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

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Abstract. Recent **singular conditions of ^{91}Zr(n,α)^{88}Sr reaction cross-section measurement** at incident energies below 5.3 MeV [Phys. Rev. C **106**, 064602 (2022)] and **previous suitable account** for the other reaction channels of neutrons incident on ^{91}Zr using a consistent model parameter set have a two-fold benefit. The fine agreement of the calculated and experimentally derived data at the incident energy related to the ground-state activation provides a full **support of the involved α-particle optical potential**. Then, cross-section underestimation around the **isoscalar giant quadrupole resonance** (ISGQR) energy, beyond any model parameter uncertainty, is found similar to former **ISGQR-*like* α-particle decay** of excited nuclei in neutron-induced reactions in 54<A<98 mass range. The **comparison** of their strengths and the **ISGQR strengths** measured by (γ,α) reaction and inelastic scattering of ^{3}He and α-particles underlines the **isotope effect** related to *Q*-value decrease with asymmetry parameter *(N-Z)/A*.

1. Introduction

The **first measurement** of ^{91}Zr*(n,α)*^{88}Sr reaction cross sections[1], performed in the 3.9–5.3 MeV incident–energy range, followed the need of reliable nuclear data for the isotopes of zirconium used in the blanket and first wall of fusion reactors while the related evaluated data changed by up to 6.4 times were found in widely used libraries including TENDL[2].

The alpha-particle optical model potential (OMP) was thought to be the reason behind this variance, other parameters of the corresponding statistical model Hauser-Feshbach (HF) and pre-equilibrium emission (PE) predictions having only a marginal influence at these incident energies. However, the TALYS[3] default **alpha-particle OMP**[4] has recently been proved to **describe well** the neutron–induced α-emission in the mass range *A*~90 including **all Zr stable isotopes**[5].

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[1]G. Zhang et al., *Cross sections of the ^{91}Zr(n,α)^{88}Sr reaction in the 3.9–5.3 MeV neutron energy region*, Phys. Rev. C **106**, 064602 (2022).

[2]A. Koning, D. Rochman, et al., *TENDL: Complete Nuclear Data Library for Innovative Nuclear Science and Technology*, Nuclear Data Sheets **155**, 1 (2019).

[3]A.J. Koning, S. Hilaire, M.C. Duijvestijn, http://www.talys.eu

[4]V. Avrigeanu, M. Avrigeanu, and C. Manailescu, Phys. Rev. C **90**, 044612 (2014).

[5]M. Avrigeanu and V. Avrigeanu, Phys. Rev. C **107**, 034613 (2023).

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,α₁)* reaction was confirmed by TALYS-1.9 calculation. The feeding, basically, of one final state reduces essentially the model parameters which could affect the results.

Following the **suitable account** of other available data for neutron–induced reactions on ^{91}**Zr**, with a consistent HF+PE parameter set already fixed[5,6], the α-OMP remains the only constraint for the *(n,α)* cross–section calculation[7,8].

Present analysis background

More recently, description of absorption as well as emission of α-particles by the same potential[4] became possible by additional consideration of (i) the pickup direct reaction (DR), and (ii) eventual isoscalar giant quadrupole resonance (ISGQR) α-particle decay[7] around ISGQR energies of A~60 and A~90 excited nuclei in nucleon-induced reactions[5,8]. Actually, these results would not have been obtained without fulfillment of the following key demands:

- **Consistent SM parameter sets** were formerly validated by **analysis of independent data,** other than the concerned reaction cross sections.
- Hence, **no further empirical rescaling factors** of the gamma and nucleon widths were needed.
- So, **compensation effects** of less accurate model parameters were **prevented**.
- Due consideration was given to the correlation between the **accuracy of the above–mentioned independent data**, the input parameters determined by their fit, and the corresponding **final uncertainties of the calculated data**.
- Suitable description of **all competitive reaction channels** was also required, for parameter sets validation.
- The analysis included the **available data for whole isotopic chains** as well as neighboring elements.

Thus, **further comparison** of the new measured and calculated *(n,α)* data **may either confirm** this OMP **or reveal non–statistical processes** to be additionally considered. Particular attention is paid to calculated cross–section uncertainties related to accuracy of primary data used to set up the consistent input parameters.

2. Nuclear-reaction model analysis

The reaction mechanisms, local approaches, and codes (STAPRE-H, DWUCK4, FRESCO) for HF+PE, collective inelastic scattering, and pickup DR account as for

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[6]V. Avrigeanu and M. Avrigeanu, Phys. Rev. C **96**, 044610 (2017).
[7]M. Avrigeanu, W. von Oertzen, and V. Avrigeanu, Nucl. Phys. A **764**, 246 (2006).
[8]V. Avrigeanu and M. Avrigeanu, Eur. Phys. J. A **57**, 54 (2021); *ibid*. **58**, 189 (2022).

