1 character.



FIG. 2. Same as of Fig. 1 at  $E_{\gamma} = 9.15$  MeV.

measured values of the azimuthal intensity asymmetries for ground-state transitions in the energy range of our experiment. The mean values of the azimuthal intensity asymmetry for  $J^{\pi} = 1^+$  and  $J^{\pi} = 1^-$  states are 0.75(7) and -0.85(9), respectively. As seen in Fig. 3, the data are separated depending on their multipolarities (*M*1 or *E*1). The deviation of the azimuthal asymmetry values from the theoretical values of  $\pm 1$  is mainly due to the finite geometry of the detector-target arrangement.



FIG. 3. Experimental azimuthal asymmetry values for E1 (open circles) and M1 (asterisk) transitions in  ${}^{52}$ Cr. The average values for E1 and M1 transitions are drawn as dotted lines.

From the present measurement using polarized photon beams, out of the 26 observed dipole excitations in the  $E_x = 5.1 \sim 9.5$  MeV range, 16 states were found to be  $1^-$  and 10 states were assigned to be  $1^+$ . The measured azimuthal asymmetries  $\epsilon$  and parity quantum number are shown in Table I. The experimental strength distribution values are taken from the earlier work [12].

#### A. E1-strength distribution for <sup>52</sup>Cr

The electric dipole excitation strength distribution of the 16  $J^{\pi} = 1^{-}$  states observed in the present work is shown in Fig. 4. The corresponding summed E1strength at  $E_x = 5.1 - 9.5$  MeV in  ${}^{52}$ Cr is  $\sum B(E1) \uparrow = 51.2(16) \times 10^{-3} e^2 \text{fm}^2$ . The lowest-lying candidate for a  $J^{\pi} = 1^{-}$  level in <sup>52</sup>Cr is observed at 5544.7 keV. This level has been investigated as a potential candidate for quadrupole-octupole two-phonon character [22]. The major part of the observed  $\sum B(E1) \uparrow$  in <sup>52</sup>Cr is distributed at  $\sim 8$  MeV excitation energy, with the strongest E1 transition at  $E_x = 7897.4$  keV. The  $B(E1) \uparrow$  value for this transition is  $19.7(10) \times 10^{-3} \text{ e}^2 \text{fm}^2$ , which exhausts almost 40% of the total B(E1) strength and 0.3% of the Thomas-Reiche-Kuhn (TRK) sum rule as reported in Ref. [12]. Pai *et al.* have suggested  $\approx 0.15\%$  of the TRK sum rule by considering the states at  $E_x = 7368.8$ , 7731.9, 7889.0, 8015.3, 8091.3, and 8179.2 keV as the  $J^{\pi} = 1^{-}$  states [12]. In our present measurement using polarized photon beams, we have found that the multipolarity of the level at  $E_x = 8015.3$  keV is  $J^{\pi} = 1^+$  instead

TABLE I. Measured asymmetries  $\epsilon$  and parity quantum number assignments for J = 1 states in  ${}^{52}Cr$ . The asymmetries are not corrected for the finite size of the detectors or attenuation effects. Measured values of  $B(M1) \uparrow$  and  $B(E1) \uparrow$  are taken from Ref. [12].

$E_x$	$E_{\gamma}$	$J^{\pi}$	$\epsilon$	$B(M1)\uparrow$	$B(E1)\uparrow$
$(\mathrm{keV})$	$(\mathrm{keV})$			$(\mu_N^2)$	$(10^{-3} \text{ e}^2 \text{fm}^2)$
5098.6	5098.4	$1^{+}$	0.80(11)	0.089(21)	
5544.7	5544.4	$1^{-}$	-0.88(10)		1.88(12)
6389.9	6389.5	$1^{-}$	-0.85(29)		0.762(77)
6462.4	6462.0	$1^{-}$	-0.80(18)		0.784(78)
6495.5	6495.1	$1^{-}$	-0.90(14)		1.367(96)
6752.0	6751.5	$1^{+}$	0.72(12)	0.075(9)	
7014.1	7013.6	$1^{-}$	-0.85(06)		1.74(25)
7090.8	7090.3	$1^{-}$	-0.87(10)		0.496(88)
7166.2	7165.7	$1^{+}$	0.63(09)	0.038(8)	
7368.8	7368.2	$1^{-}$	-0.87(26)		1.64(13)
7403.2	7402.6	$1^{-}$	-0.86(11)		0.76(11)
7524.1	7523.5	$1^{+}$	0.85(09)	0.243(18)	
7731.9	7731.3	$1^{-}$	-0.92(04)		5.96(40)
7865.1	7864.5	$1^{+}$	0.85(12)	0.232(15)	
7889.0	7888.4	$1^{-}$	-0.70(21)		2.80(26)
7897.4	7896.8	$1^{-}$	-0.86(08)		19.7(10)
8015.3	8014.6	$1^{+}$	0.70(08)	0.131(30)	
8091.3	8090.6	$1^{-}$	-0.89(05)		3.97(24)
8179.2	8178.5	$1^{-}$	-0.82(09)		4.72(98)
8765.9	8765.1	$1^{-}$	-0.87(09)		1.88(17)
8958.4	8957.6	$1^{-}$	-0.76(09)		0.93(15)
9140.3	9139.4	$1^{+}$	0.86(04)	0.898(53)	
9211.9	9211.0	$1^{+}$	0.72(03)	0.700(47)	
9236.6	9235.7	$1^{-}$	-0.88(07)		1.83(20)
9327.0	9326.1	$1^{+}$	0.57(06)	0.238(26)	
9429.0	9428.1	$1^{+}$	0.79(06)	0.295(35)	

