Neutron inelastic cross section derived from gamma-production cross sections in (n,n`γ) reactions and Pygmy Dipole Resonance

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Highly excited levels with large probabilities of decay to the ground states of the nuclei

Total neutron inelastic cross section can be obtained from the analysis of gamma-spectra produced after de-excitation of levels excited in inelastic scattering.

The sum of production cross section of all gamma-rays with transition to the ground state is the total inelastic scattering cross section.

But this analysis, using the data obtained with high-resolution gamma-detectors, can be done for medium and heavy mass nuclei up to about 4 – 5 MeV incident neutron energy. For higher energies, low gamma production cross sections and detectors efficiency to the high-energy gamma-rays make this task difficult.

As result, the sum of gamma-production cross sections for gamma-lines with decay to the ground state observed in present experiments gives only partial inelastic scattering cross section.

The difference from the total inelastic cross section can be not large. It depends not only from the conditions of the experiment, but also from nuclear structure properties of the nuclei.

Highly excited levels with large probabilities of decay to the ground states in ^{52}Cr

E_{level}(keV)	Jπ	Branching coefficient*
4815.69 9	1+,2+	0.50
5098.6 4	1	0.56
5213.7 5	1	1.00
5526.0 5	1	0
5544.7 10	(1+)	1.00
6137.0 10	2+	1.00
6389.9 5	1+	1.00
6462.4 5	1	1.00
6495.5 5	1	1.00
6752.0 5	1+	1.00
7014.5 4	1	0.81
7090.8 5	1+	1.00
7166.2 5	+	1.00
7368.8 5	1+	1.00

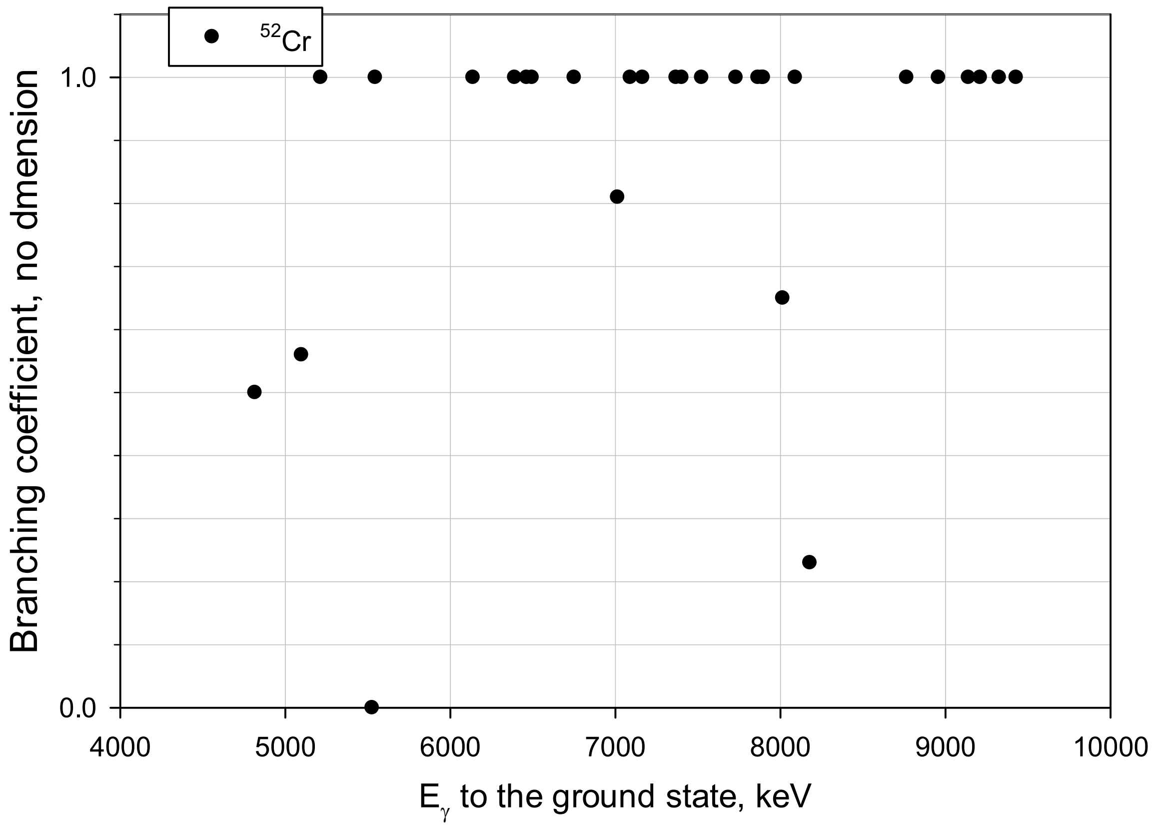
E_{level}(keV)	Jπ	Branching coefficient*
7403.2 5	1	1.00
7524.1 5	1+	1.00
7731.9 5	1-	1.00
7865.1 5	1+	1.00
7889.0 5	1	1.00
7897.4 5	1-	1.00
8015.4 4	1	0.65
8091.3 5	1	1.00
8179.3 4	1+	0.23
8765.9 5	1	1.00
8958.4 5	1	1.00
9140.3 5	1+	1.00
9211.9 5	1+	1.00
9327.0 5	1+	1.00

Branching coefficients for gamma transition to the ground state from the levels above 4 MeV in ^{52}Cr are derived from NUDAT

Most of them in the (n,n`γ) are probably not observed/accounted due to condition of measurements (detector efficiency, gamma energy resolution, …).

But all levels are excited with compound reaction mechanism. The cross section in the maximum is strongly decreasing with incident neutron energy due to the competition with other levels

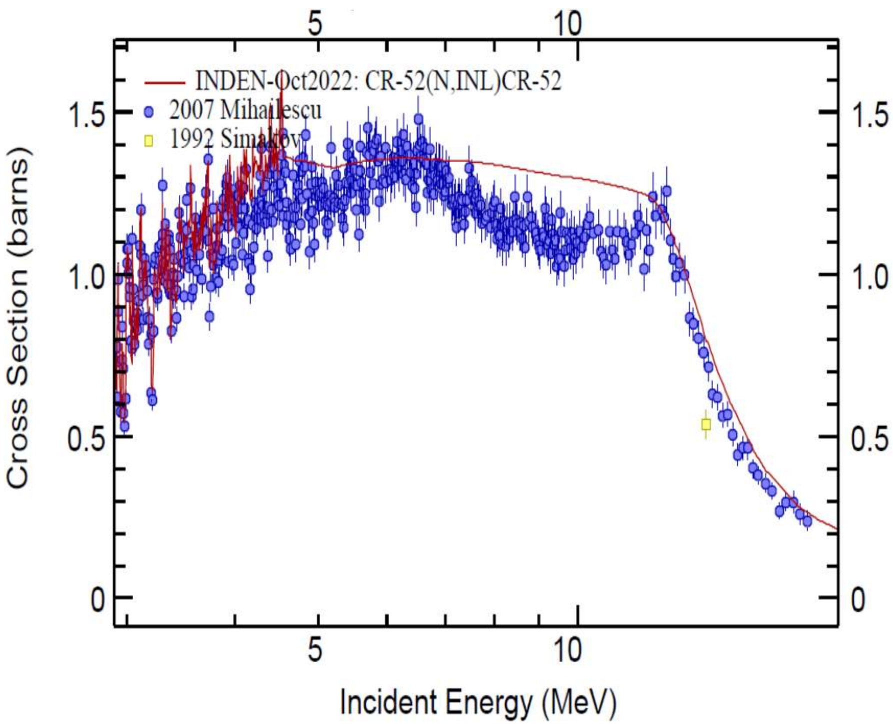
Highly excited levels with large probabilities of decay to the ground states in ^{52}Cr



