Possible evidences for Giant Quadrupole Resonances within neutron-induced α-particle emission

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Abstract. A fine agreement of recently measured and presently calculated (n,α) cross sections at a low incident energy almost entirely related to the ground-state activation, supports additionally an α-particle OMP. Further calculated underestimation of the energy dependence of these data, beyond any model parameter uncertainty, is described by a Gaussian distribution around isoscalar giant quadrupole resonance (ISGQR) energy, of ~14.2 MeV, with a peak cross section of 0.36±0.04 mb, width of 1.8±0.1 MeV, and ISGQR-like strength function of 4.3±1.9% energy weighted sum rule (EWSR). The α-particle decay of nuclei excited at ISGQR energies in (n,α) reactions is linked to ISGQR-like strength functions with even around 50% larger uncertainty than ISGQR strengths measured by ^{3}He and α-particle inelastic scattering. An isotope effect is also observed in the corresponding (γ,α) and neutron-induced α-emission data, following the Q-value decrease with the asymmetry parameter $(N-Z)/A$ of the target nuclei.

1 Introduction

The first measurement of ^{91}Zr$(n,\alpha)^{88}$Sr reaction cross sections [1] at incident energies between 3.9–5.3 MeV, followed the change of corresponding evaluated data by up to 6.4 times in the widely used libraries, including TENDL [2] based on the TALYS nuclear model code system [3]. The α-particle optical model potential (OMP) was thought to be the reason behind this variance, other parameters of the related pre-equilibrium emission (PE) and statistical model (SM) having only a marginal influence at these energies. However, the TALYS default α-OMP [4] has recently been proved to describe well the neutron–induced alpha emission in the mass range A~90 including all Zr stable isotopes [5]. Nevertheless, there are singular conditions [1] for a significant reaction modeling challenge on far better terms than usual. Thus, only α-particles leaving the residual nucleus ^{88}Sr in the ground state (g.s.) were measured, while insignificant contribution of even the first–excited state through (n,α_1) reaction was confirmed by TALYS-1.9 calculation. Since the reaction primarily populates a single final state, the number of model parameters influencing the results is significantly reduced.

2 Eventual ISGQR component

Description of absorption as well as emission of α-particles by the same OMP [4] became possible by additional consideration of (i) the pickup direct reaction (DR), and (ii) eventual isoscalar giant quadrupole resonance (ISGQR) α-particle decay [6] around ISGQR energies of A~60 and A~90 excited nuclei in nucleon-induced reactions [5, 7]. Thus, further comparison of the new measured [1] and calculated (n,α) data has been carried out to confirm either this OMP or the non–statistical processes to be additionally considered. Moreover, particular attention is paid to calculated cross section uncertainties related to accuracy of primary data used to set up the input parameters.

The reaction mechanisms, local approaches, and codes (STAPRE-H, DWUCK4, FRESCO) for SM+PE, collective inelastic scattering and pickup DR account as for (n,α) reactions on Zr, Nb, and Mo stable isotopes [5], led to results shown in Fig. 1(a). It should be emphasized the SM+PE uncertainty bands related to error bars of the fitted number of discrete levels N_d and average s-wave resonance spacing D_0^{exp} by level densities of target ^{91}Zr (gray) and residual ^{88}Sr (orange) nuclei [5, 7].

The increase of measured α-emission beyond the SM+PE+DR calculated results, at around 5.60 MeV, corresponds to the systematic ISGQR energy E_0=64/$A^{1/3}$ [10] of ~14.2 MeV for the excited nucleus ^{92}Zr, while the data energy range between 3.0 and 5.3 MeV is close to half of the systematic ISGQR width described by a Gaussian distribution around the ISGQR energy. The corresponding peak cross section of 0.36±0.04 mb, and full width at half maximum (FWHM) of 1.8±0.1 MeV in Fig. 1(b) has been related to the α-particle decay of nuclei excited at ISGQR energies [10] in (n,α) reactions [5, 7] (Fig. 2).