of  $J^{\pi} = 1^{-}$ , as assumed by Pai *et al.* [12].

Similar strong E1 transitions have been seen in the nearby nuclei with  $N \approx Z \approx 28$ . In <sup>58</sup><sub>28</sub>Ni<sub>30</sub>, the strongest E1 transition at  $E_x = 8237.3$  keV corresponds to  $B(E1)\uparrow = 18.51(28)\times10^{-3}e^2fm^2$ , which is almost 1/3 of the total identified E1 strength [24]. When we move to the Z = 26 isotone (*i.e.*,  ${}^{56}_{26}$ Fe<sub>30</sub>), the strongest E1 transition by far turned out to be at the excitation energy of  $E_x = 8239.6$  keV [23], very close to that of <sup>58</sup>Ni. The B(E1)  $\uparrow$  value corresponding to this transition is  $16.69(41) \times 10^{-3} e^2 fm^2$ . As seen in Fig. 5, the strongest transition in <sup>56</sup>Fe is accompanied by two smaller fragments at 8127.7 and 8536.3 keV, respectively. These three transitions alone correspond to 1/2 of the total E1 strength. The systematics of the distribution of the B(E1) in several fp-shell nuclei is shown in Fig. 5, which is very similar to Fig. 10 of Ref. [24], but with the updated data available for  $^{60}$ Ni [25],  $^{56}$ Fe [23], and  $^{52}$ Cr [present work]. In this comparison, we clearly see the similar pattern of strong E1 transitions in <sup>54</sup>Fe and <sup>52</sup>Cr. As pointed out by Bauwens et al. [24], this systematics seems to be broken for <sup>60</sup>Ni and <sup>48</sup>Ti, nuclei further away from closed shells.



FIG. 4. Distribution of observed  $B(E1) \uparrow [12]$  strength for resonantly excited states in  ${}^{52}$ Cr between 5.1 and 9.5 MeV is compared with values obtained from QPM calculations. A comparison of the measured and calculated QPM cumulative E1 strength is shown in the upper panel. Individual contributions and uncertainties are given in Table I.

#### **B.** *M*1-strength distribution for ${}^{52}$ Cr

In the present measurement M1 excitations are observed at excitation energies between 5.1 and 9.5 MeV with strong concentration of M1 strength around 9.2 MeV, as can be seen from Fig. 6. A weak and broad concentration of M1 strength is found at energies of  $\sim$ 7.5 MeV. Below 6.75 MeV, there is only one  $J^{\pi} = 1^+$ state at the excitation energy of  $\sim 5.1$  MeV. The total B(M1)  $\uparrow$  value in the energy range of our experimental work ( $E_x = 5.1$  to 9.5 MeV) is 2.94(9)  $\mu_N^2$ . Magnetic dipole excitations in <sup>52</sup>Cr and other N = 28 isotones were investigated by Sober et al. [19]. According to their work the M1 strength distribution in  ${}^{52}Cr$  is highly fragmented in the energy range of  $E_x = 7 - 12$  MeV, with three distinct energy regimes. Using electron-scattering, Sober *et al.* have observed many  $J^{\pi} = 1^+$  states in <sup>52</sup>Cr with different level of confidence for the multipolarity assignments [19]. We have not observed any  $J^{\pi} = 1^+$  states in the 8.1 - 9.0 MeV region, where Sober et al. have reported many  $J^{\pi} = 1^+$  states, some of them with unique multipole assignment [19]. Based on the confidence level of multipolarity assignment for the M1 transitions and detection limitation, Sober et al. recommended a total M1 strength value of  $8.1(8)\mu_N^2$  in the excitation region of 7 - 12 MeV. This value is highly suppressed with respect to their shell-model calculations [19]. The total measured M1 strength  $\sum B(M1) \uparrow$  value reduces to 5.64(22)  $\mu_N^2$ , if the M1 states with *unique* multipolarity assignment are considered only. If we consider the  $J^{\pi} = 1^+$  states observed in the present work, the total M1 strength is  $3.21(13)\mu_N^2$ , which is very close to the reported value of Pai et al. [12]. In 1998, von Neumann-Cosel et al. [9] performed shell-model calculations for the M1 strength