Branching coefficient (BC) 1 means that this gamma transition is observed but other transitions were not observed

Zero BC means that this weak transition is observed but BC can not be assigned

Highly excited levels with large probabilities of decay to the ground states in ^{52}Cr



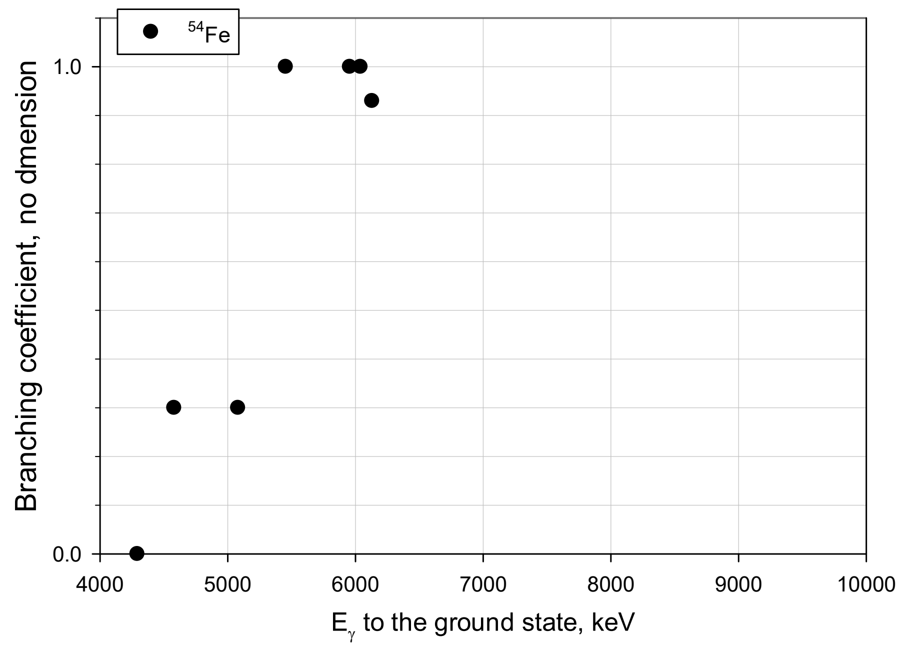
Results of Geel (2007 Mihailescu) measurements for $^{52}Cr(n,n'\gamma)$ cross section in comparison with latest evaluation (INDEN-Oct2022) and result of measurement with neutron registration (1992 Simakov).

The bent of the cross section between 6 and 12 MeV is caused by not accounted gamma transitions including from the isoscalar pygmy dipole resonance states ($J^{\pi}=1^{-}$).

Isoscalar PDR states are well excited in inelastic neutron scattering through the direct mechanism of the reaction.

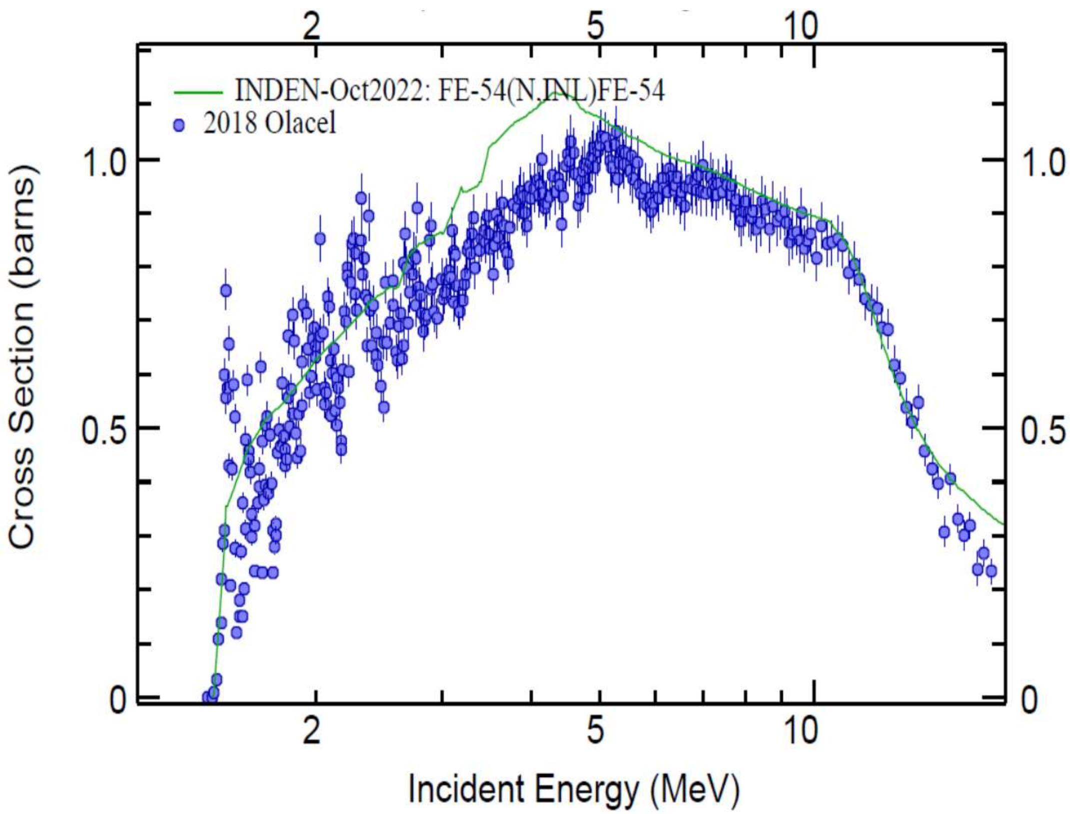
Highly excited levels with large probabilities of decay to the ground states in ^{54}Fe

E_{level}(keV)	Jπ	Branching coefficient*
4290.8 *7*	0+	0.00
4578.5 *9*	2+	0.30
5080 *4*	(1,2+)	0.30
5453 *7*	(1,2+)	1.00
5955 *8*	2+	1.00
6038 *8*	(1,2+)	1.00
6128.7 *6*	1	0.93



The data are no data for absent for Eγ > 6.2 MeV

Highly excited levels with large probabilities of decay to the ground states in ^{54}Fe



Results of Geel (2018 Olacel) measurements for $^{54}Fe(n,n'\gamma)$ cross section.

