Nuclear Resonance Fluorescence of Cr isotopes: Onset of the Pygmy Dipole Resonance

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Low-lying electric and magnetic dipole strength, particularly the Pygmy Dipole Resonance (PDR) and Spin-flip M1 excitations, of atomic nuclei have drawn considerable attention in the last decade. The concentration of E1strength below or in the vicinity of the particle separation energy is usually denoted as pygmy dipole resonance (PDR) [1]. Since this concentration of strength has a resonance-like shape, it is often referred to as pygmy dipole resonance. The PDR is commonly assumed (macroscopic picture) to result from oscillations of excess neutrons against an isospin saturated N $\approx$ Z core. However, it is already observed in many nuclei and reproduced in many microscopic model calculations; its structure is still under discussion [1, 2, 3]. In any case, the presence of extra E1 strength near the neutron separation threshold has an impact on neutron capture rates in astrophysical calculations [4]. The study of the pygmy strength is expected to provide information on the neutron skin and symmetry energy of the equation of state. Information about neutron skin and symmetry energy is extremely important for the modelling of neutron stars, in particular, the radius of neutron star is related to the symmetry energy.

So far, PDR strengths have been studied in mostly moderately heavy nuclei in the mass regions around A = 90 and A = 140. It has been observed, that, apparently the PDR starts to form near mass number A $\approx$ 50. Experimental information on ^{50,52}Cr and ^{54}Cr may provide information on the onset of the PDR in atomic nuclei as a function of nucleon numbers. In addition to E1 strength, stable *fp*-shell nuclei exhibit spin-flip M1 resonances [5], mainly from $f_{7/2} \rightarrow f_{5/2}$ orbitals, for both protons and neutrons. On the other hand, scissors-like M1 mode at low-energy (isovector orbital mode) is also expected in deformed *fp*-shell nuclei. Moreover, experimental knowledge of the magnetic dipole strength in *fp*-shell nuclei is also crucial in supernova modelling.

In the present work, real photon scattering (nuclear resonance fluorescence (NRF) [6]) of ^{50,52,54}Cr were studied up to 9.9 MeV in order to investigate low-lying dipole strength (E1 and M1) in the *fp*-shell region.

In NRF measurements, the excitation mechanism is purely electromagnetic. Intrinsic properties like spin, parity, and transition probabilities can be determined from the measured quantities (angular distribution, polarization asymmetries, γ -ray energy, and intensity) in a model-independent way. Spin quantum numbers, cross sections $\mathbf{I}_{i,0}$ (energy-integrated scattering cross sections for exciting a state i and de-exciting this state to the ground state 0), ground-state transition widths $\mathbf{\Gamma}_0$, and transition strengths B(M1) were measured at the Darmstadt High Intensity Photon Setup (DHIPS) [7] setup. A series of NRF experiments were performed at TU Darmstadt and at Duke University. The NRF experiment of ^{52}Cr was performed at the superconducting Darmstadt electron linear accelerator S-DALINAC using unpolarized bremsstrahlung with end-point energies of 8.0(1) and 9.9(1) MeV, respectively. On the other hand two measurements on ^{50}Cr and ^{54}Cr were carried out with bremsstrahlung at endpoint energies of 7.5(1) MeV and 9.7(1) MeV, respectively. The measurements with 7.5(1) MeV and 8.0(1) MeV bremsstrahlung have been carried out to identify transitions via intermediate states. Target nuclei are excited by the resonant absorption of photons and subsequently decay either directly or via intermediate states to the ground state. Scattered γ rays were detected by three HPGe detectors with 100% efficiency relative to a standard 3 in. × 3 in. NaI detector at a γ-ray energy of 1.3 MeV. They are placed at polar angles of 90° and 130° with respect to the incident beam. A representative photon scattering spectra of the ^{52}Cr(γ,γ') reaction between 3500 and 10 000 keV for the detector at 130◦, measured at end-point energy $E_0 = 9.9(1)$ MeV, are shown in Figs. 1(a), 1(b), and 1(c).