FIG. 5. Distribution of observed E1 excitation strength in several fp-shell nuclei. Note the range of y-axis for <sup>48</sup>Ti.



FIG. 6. Distribution of observed  $B(M1)\uparrow [12]$  strength in <sup>52</sup>Cr in the energy range between 5.1 and 9.5 MeV is compared with the values obtained from QPM calculations. A comparison of the measured and calculated QPM cumulative M1 strength is shown in the upper panel. Individual contributions and uncertainties are given in Table I.

distribution in <sup>52</sup>Cr, as well as in other N = 28 isotones, namely <sup>48</sup>Ca, <sup>50</sup>Ti, and <sup>54</sup>Fe. The total B(M1) strength in <sup>52</sup>Cr, using the bare g-factor, is  $15.60\mu_N^2$ . The ratio of the measured and calculated B(M1) strength, commonly termed as quenching factor, was found to be of 0.75 [9] for the N = 28 isotones. In <sup>48</sup>Ca (N = 28, Z = 20) the M1 strength is essentially concentrated in a single transition at  $E_x = 10.23$  MeV, with  $\sum B(M1) \uparrow = 4.0(3)\mu_N^2$ . If we look at the other N = 28 isotones, the strongest M1transitions occur at  $E_x = 8.56$ , 9.14, and 10.53 MeV in <sup>50</sup>Ti, <sup>52</sup>Cr, and <sup>54</sup>Fe, respectively. The excitation energy of the strongest M1 transition in these nuclei is moving to higher energies as Z increases from 22 to 26, i.e., more protons are available in the *fp*-shell. In 2006 Li *et al.* provided the first evidence for a spin-flip M1 resonance in <sup>40</sup>Ar using polarized beams of energy between 7.7 and 11.0 MeV produced at the HIγS facility [26]. The M1 state was found at  $E_x = 9.757$  MeV, and the corresponding B(M1) strength value is 0.148(59)  $\mu_N^2$ .

In fp-shell nuclei near N = Z, the structure of M1 resonances is expected to be dominated by 1p1h spin-flip excitations, such as  $1f_{7/2} \rightarrow 1f_{5/2}$ , for both protons and neutrons. On the upper side of the fp-shell nuclei with  $A \sim 60$ , the M1 strength distribution is somewhat scattered, as expected for semi-magic nuclei [23–25]. The distribution of M1-excitation strengths for  $\frac{56}{26}$ Fe<sub>30</sub>,  $\frac{58}{28}$ Ni<sub>30</sub>, and  $\frac{60}{28}$ Ni<sub>32</sub> ( $N \approx Z \approx 28$ ) is shown in Fig. 9 of Ref. [25]. The two accumulations of  $J^{\pi} = 1^+$  states in these nuclei at energies of around 8 and 9 MeV excitation correspond to the iso-scalar and iso-vector spin-flip M1 resonances [1, 25].