3 ISGQR-like α-particle decay outlook

Based on the ISGQR energies [10], peak cross sections and widths of ISGQR-like α-particle decay of excited nuclei in neutron–induced reactions [5, 7], the related energy–weighted integrals S^{E2} are given by the approxi-

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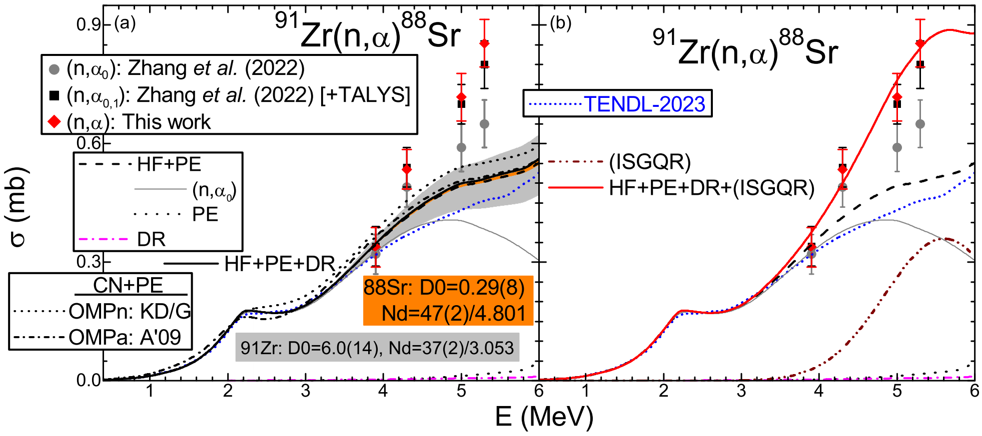

Figure 1. Comparison of cross sections measured [1] (dots), calculated for ^{91}Zr$(n,\alpha)^{88}$Sr (thin solid curve), and deduced for $(n,\alpha_{0,1})$ [1] (squares) and (n,α) reactions hereafter (diamonds), with evaluated [2] (short–dotted) and calculated DR (dash-dotted), PE (dotted), and SM+PE (dashed) (n,α) components, and (a) SM+PE results using other OMPs either for neutrons (short-dashed) [8] or α-particles (short-dash-dotted) [9], and SM+PE+DR sum (solid), and (b) ISGQR-like component (dash-dot-dotted) and further sum (solid).

