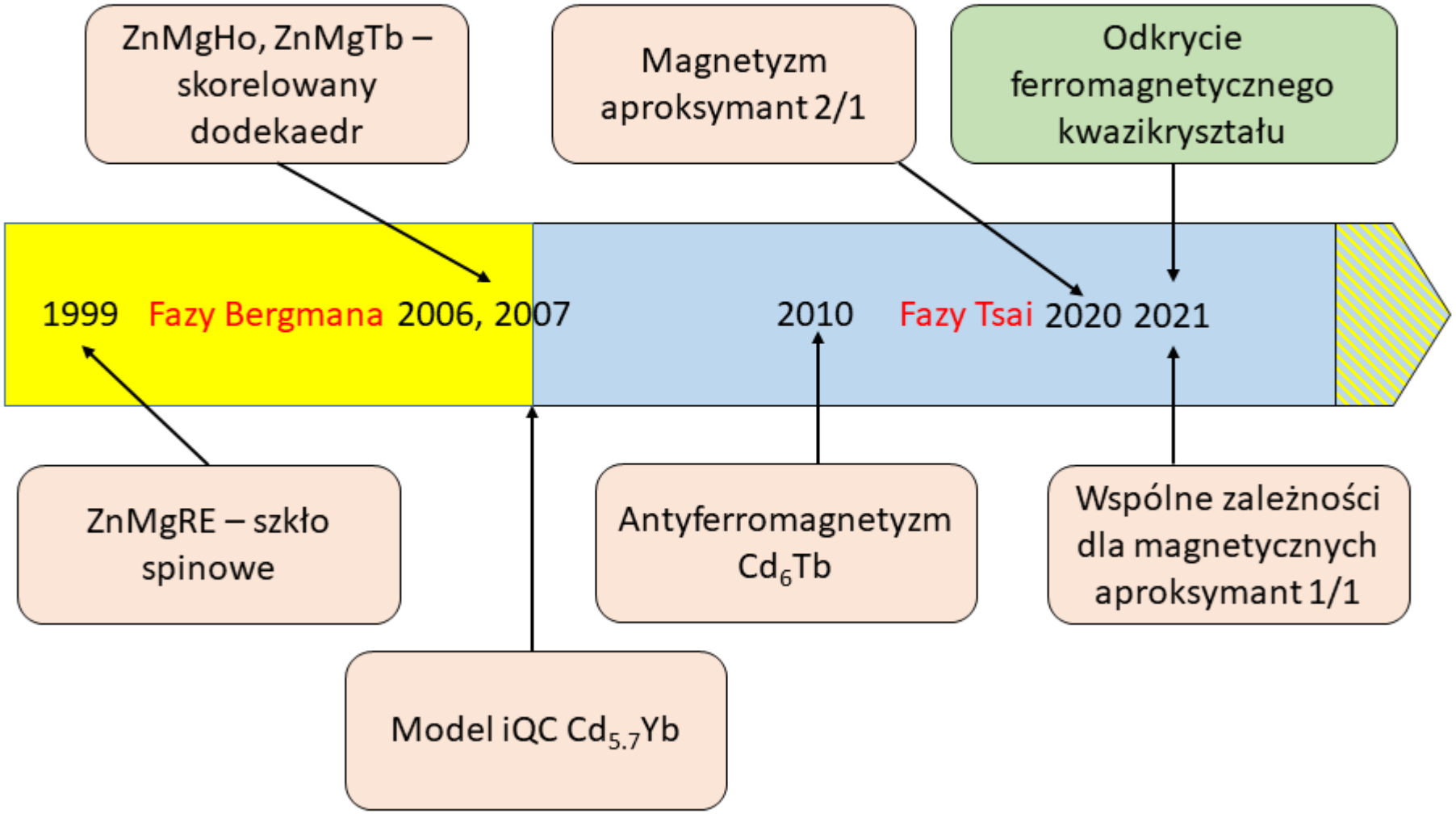
Oddziaływania magnetyczne w kwazikryształach

Dr inż. Ireneusz Bugański
Katedra Fizyki Materii Skondensowanej

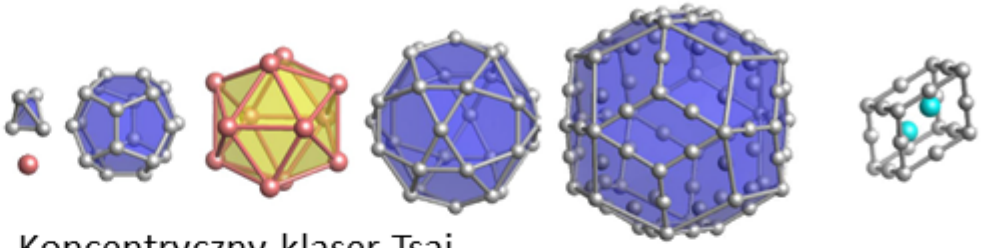
Kraków, 10.11.2023


ZnMgHo, ZnMgTb – skorelowany dodekaedr
Magnetyzm aproksymant 2/1
Odkrycie ferromagnetycznego kwazikryształu
1999
Fazy Bergmana
2006, 2007
2010
Fazy Tsai
2020
2021
ZnMgRE – szkło spinowe
Antyferromagnetyzm Cd_6Tb
Wspólne zależności dla magnetycznych aproksymant 1/1
Model iQC $Cd_{5.7}Yb$