^{54}Fe with Z=26 has magic number on neutrons (N=28).

Strong competition from (n,p) reaction reduces the inelastic scattering cross section.

Highly excited levels with large probabilities of decay to the ground states in ^{56}Fe

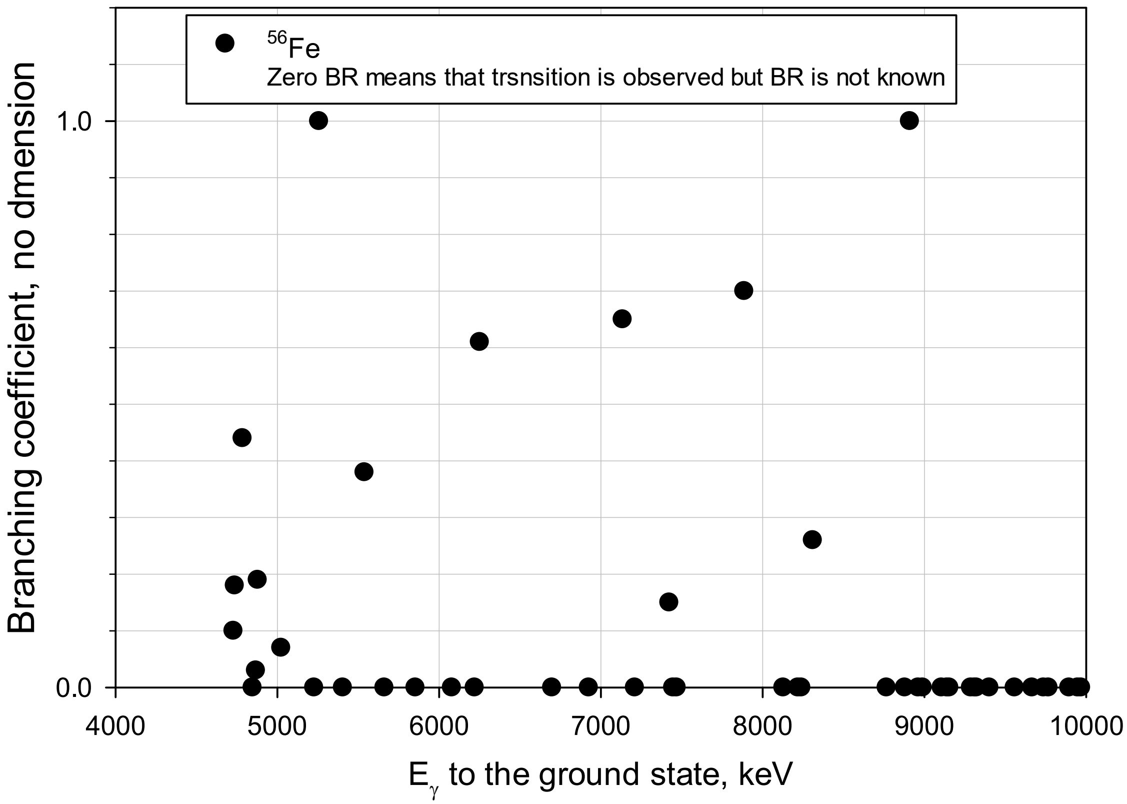
E_{level}(keV)	Jπ	Branching coefficient*
4085.93	1,2+	0.25
4539.5 *6*	1+,2+	0.13
4658.26	2+,3+,4+	<0.02
4728.14	2+	0.10
4737.33	2+	0.18
4784.12	1,2+	0.44
4847.9 *3*	2+	0
4866.52	1,2+	0.03
4878.0 *6*	2+	0.19
5023.49	1,2+	0.07
5227.3	1	0
5256.9 *3*	2+	1.00
5402.3 *1*	GE 1	0
5538.07	1,2+	0.38

E_{level}(keV)	Jπ	Branching coefficient*
5661.18		0
5853 *2*		0
6078 *3*		0
6219 *3*		0
6250.78	1	0.61
6698 *1*	1	0
6926 *2*	1-	0
7135 *3*	1	0
7167.27	1	0.65
7211.5	1	0
7422.67	1,2+	0.15
7446.5	1	0
7468.5	1	0
7886.54	1,2+	0.70

E_{level}(keV)	Jπ	Branching coefficient*
8128 *2*	1	0
8219 *4*		0
8239.7	1	0
8309.59	1,2+	0.26
8767 *3*		0
8879 *4*		0
8909.9	1,2+	1.0
8962 *4*		0
8989 *4*		0
9107 *4*		0
9140.3	1-	0
9154 *4*		0
9287 *3*		0
9311 *4*		0

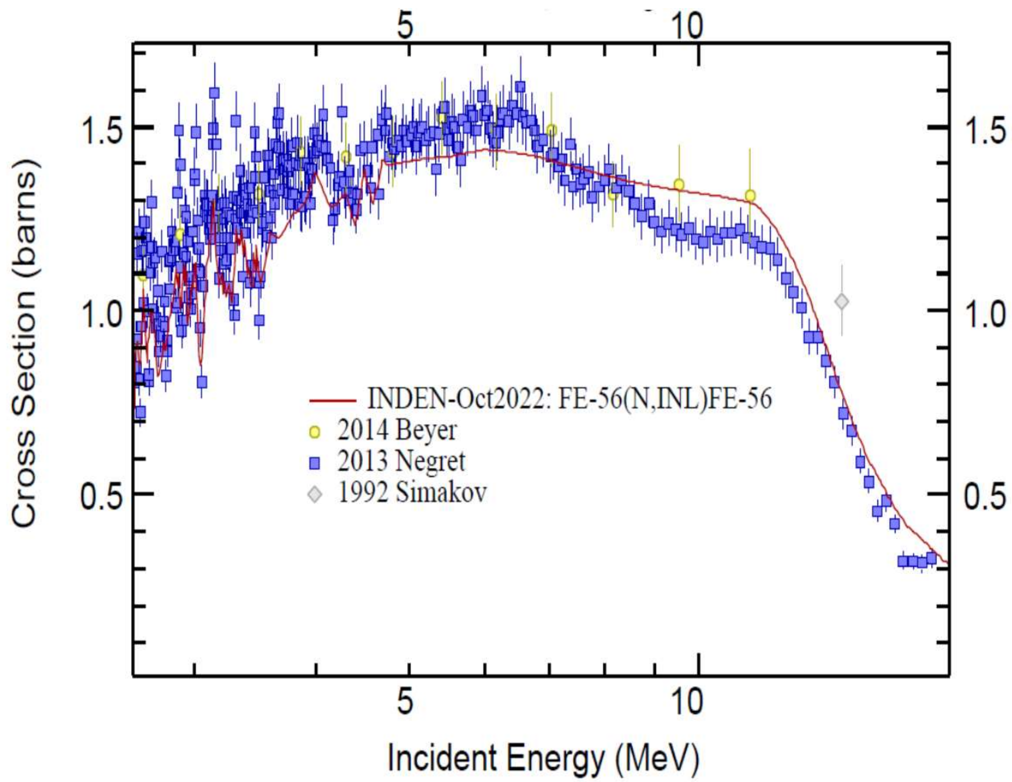
^{56}Fe is a most studied nucleus.with many dipole transitions to the GS

Highly excited levels with large probabilities of decay to the ground states in ^{56}Fe



^{56}Fe has most complete branching coefficients table for transitions to the GS from levels up to 10 MeV

Highly excited levels with large probabilities of decay to the ground states in ^{56}Fe



Results of Geel (2013 Negret) measurements for $^{56}Fe(n,n')$ cross section in comparison with latest evaluation (INDEN-Oct2022) and results of measurement with neutron registration (1992 Simakov, 2014 Beyer).