(n,α) reactions on Zr, Nb, and Mo stable isotopes[5], results (**Fig. 1a**):

- PE and DR components: only around 3% and 1.3%, respectively, at largest E_n;
- fine agreement of measured/calculated cross sections at lowest E_n incident energy, almost entirely related to the g.s. activation: check of α-particle OMP[4];
- HF+PE component: OMP(n) effects: <10%, as well as
- NLD effects due to fitted N_d and D_0 error bars: <0.6% (^{88}Sr), <13% (^{91}Zr);
- obvious underestimation particularly around/at higher E_n of 5.3 MeV: ~70%

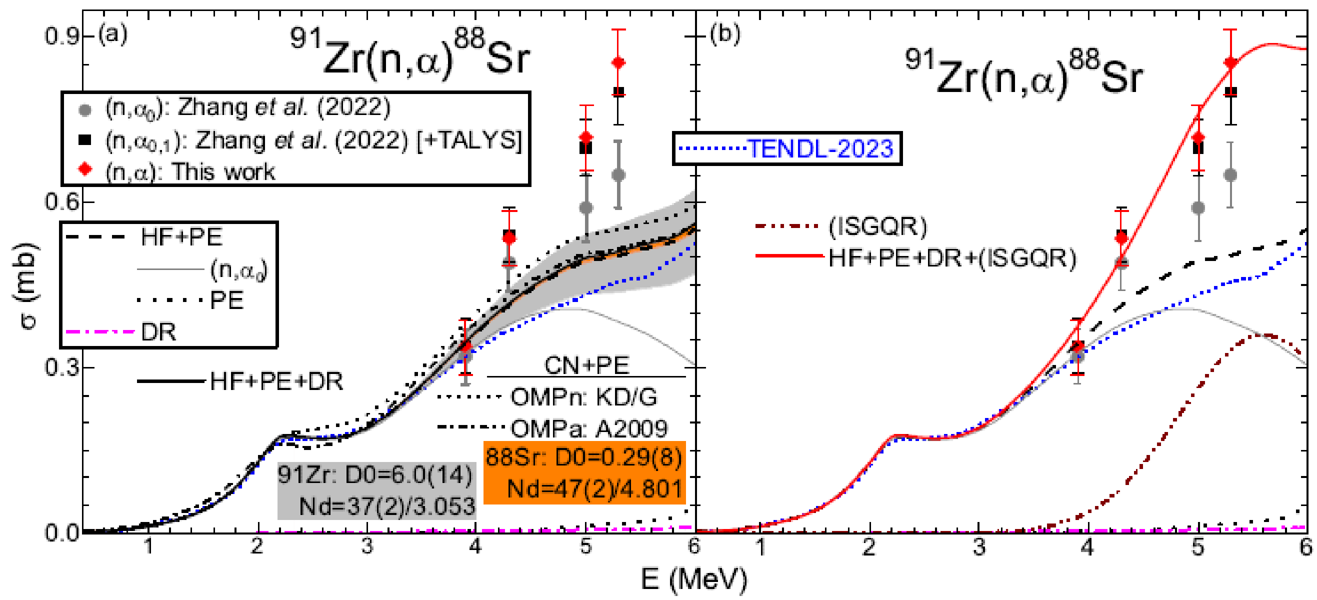

Fig. 1. Comparison of cross sections measured[1] (dots), calculated for ^{91}Zr*(n,α$_0$)*^{88}Sr reaction (thin solid curve), and deduced for *(n,α$_{0,1}$)* reaction[1] (squares) and *(n,α)* reaction in this work (diamonds), with evaluated[2] (short–dotted) and calculated values for *(n,α)* reaction DR (dash-dotted), PE (dotted), and HF+PE (dashed) components, as well as (a) HF+PE+DR sum (solid), HF+PE uncertainty bands related to error bars of fitted N_d and D_0 by level densities of target ^{91}Zr (gray) and residual ^{88}Sr (orange), and HF+PE results using other OMPs for α-particles (short-dash-dotted) or neutrons (short-dashed), and (b) ISGQR-*like* component (dash-dot-dotted) and HF+PE+DR+ISGQR-*like* sum (solid).