#### IV. THEORETICAL APPROACH AND ANALYSIS OF THE *E*1 AND *M*1 EXPERIMENTAL DATA FOR <sup>52</sup>CR

To interpret the experimentally observed electric and magnetic dipole strength distributions of  ${}^{52}$ Cr, a detailed treatment of the multi-quasiparticle and multi-phonon structure of the low-energy  $1^+$  and  $1^-$  excited states is required. To investigate the spectral fragmentation pattern of the M1 and E1 strengths functions below and around the neutron-emission threshold  $(S_n = 12.034)$ MeV), calculations in the framework of the nuclear EDF theory for the description of the nuclear ground state [27] and an extended version of the QPM [13, 14, 28] have been performed. Consistent with previous investigations of E1, E2, and M1 strength functions in various nuclei [3, 6, 14, 29–32], the present QPM calculations are performed with single-particle energies obtained in a selfconsistent manner from our EDF approach linked to fully self-consistent Hartree-Fock-Bogoliubov (HFB) calculations [13, 14, 27]. The excited states are calculated with a residual interaction represented in separable form. The strength parameters are fixed empirically for the E1 calculations [28, 33]. In the case of M1 they were obtained from QRPA calculations performed within the density matrix expansion (DME) discussed in ref. [27]. As a further advantage over other QRPA models, the QPM approach incorporates a multi-phonon model space built of natural and unnatural parity states. Here, the model basis is constructed of one-, two-, and three-phonon (microscopically described) configurations with  $J^{\pi}$  ranging from  $1^{\pm}$  to  $6^{\pm}$  and excitation energies  $E_x$  up to 9.8 MeV, in agreement with the range of the experimental data. In this sense our QPM calculations are considerably more elaborate than those reported by Pai *et al.* in Ref. [12]. More details on the comparison could be found in Ref. |34|.

Systematic QRPA and QPM calculations of the electric dipole response in different isotopic and isotonic chains of nuclei [13, 14, 29, 30, 32] indicate enhanced E1 strength in the energy range below the neutron threshold with respect to the shape of a Lorentz-like strength function used to analyze the GDR [32, 35]. A common observation is that the total E1 QRPA strength associated with the PDR increases with the increase of the isospin asymmetry of the nucleus defined by the N/Z ratio. In this connection, a correlation between the total PDR strength obtained in QRPA calculations and the neutron skin thickness [13, 14, 29, 30], which in neutron-rich nuclei is defined by the differences of neutron and proton root-meansquare (RMS) radii,  $\delta r = \sqrt{\langle r^2 \rangle_n} - \sqrt{\langle r^2 \rangle_p}$ , is found [13, 14, 29, 30]. Similar results are also obtained from various experiments [2].

From our EDF mean-field calculations we derive that the  ${}^{52}$ Cr nucleus exhibits a neutron skin with a thickness of  $\delta r = 0.056$  fm. As a result, the first QRPA  $1_1^-$  state with excitation energy  $E_x = 8.366$  MeV, and the second QRPA  $1^-$  state with excitation energy  $E_x = 9.473$  MeV are almost pure neutron two-quasiparticle states, where the major contribution is due to transitions from weakly bound orbitals:  $1d_{3/2} \rightarrow 2p_{3/2}$ ,  $2s_{1/2} \rightarrow 2p_{3/2}$ and  $1f_{7/2} \rightarrow 1g_{9/2}$ . Taking into account these considerations, the energy range below ~ 9.5 MeV could be associated with a genuine PDR mode. Theoretically, this can be seen also from the evolution of the proton and neutron transition densities, which show a behavior typical for PDR nuclei [14, 32]. The total PDR strength obtained from the QRPA calculations in <sup>52</sup>Cr is  $\Sigma_{0MeV}^{9.5MeV}B(E1; g.s. \rightarrow 1_{PDR})_{QRPA} \uparrow = 13 \times 10^{-3} \text{ e}^2\text{fm}^2$ , which exhausts about 0.1% of the TRK sum rule.

As the excitation energy is increased, the isovector contribution to the dipole strength increases, and the structure of the state vectors shows an increase of the out-of-phase neutron to proton contribution and related energy-weighted sum rules, which is generally associated with the GDR [14, 32]. The corresponding strength function begins to follow closely its Lorentzian fall-off, often assumed for the GDR in data analyses [35].