There are probably the problems with normalization of data in Geel measurements. The bent of the cross section between 6 and 12 MeV may be explained by presence of isoscalar pygmy dipole resonance states ($J^p=1^-$)

Highly excited levels with large probabilities of decay to the ground states in ^{208}Pb

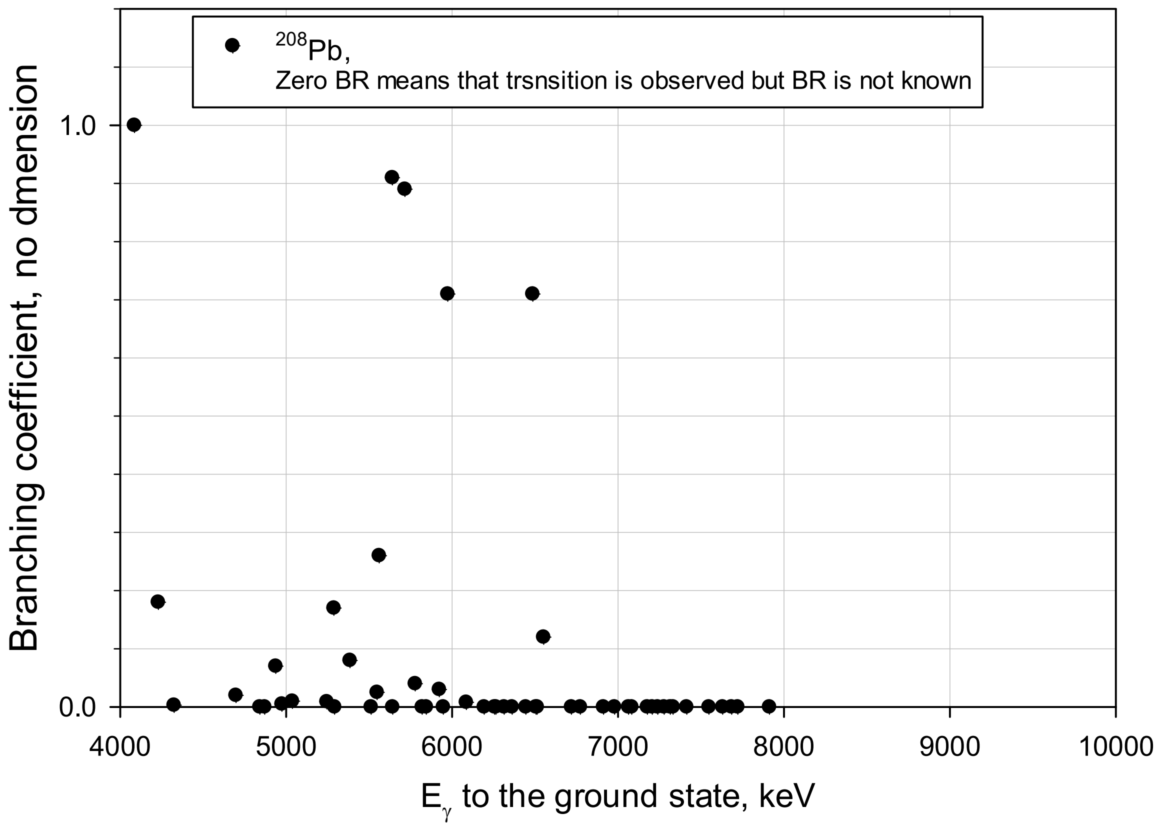
E_{level}(keV)	Jπ	Branching coefficient
4085.52	2+	1.00
4229.59	2−	0.18
4323.94	4+	0.003
4698.32	3−	0.02
4841.60	1−	0
4868.35	0+	0
4937.19	3−	0.07
4973.91	3−	0.005
5037.53	3−	0.01
5127.35	2−,3−	0.88
5245.24	3−	0.009
5286.48	2,3−	0.17
5291.90	1−	0
5384.59	3−	0.08

E_{level}(keV)	Jπ	Branching coefficient*
5511.78	1-	0
5548.113	2-	0.025
5561.31	2+	0.26
5639.55	1-	0.91
5641.98	1,2+	0
5715.53	2+	0.89
5777.96	2-,3-	0.04
5819.49	1+,2+	0
5844.49	1+	0
5923.67	2-	0.03
5946.77	1-	0
5973.0 *4*	2+	0.71
6086.56	1-	0.008
6193.1 *4*	2+	0

E_{level}(keV)	Jπ	Branching coefficient*
6255.68	2+	0
6263.7	1-	0
6313.9	1-	0
6361.6	1-	0
6444.4	3-	0
6486.5	1-	0
6505.6	1	0.71
6512.8	1	0
6551.93	1-,2,3-	0
6719.8	1-	0.12
6773.4	1,2,3-	0
6913 *4*	2+	0
6980 *40*	1,2+	0
7063.53*0*	1-	0