3. Eventual ISGQR component

The increase of measured α-emission beyond the HF+PE+DR calculated results:

- close to E_n=5.60 MeV corresponding to excited CN (^{92}Zr) systematic ISGQR energy[9] $E_0=64/A^{1/3}$~14.2 MeV, and
- data energy range (3.0-5.3 MeV) close to half of the systematicISGQR width, described by a Gaussian distribution around the ISGQR energy[9], with:
- peak cross section of 0.36±0.04 mb, and
- full width at half maximum (FWHM) of 1.8±0.1 MeV (**Fig. 1b**),

that could be related to the α-particle decay of nuclei excited at ISGQR energies[9] in *(n,α)* reactions[5,8] (**Fig. 2**):

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[9] M. N. Harakeh and A. van der Woude, *Giant Resonancesl* (Oxford University Press, New York, 2001); U. Garg, https://arxiv.org/pdf/2207.06785.pdf (2022).

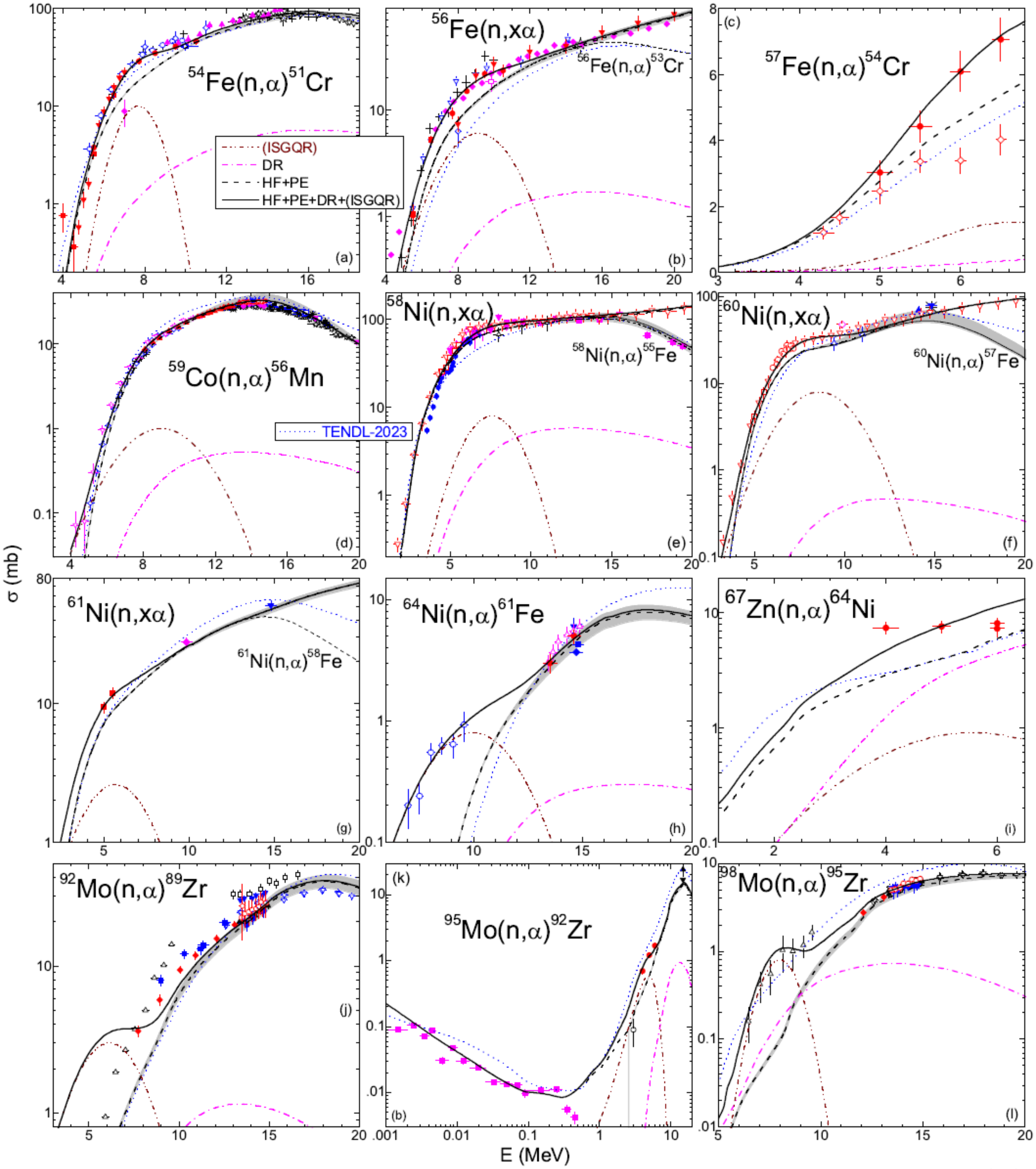

Fig. 2. Comparison of measured (EXFOR) and calculated *(n,α)* cross sections of ^{54,56,57}Fe, ^{59}Co, ^{58,60,61,62,64}Ni, ^{67}Zn, and ^{92,95,98}Mo (solid curves): ISGQR-*like* (dash-dot-dotted), DR (dash–dotted), HF+PE (dashed) components, and residual–nuclei NLD uncertainty bands[5,8].