Theoretically, it is clear that the QRPA is unable to account for higher multi-particle-multi-hole correlations and interactions resulting from core polarization effects [36]. The latter could induce dynamical effects related to redistribution of strength, and strongly affect the gross and fine structure of dipole strength functions. By comparing the QRPA with the multi-phonon QPM calculations, it is seen that the pure two-quasiparticle QRPA strengths in the PDR region is strongly fragmented over many  $1^-$  excited states, once the coupling to multiphonon configurations takes place. The lowest-lying 1<sup>-</sup> state, which is without a QRPA counterpart, is predominantly given by a two-phonon quadrupole-octupole excitation [37] of the  $[2_1^+ \otimes 3_1^-]$  configuration, which accounts for  $\approx 75\%$  of the QPM wave function. These results are obtained when the QPM multi-phonon basis is truncated at 9 MeV. In this case the calculated value for the energy of the  $1_1^-$  state is  $E_{QPM} = 5.61$  MeV, and the reduced transition probability is  $B(E1; g.s. \rightarrow 1_1^-)_{QPM} \uparrow =$  $6.66 \times 10^{-3} \; \mathrm{e^2 fm^2}.$  In comparison, the experimental value ues are  $E_{exp} = 5.545$  MeV and  $B(E1; g.s. \rightarrow 1^{-}_{1})_{exp} \uparrow =$  $1.88(12) \times 10^{-3} e^2 fm^2$ . The collectivity of the  $1_1^-$  state strongly depends on the model configuration space used in the calculations. The increase of the energy range of the two- and three-phonon configurations up to 9.8 MeV leads to a more collective  $\mathbf{1}_1^-$  state with lower excitation energy  $E_{QPM} = 5.463 \text{ MeV}$  and  $B(E1; g.s. \rightarrow 1^-_1)_{QPM} \uparrow$ =  $17.56 \times 10^{-3} e^2 \text{fm}^2$ . The strongest QPM  $1_{max}^-$  state in the energy range below 9.8 MeV is located at  $E_{QPM} =$ 8.270 MeV and the corresponding transition probability is  $B(E1; g.s. \to 1_{max}^{-})_{QPM} \uparrow = 28.14 \times 10^{-3} \text{ e}^{2} \text{fm}^{2}$ . The theoretical results compare well with the experimental findings, which give for this state  $E_{exp} = 7.897$  MeV and  $B(E1; g.s. \to 1_{max}^{-})_{QPM} \uparrow = 19.7(10) \times 10^{-3} \text{ e}^2 \text{fm}^2$ , and also with the QPM calculations of Pai et al. [12]. The QPM calculations indicate that the  $1_{max}^{-}$  state contains contributions of the low-energy tail of the GDR, which is the reason for the strong B(E1) transition rate.

Furthermore, the 1<sup>-</sup> states associated with the PDR mode in <sup>52</sup>Cr are widely distributed in the energy range  $E_x \approx 6.6$  - 11.6 MeV. The structure of these states incorporates decay fragments of the  $1_1^-$  and the  $1_2^-$  QRPA states, related to the PDR mode, but it also contains contributions of multi-phonon components and core polarization effects from the GDR. As a result, the three-phonon QPM calculations give much more low-energy B(E1) strength than obtained for the QRPA pure PDR strength. The experimental data also show a sequence of states in the theoretical predicted PDR energy range, but they are more fragmented.

For the whole measured energy range  $E_x = 5.1$ - 9.5 MeV the QPM calculations predict a summed B(E1) strength of  $\sum B(E1)_{QPM} \uparrow = 111 \times 10^{-3} e^2 \text{fm}^2$ . In comparison, the experiment finds  $\sum B(E1)_{exp} \uparrow = 51.2(16) \times 10^{-3} e^2 \text{fm}^2$ , approximately a factor of two less strength.

The comparison between the measurements and the QPM calculations of the cumulative B(E1) strength and the spectral distribution in  ${}^{52}Cr$  is presented in the upper panel of Fig. 4. In general, the shape of the QPM cumulative B(E1) strength as well as the 1<sup>-</sup> level distribution are found to be in very good agreement with the experimental data. The observed difference between the measured and calculated total B(E1) values could be related to experimental sensitivity limits and branchings to excited states, which are unaccounted for by the existing dipole data in  ${}^{52}$ Cr. In this connection, the experimental value for the total B(E1) strength represents a lower limit only. More details on this issue are discussed in [3, 34, 38]. For example, cascade simulations for the  $^{90}$ Zr nucleus described in Ref. [6] give a 76(10)% mean branching ratio for ground-state transitions of  $1^+$  levels for excitation energies below 10 MeV, resulting in an increase of the measured total B(M1) strength of about 25%.