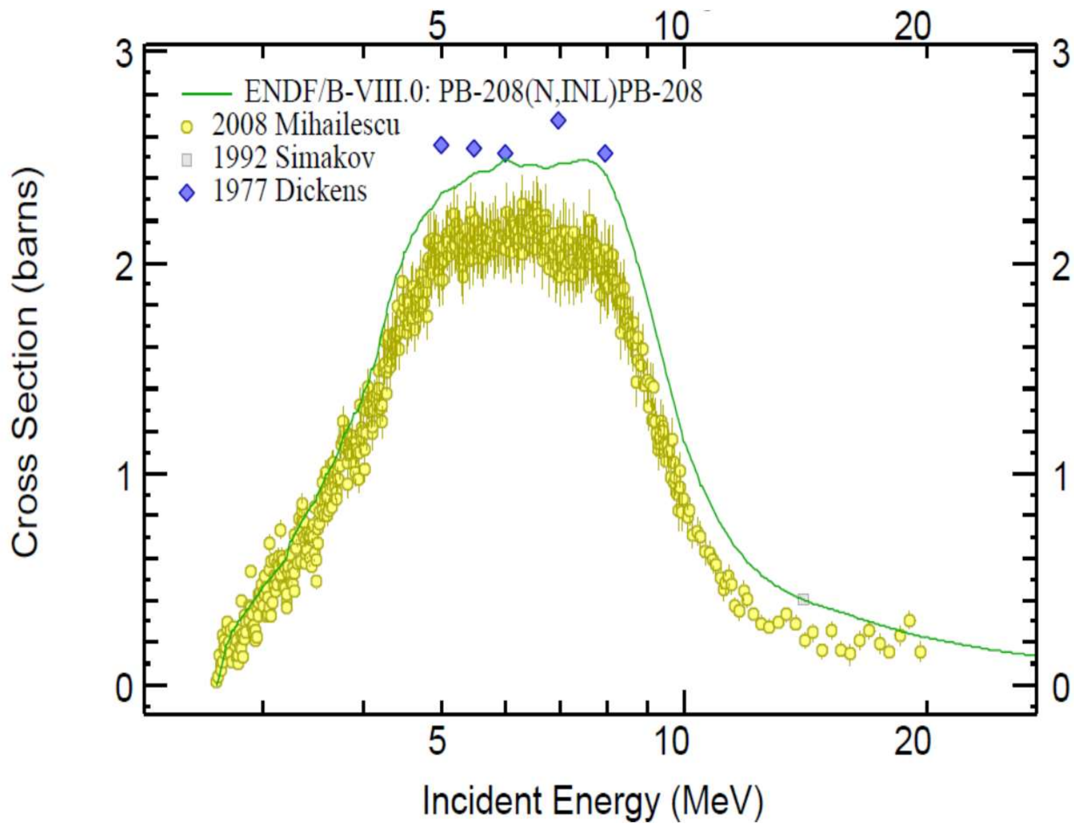
Double magic ^{208}Pb nuclei has many known gamma-transition to the GS from levels up to 8 MeV

Highly excited levels with large probabilities of decay to the ground states in ^{208}Pb



^{208}Pb has high inelastic scattering threshold and low (n,2n) threshold

Highly excited levels with large probabilities of decay to the ground states in ^{208}Pb



Results of Geel (2008 Mihailescu) measurements for ^{208}Pb(n,n’) cross section in comparison with latest evaluation (ENDF/B-VIII.0) and result of measurement with gamma (1977 Dickens) and neutron registration (1992 Simakov).

1977 Dickens measurement were done with gamma-registration under angle 125 degree and with normalization uncertainty not better than 12%.

Highly excited levels with large probabilities of decay to the ground states: conclusion

- **There are many direct gamma-transitions to the ground state from levels with energy above 4 MeV.**
- **They are not accounted in the derivation of the total inelastic cross section in (n,n'γ) experiments. The authors of measurements pay attention at this fact (but in EXFOR they are compiled not as partial).**
- **The transitions have mostly the multipolarity 1.**
- **The branching coefficients for these transitions are badly known for levels with excitation energy above 4 -5 MeV. The experimental data are incomplete because they are limited on the energy of registered gammas and probes for excitation of levels.**

Contribution of Pigmy Dipole Resonance (PDR) in neutron inelastic scattering

- **It was shown in many experimental and theoretical works, that giant dipole resonance (GDR) in nuclei may have pygmy dipole resonance as the low-energy branch of the GDR.**
- **The strength of PDR is a few per-cents in the units of energy weighted sum rules (EWSR).**
- **Because the mean energy of PDR may be two and more times less than GDR, the integral strength of these states will be higher than few per-cents.**
- **Below we will refer at the 2022 review by Lanza and Vetturi on the Pygmy Dipole Resonances freely published at the (https://arxiv.org/abs/2202.07589)**

Properties of Pigmy Dipole Resonance (PDR)

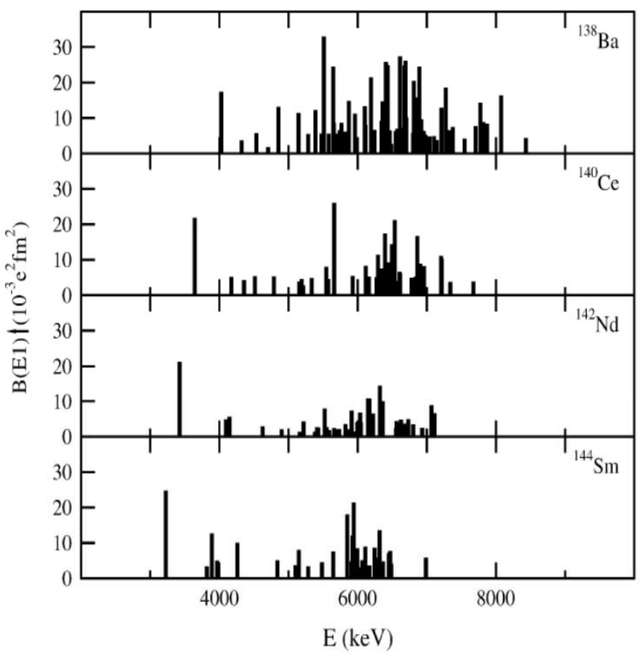


Fig. 2 Dipole reduced transition probabilities B(E1) measured in a photon scattering experiment for five stable even *N*=82 isotones. Taken with permission from [Volz et al., 2006]. ©2006 by Elsevier.

- **PDR states have $J^{\pi}=1^{-}$. They appear as a small "bump" at the left slope of the Giant Dipole Resonances**
- **PDR states (discrete and continuum) lay in the excitation energy near the neutron binding energy in the nuclei**
- **They are complex states with rather large branching coefficients of decay to the ground state**

Isoscalar and isovector PDR states

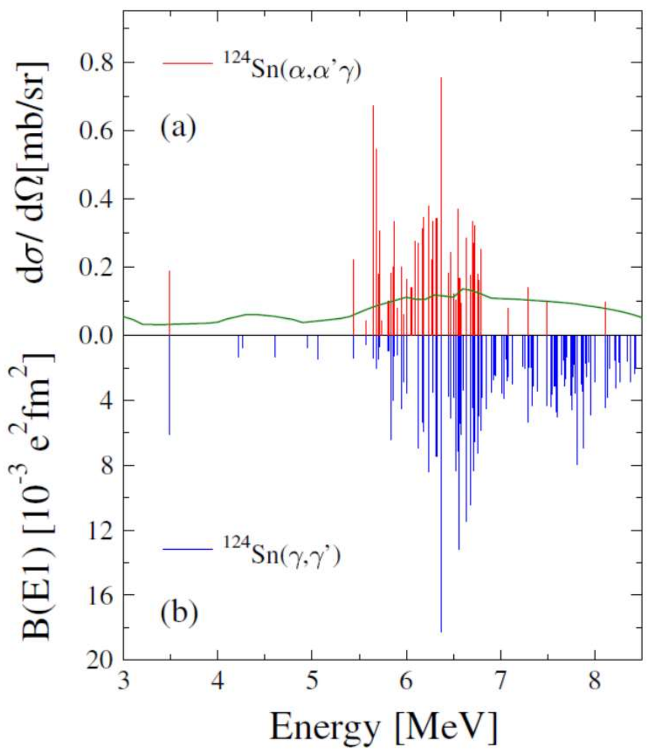


Fig. 3 (Color online) Cross section for the excitation of the dipole states in ^{124}Sn for the reaction $(\alpha,\alpha'\gamma)$ at E_α=136 MeV (panel a) is compared with the B(E1) measured with a (γ,γ') reaction (panel b). Taken with permission from [Endres et al., 2010]. ©2010 by APS.