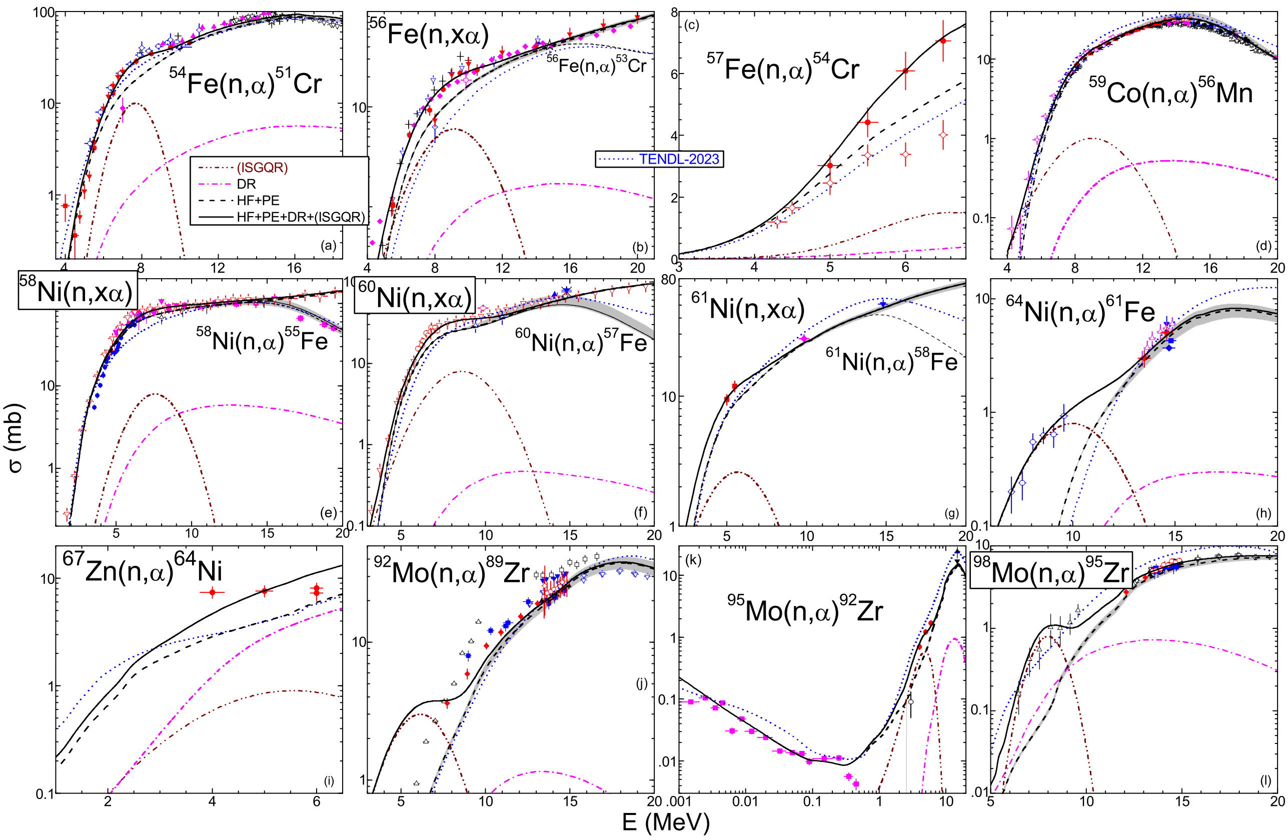

Figure 2. Comparison of measured [11] and calculated $(n,x\alpha)$ data of ^{54,56,57}Fe, ^{59}Co, ^{58,60,61,62,64}Ni, ^{67}Zn, and ^{92,95,98}Mo (solid curves), ISGQR-like (dash-dot-dotted), DR (dash–dotted), and SM+PE (dashed) components, and residual–nuclei NLD uncertainty bands [5, 7].

mation $\int\sigma^{GQR}dE/E^2=(1/E_0^2)\int\sigma^{GQR}dE$ [12]. The error brought by this estimation is negligible in comparation to the systematic/statistical uncertainties of the integrated yields $\int\sigma^{GQR}dE$ as (i) the ISGQR energy standard deviation of $1.7/A^{1/3}$ MeV [10], (ii) ~10% for assessment of ISGQR-like peak cross sections and FWHMs (but ~20% of FWHM due to sparse data at lowest energies for ^{55,57,58}Fe, ^{68}Zn, and ^{93}Mo, as well as ~20% of peak cross sections for ^{59,61,63,65}Ni and ^{99}Mo, with increased statistical uncertainty of measured (n,α) cross sections corresponding to ISGQR energies), and (iii) systematic uncertainty of SM+PE+DR analysis setting up the ISGQR-like extra-yield, leading to an overall 45–55% uncertainty of the energy–weighted integral.