In Ref. [6], the quenching phenomenon of the nuclear spin-flip magnetic response of <sup>90</sup>Zr was investigated. Theoretically, the description of the fine structure of the M1 strength requires the analysis of the complete spectrum of  $1^+$  excited states by accounting for core polarization effects. The latter contributions were successfully described by the three-phonon QPM [3, 6]. In contrast to many other approaches in which the genuine many-body effects originating from core polarization are left unaccounted for, in our approach the deviation of static and transition magnetic moments from the accepted values could be attributed mainly to mesonic and sub-nucleonic contributions to the transition operators [39, 40]. Those effects, coming from hard processes, are connected with energy and momentum scales much different from the nuclear low-energy region. Schematically, they are taken into account by a renormalization of the spin-g factor whose 'quenched' value should be related to the lower limit of the quenching, indicating the amount of strength located outside of the model space, and accounting also for the contributions from the hard

scale of mesonic and sub-nucleonic degrees of freedom. Hence, following previous QPM calculations [33], the M1 transitions are calculated with a quenched effective spinmagnetic factor  $g_{eff}^s = 0.8g_{bare}^s$ , where  $g_{bare}^s$  denotes the bare spin-magnetic moment. This value agrees very well with shell-model calculations and the experimental data for N = 28 nuclei from Refs.[41, 42], where  $g_{eff}^s$ =  $0.75 g_{bare}^s$  is obtained. In particular, from a comparison to Gammow-Teller(GT) strengths in various fp-shell N = 28 nuclei extracted from charge-exchange reactions, Monte Carlo shell-model studies [43] support our value of  $g_{eff}^s = 0.8g_{bare}^s$ , however with uncertainties of about 20%. In contrast, in the QPM calculations of Pai *et al.* [12] the smaller value of  $g_{eff}^s = 0.6 g_{bare}^s$  was used in order to reproduce the experimental M1 data in  $^{52}$ Cr, which were theoretically overestimated otherwise.

A reliable description of the fragmentation pattern of the magnetic dipole (M1) response function is important for understanding the spin dynamics of the nucleus. The analysis of the QRPA M1 strength of  $1^+$  excitations with energies up to  $E_x = 20$  MeV indicates that this part of the spectrum is mostly due to single p - h excited states of spin-flip type related to the excitation of neutron and proton  $1f_{7/2} \rightarrow 1f_{5/2}$  two-quasiparticle components, respectively. The latter dominate the structure of the first two lowest-lying QRPA  $1^+$  excited states, the  $1^+_1$ state at  $E_x = 8.92$  MeV and the  $1^+_2$  state at  $E_x = 10.53$ MeV, which share more than 95% of the total  $B(M1) \uparrow$  $= 10.3 \ \mu_N^2$  up to  $E_x = 20$  MeV. In the excitation energy range between 10 and 20 MeV we find also contributions of  $1d_{5/2} \rightarrow 1d_{3/2}, 2p_{3/2} \rightarrow 2p_{1/2}, 1d_{3/2} \rightarrow 2d_{5/2}, 1p_{1/2} \rightarrow 2p_{3/2}$ , and  $1p_{3/2} \rightarrow 2p_{1/2}$  transitions. For comparison, the shell-model calculations of Refs. [41, 42] include the valance fp-shells only.

Including only the orbital term of the nuclear magnetic moment in the QPRA calculations, we obtain the pure orbital QPRA M1 strength. It is found to be very small, approximately 3.3 % of the total QPRA B(M1) transition probability, which includes both spin-flip and orbital contributions up to  $E_x = 20$  MeV. In general, the interference between spin-flip and orbital M1 strengths leads to the suppression of the total M1 response, as was also reported in [6].

The detailed studies of the M1 fragmentation pattern based on three-phonon QPM calculations show that the coupling of natural parity phonons to multi-phonon 1<sup>+</sup> states induces additional orbital contributions to the M1transitions. Consequently, the observed M1 strength at excitation energies between 5 and 10 MeV contains an orbital part of about 11%, which is less than that found for the case of <sup>90</sup>Zr [6]. The excited 1<sup>+</sup> states at about  $E_x = 5$  MeV contain mainly orbital contributions. For the higher-lying 1<sup>+</sup> states the spin-flip part of the wave function is dominant.

In general, the multi-phonon QPM calculations indicate that the M1 strength distribution below  $E_x =$ 10 MeV could be related to fragmentation of the  $1^+_1$  and  $1^+_2$  QRPA states. Thus, in this energy region about 90% of the fragmented first QRPA  $1_1^+$  and only about 5% of the fragmented second QRPA  $1_2^+$  state is located. The latter gives a significant contribution to the M1 spin-flip strength at energies above 10 MeV, the energy range which includes the neutron-separation energy as well. Experimentally, it is a formidable task to distinguish these  $1^+$  states in the vicinity of the neutron-threshold from background components and the GDR. However, we can explore this region theoretically in the QPM. The model predicts strongly fragmented M1 strength, related mainly to the decay of the  $1_2^+$ (QRPA) state over a considerable number of  $1^+$  states with relatively small transition probabilities and total  $\Sigma_{10MeV}^{12.5MeV}B(M1) \uparrow$  of  $\approx 6 \ \mu_N^2$ . This is a considerable amount of M1 strength which deserves further experimental attention.