- **The PDR has two components - isoscalar and isovector which a mixed.**
- **The isoscalar components of PDR states are well excited in direct inelastic scattering of neutrons, protons, alpha particles, … .**
- **The isovector components of PDR states are better excited in the gamma-scattering.**
- **Because isospin is not good quantum number, there is practically no clean isoscalar or isovector states.**

Isoscalar and isovector PDR states

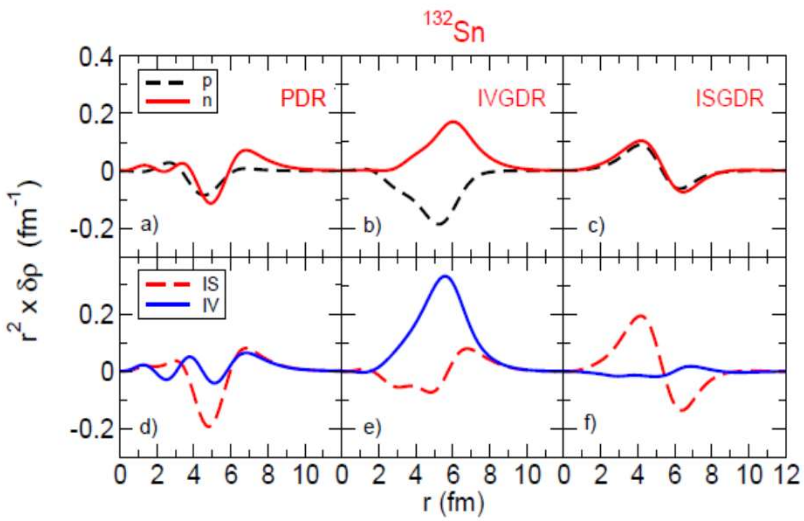
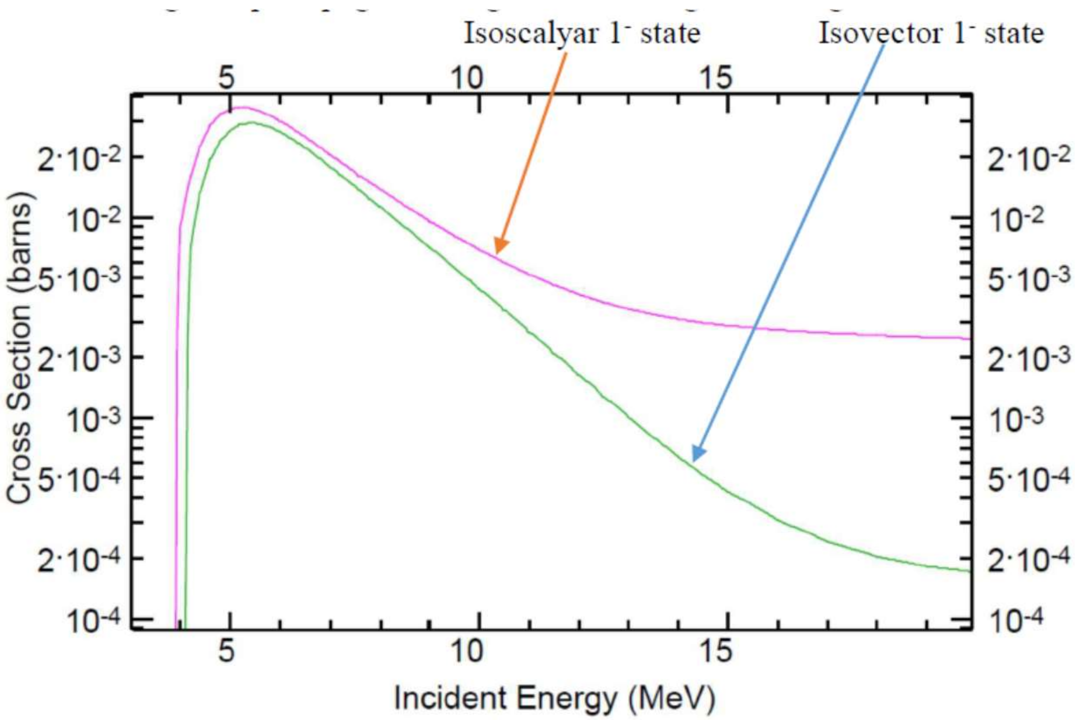


Fig. 6 (Color online) In the top panels, the RPA proton (dashed black line) and neutron (solid red line) transition densities are shown for the three shaded areas of the dipole strength distributions in ^{132}Sn of Fig. 5. The corresponding isovector (blue solid line) and isoscalar (red dashed line) transition densities are shown in the bottom panels.

The typical transitional densities for isoscalar and isovector states in the region of PDR, isovector giant dipole resonance and isoscalar giant dipole resonance.

The transition density of the isoscalar PDR has a maximum near the surface of the nucleus and the transition potential of neutron scattering with the excitation of the isoscalar PDR will be large.