4. Neutron–induced ISGQR-*like* α-decay outlook

Beyond ISGQR energies[9], peak cross sections and widths of ISGQR-*like* α-particle decay of excited nuclei in neutron–induced reactions[5,8], the integrated yields $\int\sigma^{GQR}dE$ of their Gaussian distributions (**Table 1**), the related energy–weighted integrals S^{E2} are given by the approximation[10] $\int\sigma^{GQR}dE/E^2=(1/E_0)^2\int\sigma^{GQR}dE$ with a

[10]K. Raghunathan et al., *Alpha particle capture through the giant electric resonances in 90Zr*, Phys. Rev. C **22**, 2409 (1980).

Table 1. The ISGQR energies *64/A*$^{1/3}$, ISGQR-*like* peak cross sections, FWHM, integrated yields, and corresponding ISGQR strength functions as well as EWSR fractions, for neutron induced α-emission (this work and Refs.[5,8]).

Excited nucleus	E_0 (MeV)	σ_0 (mb)	Γ (MeV)	$\int\sigma^{GQR}dE$ (mb MeV)	S^{E2}_{-2} (μb/MeV)	(% SR^{E2}_{-2})
^{55}Fe	16.829	10	2.1	22.6	79.7	204
^{57}Fe	16.630	6	4	25.6	92.5	239
^{58}Fe	16.534	1.5	2.4	3.76	13.8	35.8
^{60}Co	16.348	1	4.5	4.8	17.8	43.5
^{59}Ni	16.440	8	3.4	29.1	108	243
^{61}Ni	16.258	8	4.1	35.1	133	303
^{62}Ni	16.170	2.6	4.4	12.1	46.1	106
^{63}Ni	16.084	0.3	4	1.28	4.9	11.4
^{65}Ni	15.918	0.8	4.1	3.51	13.9	32.3
^{68}Zn	15.680	0.9	3.9	3.76	15.3	31.5
^{92}Zr	14.177	0.36	1.8	0.68	3.4	4.3
^{93}Mo	14.126	3	4	12.8	64.1	74.8
^{96}Mo	13.977	0.6	2.8	1.81	9.2	10.9
^{99}Mo	13.835	0.8	1.9	1.6	8.4	10

negligible error compared to the yields systematic/statistical uncertainties as per se:
- the ISGQR energy standard deviation[9] of 1.7/A$^{1/3}$ MeV,
- ~10% for assessment of ISGQR-*like* peak cross sections and FWHMs except:
- ~20% of FWHM due to sparse exp. data at lowest E_n for ^{55,57,58}Fe, ^{68}Zn, ^{93}Mo
- ~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,
- systematic uncertainty of HF+PE+DR analysis setting up the ISGQR-*like* extra-yield, leading to an overall 45–55 % energy–weighted integral total uncertainty.

Related **energy weighted sum rule** (EWSR) fractions $SR^{E2}=0.22Z^2/A^{1/3}$ μb/MeV **compared to** EWSR fractions of the ISGQR strength functions measured by **inelastic scattering** of **^{3}He/α-particles** and ***(γ,α)*** **reaction**, vs *(N-Z)/A* (Fig. 3):
- spreading much larger than systematics[9] of scattering data, between 50–100%
- closer to ***(γ,α)*** data[11], with an average decrease as a function of *(N −Z)/A*
  - in between 50-100% systematics: ^{58}Fe, ^{60}Co, ^{62}Ni, ^{68}Zn, ^{93}Mo
  - larger EWSR fractions for: ^{55,57}Fe and ^{59,61}Ni
  - significantly lesser for ^{63,65}Ni, **^{92}Zr**, ^{96,99}Mo
- corresponding to isotope (Q-value) effect of **n**–induced emission of CPs[12]

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[11]E. Wolynec et al., Phys. Rev. Lett. **42**, 27(1979); E. Wolynec et al., Phys. Rev. C **22**, 1012 (1980); W. R. Dodge et al., Phys. Rev. C **24**, 1952 (1981).
[12]N. Molla et al., Nucl. Phys. A **283**, 269 (1977); D.G. Gardner, Nucl. Phys. **29**, 373 (1962).