The corresponding energy weighted sum rule (EWSR) fractions SR^{E2}=$0.22Z^2/A^{1/3}$ μb/MeV, compared to EWSR

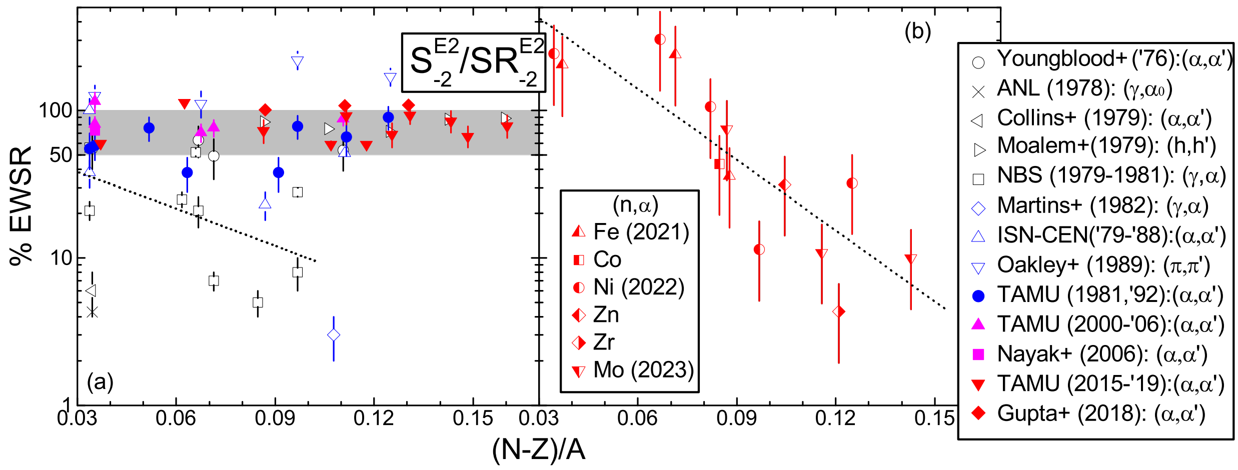

Figure 3. Comparison of ISGQR-like strength functions for neutron induced α-emission on nuclei with $54 \leq A \leq 98$, and ISGQR strength functions measured by ^{3}He and α-particle inelastic scattering and (γ, α) reaction [11] vs. $(N-Z)/A$ asymmetry parameter, with the band of systematic values between 50–100%, and linear fit (dotted lines) of (a) (γ, α) and (b) neutron induced α-emission measurements.

fractions of the ISGQR strength functions obtained through ^{3}He and α-particles inelastic scattering and (γ, α) reaction [11] analysis, show in Fig. 3(a) a spreading much larger than the previous data systematics, i.e. between 50–100% [10]. However, it is closer to that of (γ, α) data, with an average decrease as a function of $(N-Z)/A$ asymmetry parameter. Actually, they are (i) in between 50-100% for ^{58}Fe, ^{60}Co, ^{62}Ni, ^{68}Zn, and ^{93}Mo, (ii) larger for ^{55,57}Fe and ^{59,61}Ni, and (iii) significantly lesser for ^{63,65}Ni, ^{92}Zr, and ^{96,99}Mo, as shown in Fig. 3(b). In fact, there is an obvious average decrease of the ISGQR-like S^{E2} as a function of $(N-Z)/A$ for the neutron induced α-emission, similar to the isotope effect of neutron-induced emission of charged particles [13] noticed formerly by Gardner for the (n, p) reaction [14] as a Q-value effect.

4 Conclusions

Fine agreement of recently measured [1] and SM+PE+DR (n, α) cross sections at lowest incident energy, almost entirely related to the g.s. activation, supports additionally the α-particle OMP [4]. The α-particle decay of nuclei excited at ISGQR energies [10] in (n, α) reactions [5, 7] is linked to ISGQR-like strength functions with around 50% larger uncertainty than ISGQR strengths measured by ^{3}He and α-particle inelastic scattering. Finally, there is an isotope effect of corresponding (γ, α) and neutron-induced α-emission data, following Q-value decrease with asymmetry parameter ($(N-Z)/A$ of target nuclei.

This work has been partly supported by The Executive Unit for the Financing of Higher Education, Research, Development and Innovation (UEFISCDI) (Project No. PN-III-ID-PCE-2021-1260) and carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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