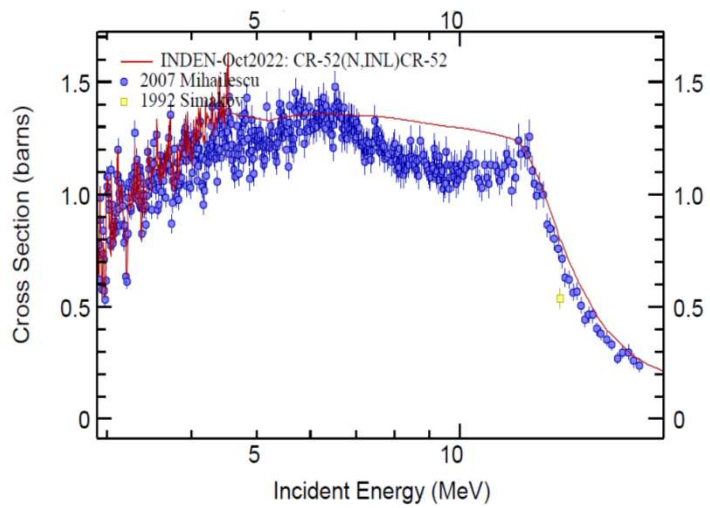
(n,n’γ) reaction with excitation of PDR

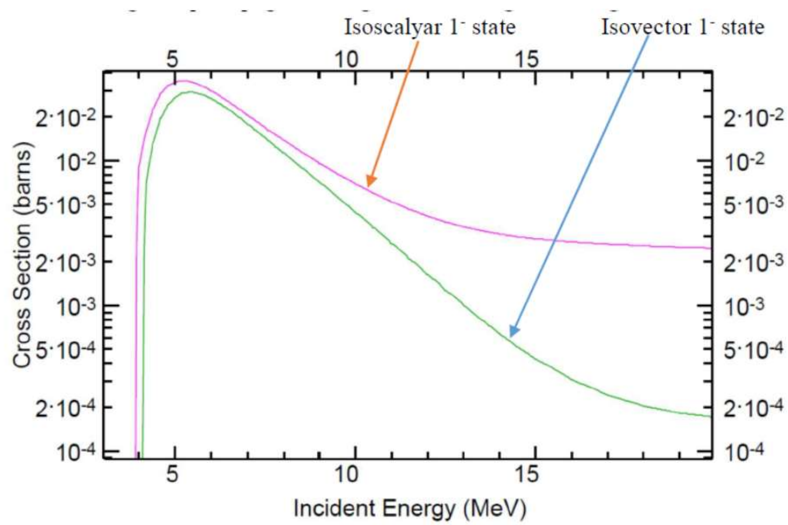


The difference in the excitation cross sections by neutrons of “pure” isoscalar and isovector 1^- states

- **The excitation function for each level has contribution from compound and direct reaction mechanisms.**
- **Compound mechanism is sensitive to the J^π of the state.**
- **The direct mechanism of excitation of isoscalar PDR states will contribute in the high-energy tale of excitation function.**

Pecularities of (n,n’) reaction with partial registration of gamma-trasitions to the ground state

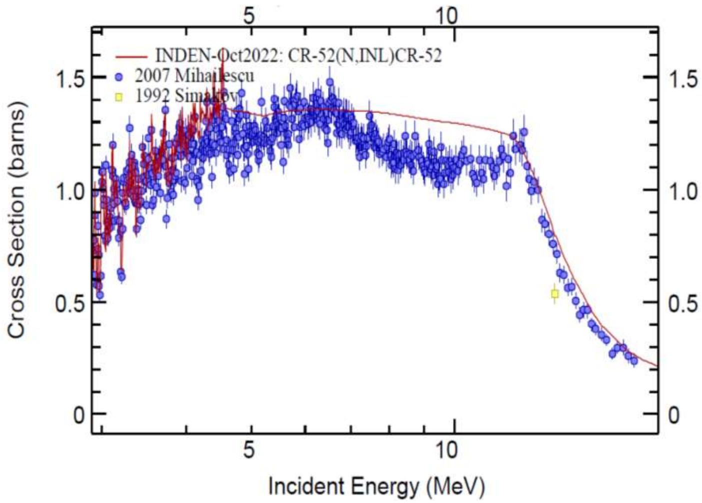


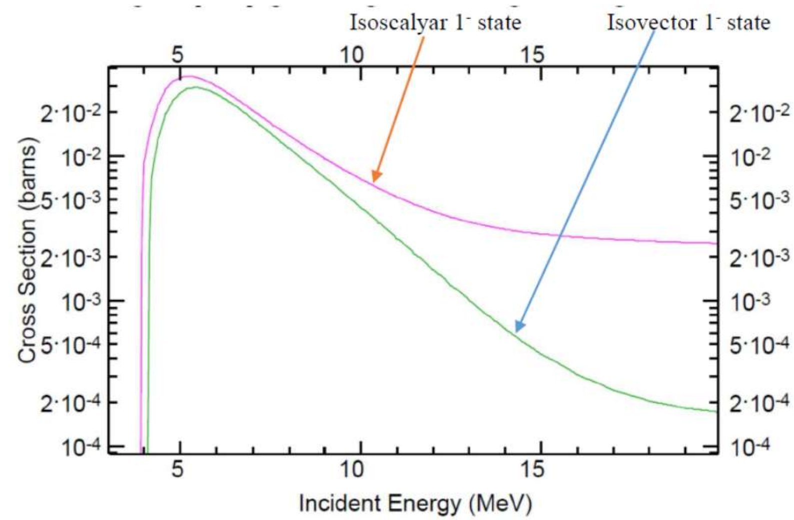


The bent in the inelastic cross section, can be explained by the following:

- **The excitation through the compound reaction mechanism of the IS and IV PDR state is strongly increased above the threshold not depending from the type.**
- **For higher energies the IS states have contribution of the direct reaction mechanism weakly dependent from energy and IV – exponential fall of compound mechanism**

Pecularities of (n,n’) reaction with partial registration of gamma-trasitions to the ground state





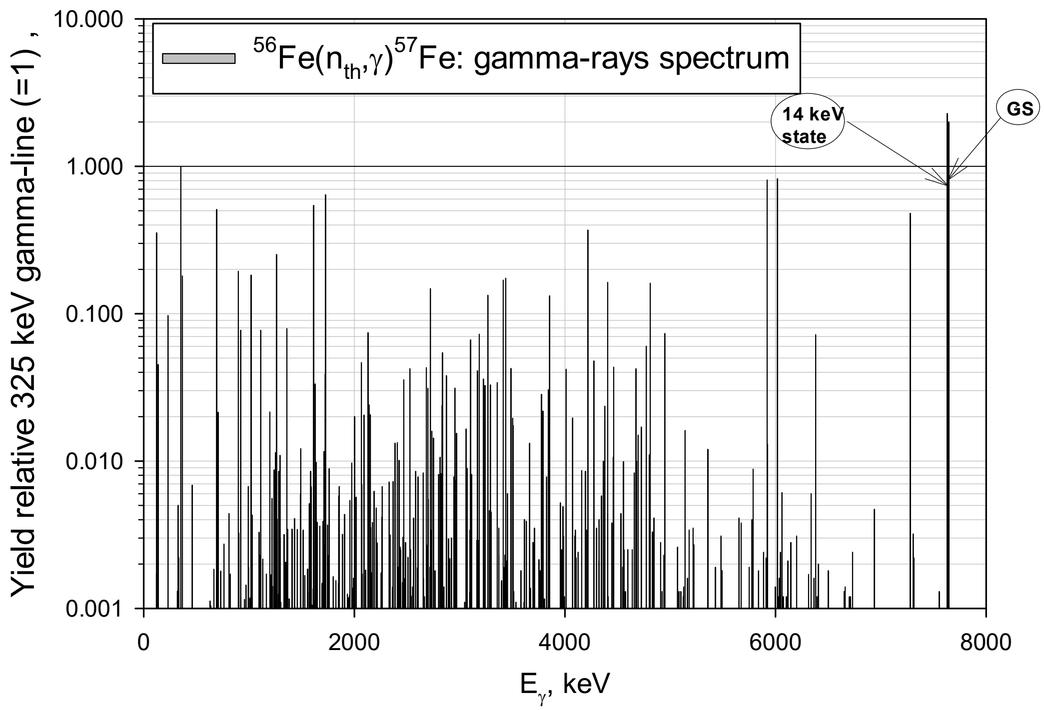
- **Due to missed gamma-transitions, (n,n’) cross section obtained by summation of gamma-transitions to the GS will be always below the real values.**
- **The bent is because with increase of the neutron energy, PDR transitions do not contribute in the sum, but with further increase their relative contribution is going smaller and smaller due to compound mechanism competition with excitation of higher levels**

Pecularities of (n,n’) reaction with partial registration of gamma-trasitions to the ground state: conclusion

The incompleteness of the results of inelastic cross section measurements with prompt gamma registration is mainly due to absence of registration of direct gamma transitions to the ground state from the region of neutron binding energy where PDR resonance is located.