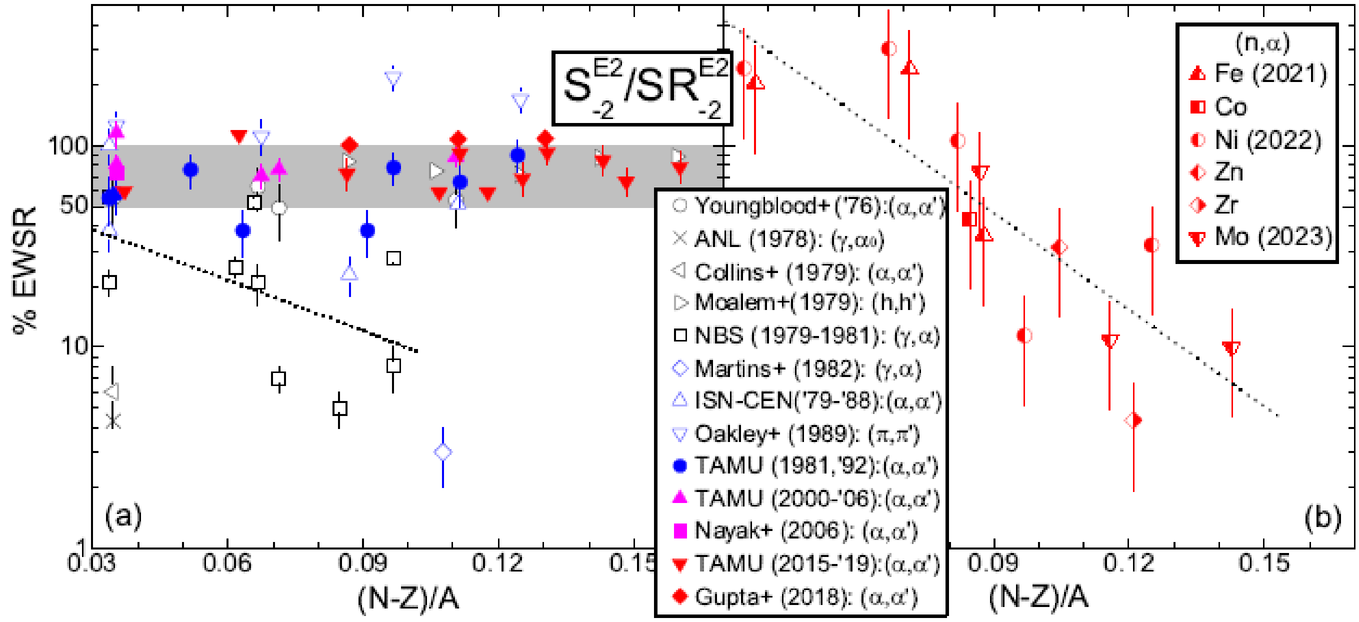

Fig. 3. Comparison of EWSR fractions of ISGQR-*like* strength functions for neutron induced α-emission on target nuclei with 54≤A≤98 (Table 1), and ISGQR strength functions measured by inelastic scattering of ^{3}He and α-particles, and *(γ,α)* reaction (EXFOR) vs. the *(N−Z)/A* asymmetry parameter, including the band of systematic values between 50–100% for the latter data, and a linear fit (dotted lines) of (a) the *(γ,α)* measurements, and (b) neutron induced α-emission.

5. Conclusions

- Fine agreement of measured/ HF+PE+DR cross sections at lowest E_n, almost entirely related to the g.s. activation: **check of α-particle OMP**[4]
- HF+PE+DR underestimation beyond any model parameter uncertainty of these *(n,α)* cross–section energy dependence: described by a **Gaussian distribution:**
    - **around ISGQR energy** of ~14.2 MeV, with
    - peak cross section of 0.36±0.04 mb,
    - width (FWHM) of 1.8±0.1 MeV, and
    - ISGQR-*like* strength function of 4.3±1.9% EWSR (too low!?)
- α-particle decay of nuclei excited at ISGQR energies[9] in *(n,α)* reactions[5,8]:
    - ISGQR-*like* strength functions with larger uncertainty of around 50% vs. ISGQR strengths measured by inelastic scattering of 3He/α-particles
    - isotope effect of corresponding *(γ,α)* and *(n,α)* reaction data, following Q-value decrease with asymmetry parameter *(N −Z)/A* of target nuclei.
- Further measurements of increased accuracy, at ISGQR related energies, for isotopes at both *(N − Z)/A* limits, would be helpful.

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