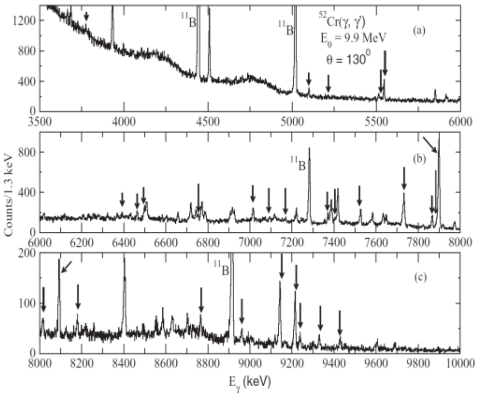

Fig. 1 Photon scattering spectra of the $^{52}Cr(\gamma, \gamma')$ reaction between 3500 and 10000 keV. Ground-state transitions of ^{52}Cr are indicated by arrows, and unmarked peaks correspond to inelastic transitions or escape peaks, or result from background radiation.

All total 32, 28 and 52 spin-1 states were observed in ^{50}Cr, ^{52}Cr, and ^{54}Cr, respectively. The parity quantum numbers of these states have been determined at the High Intensity Gamma-ray Source (HIγS) of the Triangle Universities Nuclear Laboratory in Durham, NC, USA.

Calculations within the microscopic quasiparticle-phonon nuclear model (QPM) were performed using a basis which includes one-, two-, and three-phonon configurations to interpret the dipole strength distributions of $^{50,52,54}Cr$ in a microscopic way [8,9]. The QPM results agree well with the experimental findings for all nuclei. In these calculations, the main one-phonon components of the strongest 1^- state are located below 10 MeV and do not belong to the giant dipole resonance. This feature usually describes the presence of PDR strength.

The ratio of the total observed E1 transition strength up to 9.7 MeV to the TRK Energy Weighted Sum Rule (EWSR) was calculated for $^{50,52,54}Cr$ isotopes. Thomas-Reiche-Kuhn Energy Weighted Sum Rule (EWSR), gives an approximation for the summed up electric dipole transition strength as function of proton and neutron number. It has been observed that the TRK sum rule exhaustion amounts to about 0.18% (almost constant) for both ^{50}Cr and ^{52}Cr, and increases rather drastically in ^{54}Cr [9], as shown in Fig 2.

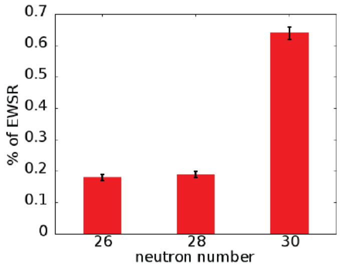

Fig. 2 Exhausted percentage of the EWSR for ^{50}Cr, ^{52}Cr, and ^{54}Cr [9].

This interesting result indicates on one hand at the important role of valence neutrons for the building of the low-lying E1 strength and on the other hand highlights the major role of shell structure on the properties of the PDR questioning in its fully collective character. Experimental results are also indicating that onset of the PDR takes place in ^{50}Cr (in mass number $A \approx 50$).

On the other hand, strong M1 transitions appear in ^{50}Cr [10], ^{52}Cr [8], and ^{54}Cr near 9 MeV excitation energy due to the $f_{7/2} \rightarrow f_{5/2}$ spin-flip M1 resonance. In addition to spin-flip M1 resonance, the strongly excited 1^+ state at 3.63 MeV excitation energy of ^{50}Cr [10] is emerged as a scissor mode like state.

The interesting results obtained in these works will be discussed.

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References

[1] D. Savran, T. Aumann, and A. Zilges, Prog. Part. Nucl. Phys. **70**, 210 (2013).
[2] P.-G. Reinhard and W. Nazarewicz, Phys. Rev. C **87**, 014324 (2013).
[3] J. Piekarewicz, Phys. Rev. C **83**, 034319 (2011).
[4] S. Goriely, Phys. Lett. B **436**, 10 (1998).
[5] K. Heyde, P. von Neumann Cosel, and A. Richter, Rev. Mod. Phys. **82**, 2365 (2010).
[6] U. Kneissl, N. Pietralla, and A. Zilges, J. Phys. G 32, R217 (2006).
[7] K. Sonnabend et al., Nucl. Instrum. Methods Phys. Res. A **640**, 6 (2011).
[8] H. Pai et al., Phys. Rev. C **88**, 054316 (2013).
[9] P. C. Ries et al., Journal of Physics: Conference Series **724** (2016) 012040
[10] H. Pai et al., Phys. Rev. C **93**, 014318 (2016)