The total QPM M1 strength summed over  $1^+$  states from  $E_x = 5$  to 9.5 MeV can be compared directly with the present data. The results are presented in Fig. 6. The theoretical findings give  $\Sigma_{5\text{MeV}}^{9.5\text{MeV}}B(M1)_{\text{QPM}}\uparrow = 3.1$  $\mu_N^2$ . which is in good agreement with the experimental value of  $\Sigma_{9.5\text{MeV}}^{5.1\text{MeV}}B(M1)_{exp}\uparrow = 2.94(9)$   $\mu_N^2$ . However, one should take into account that this experimental value for the B(M1) strength does not include the contributions of branchings to excited states, which might increase the measured total M1 strength.

#### V. CONCLUSIONS

 ${}^{52}\text{Cr}(\gamma,\gamma')$  photon scattering experiments have been performed using the nearly monoenergetic, 100% linearly polarized photon beams produced at the HI $\gamma$ S facility of TUNL. Twenty beam energies have been used to cover the energy range from 5.0 to 9.5 MeV and to uniquely identify and measure the dipole excitations in  ${}^{52}\text{Cr}$ . Twenty six dipole excitations were identified and their parity quantum values were unambiguously determined from the measured azimuthal intensity asymmetry of nuclear resonance fluorescence transitions. The distributions of magnetic and electric excitations have been discussed in detail with experimentally measured [from Ref.[12]] values of  $\sum B(E1) \uparrow = 51.2(16) \times 10^{-3} e^2 f m^2$ and  $\sum B(M1) \uparrow = 2.94(9) \mu_N^2$ .

- K. Heyde, P. von Neumann Cosel, and A. Richter, Rev. Mod. Phys. 82, 2365 (2010).
- [2] D. Savran, T. Aumann, and A. Zilges, Prog. Part. Nucl. Phys. 70, 210 (2013).
- [3] A. Tonchev et al., Phys. Rev. Lett. 104 072501 (2010).
- [4] N. Pietralla *et al.*, Phys. Rev. Lett. **88**, 012502 (2002).
- [5] M. Arnould and S. Goriely, Phys. Rep. 384, 1 (2003).
- [6] G. Rusev et al., Phys. Rev. Lett. 110, 022503 (2013).
- [7] W. Steffen *et al.*, Phys. Lett. **B 95**, 23 (1980).
- [8] V. Derya et al., Phys. Lett. B 730, 288 (2014).
- [9] P. von Neumann-Cosel, A. Poves, J. Retamosa, and A.

From three-phonon QPM calculations of the electric dipole response in  ${}^{52}$ Cr, specific signals of a new mode of excitation related to PDR are observed. As a common feature in neutron-rich nuclei, the structure of the PDR excited states in  ${}^{52}$ Cr is dominated by neutron components directly connected to the presence of a neutron skin. The generic character of the PDR is further confirmed by the investigation of related transition densities. The PDR energy location and its total B(E1) strength are predicted.

The observation of the spin-flip M1 resonance structure around 9.1 MeV in  ${}^{52}$ Cr has been discussed along with the systematics of the distribution of dipole excitation in fp-shell nuclei. Such a concentration of M1strength around 9.2 MeV is further confirmed in threephonon QPM calculations and explained as fragmented spin-flip 1<sup>+</sup> excitations.

In these studies a common observation is that the QRPA is unable to describe the low-energy nuclear dipole response in details. This can be achieved only if one takes into account the contribution of multi-phonon coupling. which explains the observed fragmentation pattern of the E1 and M1 strength and their absolute value. In addition, the theoretical investigations of the fragmentation pattern of the M1 strength indicate that the contribution of the orbital part of the magnetic moment is mainly due to coupling of multi-phonon states. The effect is estimated to account for about 11% of the total M1 strength below the neutron-emission threshold. The good agreement of the calculated and measured total M1 strength is a signature that the quenching is handled reliably in the chosen approximation. A better understanding could be achieved with more comprehensive knowledge of the nature of the intrinsic nuclear moments, meson-exchange currents and branching ratios from excited states, which might be of importance for further improvements.

#### ACKNOWLEDGMENTS

We are grateful to the HI $\gamma$ S staff for providing excellent photon beams during our experiments. This work was supported by the U.S. Department of Energy Grant No DE-FG02-97ER41033 and BMBF grant 05P12RGFTE.