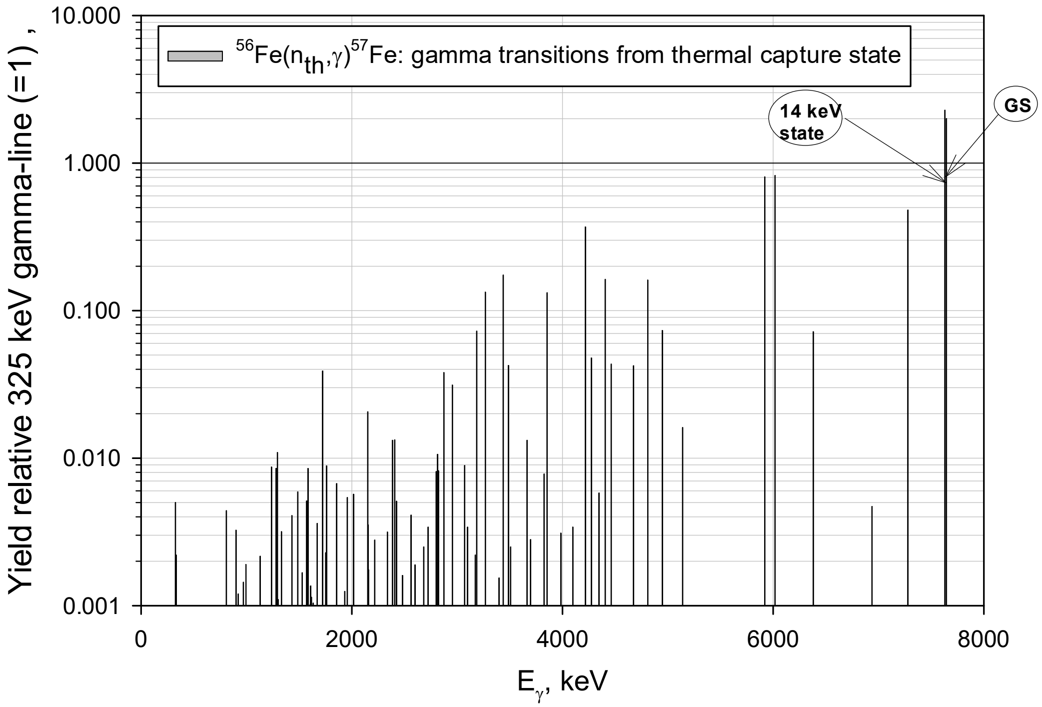
To improve the completeness, the gamma rays with energies above 4 MeV appearing in the gamma-spectrum should be measured.

PDR in neutron capture measurements



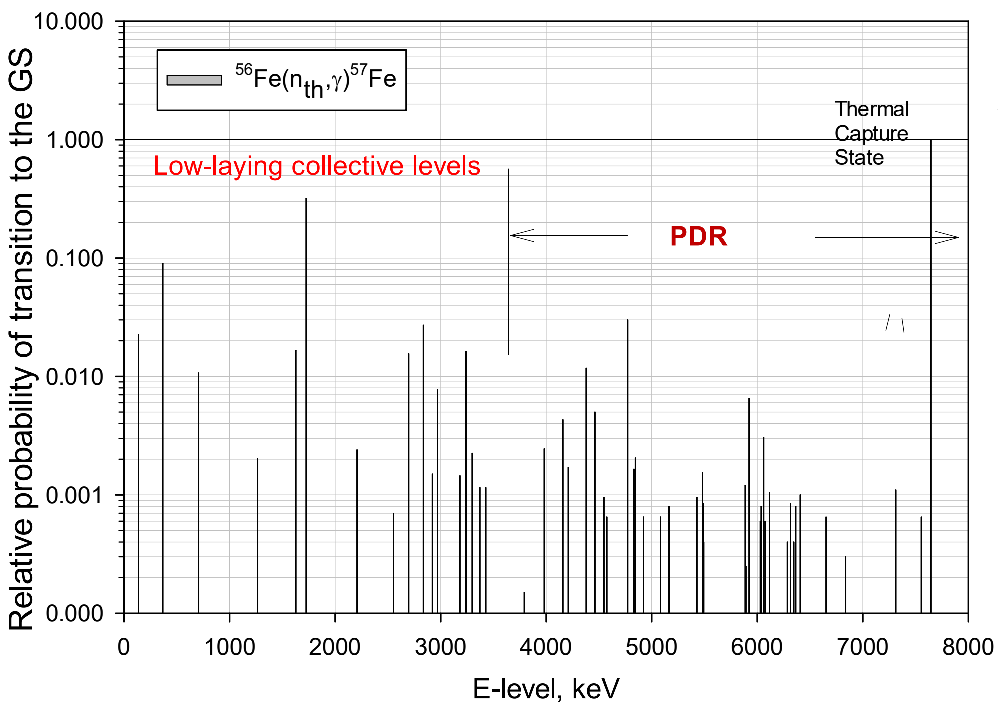
Novel measurements at cold beam of Budapest reactor (*R.B. Firestone et al., Thermal neutron capture cross section for $^{56}Fe(n,\gamma)$, PR/C,95,014328,2017*) were done with placing of 448 gamma-lines between 97 levels and thermal capture state.

PDR in neutron capture measurements



The gamma-ray strength of transition from thermal capture state of ^{57}Fe

PDR in neutron capture measurements



The gamma-ray strength for transitions to the ground state of ^{57}Fe

PDR in neutron capture: interpretation of experimental results (as hypothesis)

- Excited states of ^{57}Fe in a week coupling model can be presented as states of ^{56}Fe coupled with extra neutron with J^p=1/2$^-$.
- Low laying collective levels of one-phonon nature in ^{56}Fe with J^p=2+,3-,4+, … are known and this branch of collective excitations is below 4 MeV.
- The PDR states with high probability of the decay to the GS are at energy above 4 MeV.
- It is interesting to measure ^{53}Cr thermal capture gamma-rays at unique cold neutron beam. Thermal capture at ^{53}Cr is at order of magnitude higher than at ^{56}Fe. ^{54}Cr has much lower level density than ^{57}Fe. These two factors will allow to place more observed gamma-transitions in the decay scheme. The neutron capture state is at the 9719 keV excitation energy. This allows to see if the PDR states are extended up to 10 MeV.