Richter, Phys. Letts. B 443, 1 (1998).

- [10] A. Richter, Prog. Nucl. Part. Phys. 13, 1 (1984).
- [11] A. Bohr and B.R. Mottelson, Nuclear Structure (Benjamin, New York, 1975).
- [12] H. Pai et al., Phys. Rev. C 88, 054316 (2013).
- [13] N. Tsoneva, H. Lenske, Ch. Stoyanov, Phys. Lett. B586, 213 (2004).
- [14] N. Tsoneva, H. Lenske, Phys. Rev. C 77, 024321 (2008) and refs. therein.
- [15] H.R. Weller, M.W. Ahmed, H. Gao, W. Tornow, Y.K. Wu, M. Gai, and R. Miskimen, Prog. Part. Nucl. Phys.

**62**, 257 (2009).

- [16] S. L. Hammond, A. S. Adekola, C. T. Angell, H. J. Karwowski, E. Kwan, G. Rusev, A. P. Tonchev, W. Tornow, C. R. Howell, J. H. Kelley, Phys. Rev. C 85, 044302 (2012)
- [17] P.M. Goddard et al., Phys. Rev. C 88, 064308 (2013).
- [18] C. Romig et al., Phys. Rev. C 88, 044331 (2013).
- [19] D.I. Sober, B.C. Metsch, W. Knüpfer, G. Eulenberg, G. Küchler, A. Richter, E. Spamer, and W. Steffen, Phys. Rev. C 31, 2054 (1985).
- [20] N. Kumagai et al., Nucl. Phys. A 329, 205 (1979).
- [21] U.E. P. Berg *et al.*, Phys. Lett. B **103**, 301 (1981).
- [22] J. Enders et al., Nucl. Phys. A 636, 139 (1998).
- [23] T. Shizuma, T. Hayakawa, H. Ohgaki, H. Toyokawa, T. Komatsubara, N. Kikuzawa, T. Inakura, M. Honma, and H. Nakada, Phys. Rev. C 87, 024301 (2013).
- [24] F. Bauwens, J. Bryssinck, D. De Frenne, K. Govaert, L. Govor, M. Hagemann, J. Heyse, E. Jacobs, W. Mondelaers, and V. Yu. Ponomarev, Phys. Rev. C 62, 024302 (2000).
- [25] M. Scheck *et al.*, Phys. Rev. C 88, 044304 (2013).
- [26] T.C. Li et al., Phys. Rev. C 73, 054306 (2006).
- [27] F. Hofmann and H. Lenske, Phys. Rev. C 57, 2281

(1998).

- [28] V.G. Soloviev, Theory of complex nuclei (Oxford: Pergamon Press, 1976).
- [29] S. Volz et al., Nucl. Phys. A 779, 1 (2006).
- [30] R. Schwengner et al., Phys. Rev. C 78 064314 (2008).
- [31] N. Tsoneva, H. Lenske, Phys. Lett. **B695** 174 (2011).
- [32] R. Schwengner et al., Phys. Rev. C 87, 024306 (2013).
- [33] A. I. Vdovin *et al.*, Yad. Fiz. **30**, 923 (1979).
- [34] B. Özel-Tashenov et al., Phys. Rev. C 90, 024304 (2014).
- [35] B. L. Berman, At. Data Nucl. Data Tables 15, 319 (1975).
- [36] N. Tsoneva, H. Lenske, arXiv:1410.2458 [nucl-th], EPJ Web of Conferences (www.epj-conferences.org) accepted.
- [37] V. Yu. Ponomarev, Ch. Stoyanov, N. Tsoneva, M. Grinberg, Nucl. Phys. A635, 470 (1998).
- [38] D. Savran et al., Phys. Rev. Lett. 100, 232501 (2008).
- [39] A. Arima and H. Horie, Prog. Theor. Phys. 11, 509 (1954).
- [40] A. Arima, Hyperfine Interactions 78, 67 (1993).
- [41] P. von Neumann-Cosel *et al.*, Phys. Lett. **B443**, 1 (1998).[42] K. Langanke, G. Martinez-Pinedo, P. von Neumann-
- Cosel, A. Richter, Phy. Rev. Lett. **93**, 202501 (2004). [43] S.E. Koonin, D.J. Dean, K. Langanke, Annu. Rev. Nucl.
- [43] S.E. Koonin, D.J. Dean, K. Langanke, Annu. Rev. Nucl Part. Sci. 47, 403 (1997).