Kwazikryształy ikozaedryczne typu Tsai

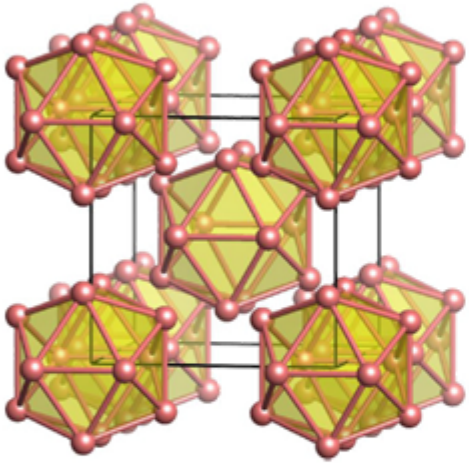
Kwazikryształy ikozaedryczne:

- Tsai
- Bergman
- Mackay

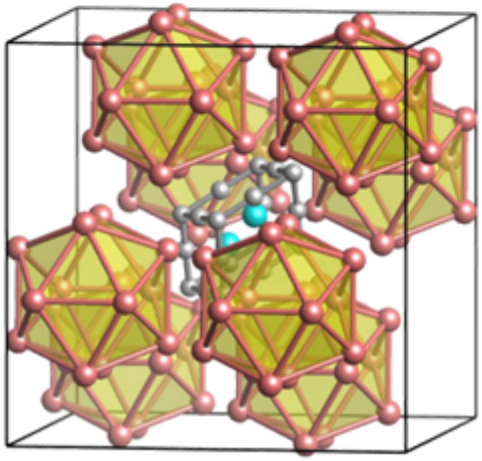


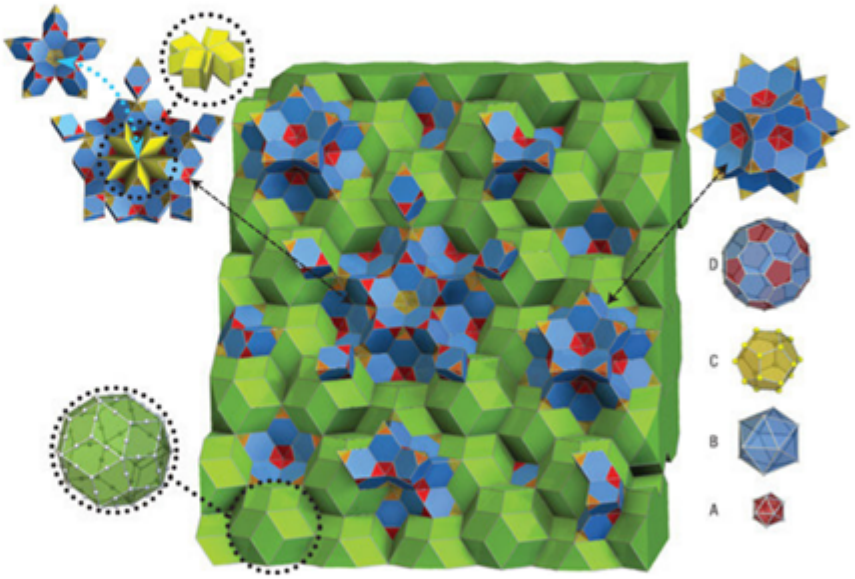
Koncentryczny klaser Tsai

Aproksymanta 1/1



Aproksymanta 2/1





[8] H. Takakura *et al.*, (2007) Nature Mat. **6**, 58-63 $i - Cd_{5.7}Yb$

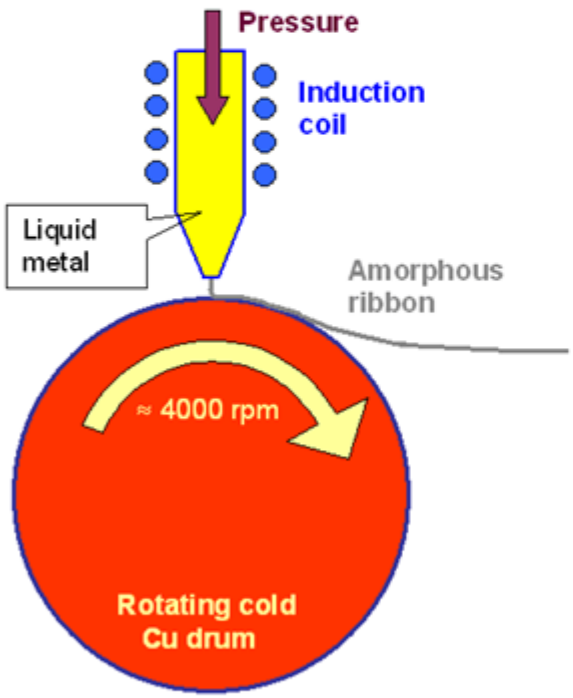
$$\tau = 1.618\ldots \approx \frac{1}{1}, \frac{2}{1}, \frac{3}{2}, \frac{5}{3}, \ldots$$

Główne stopy:

- ZnSc, Zn-T-Sc (T=Mn, Co, Fe, Ni)
- CdRE, Cd-Mg-RE (RE- rare earth)
- Ag-In-RE
- Au-Ga-RE

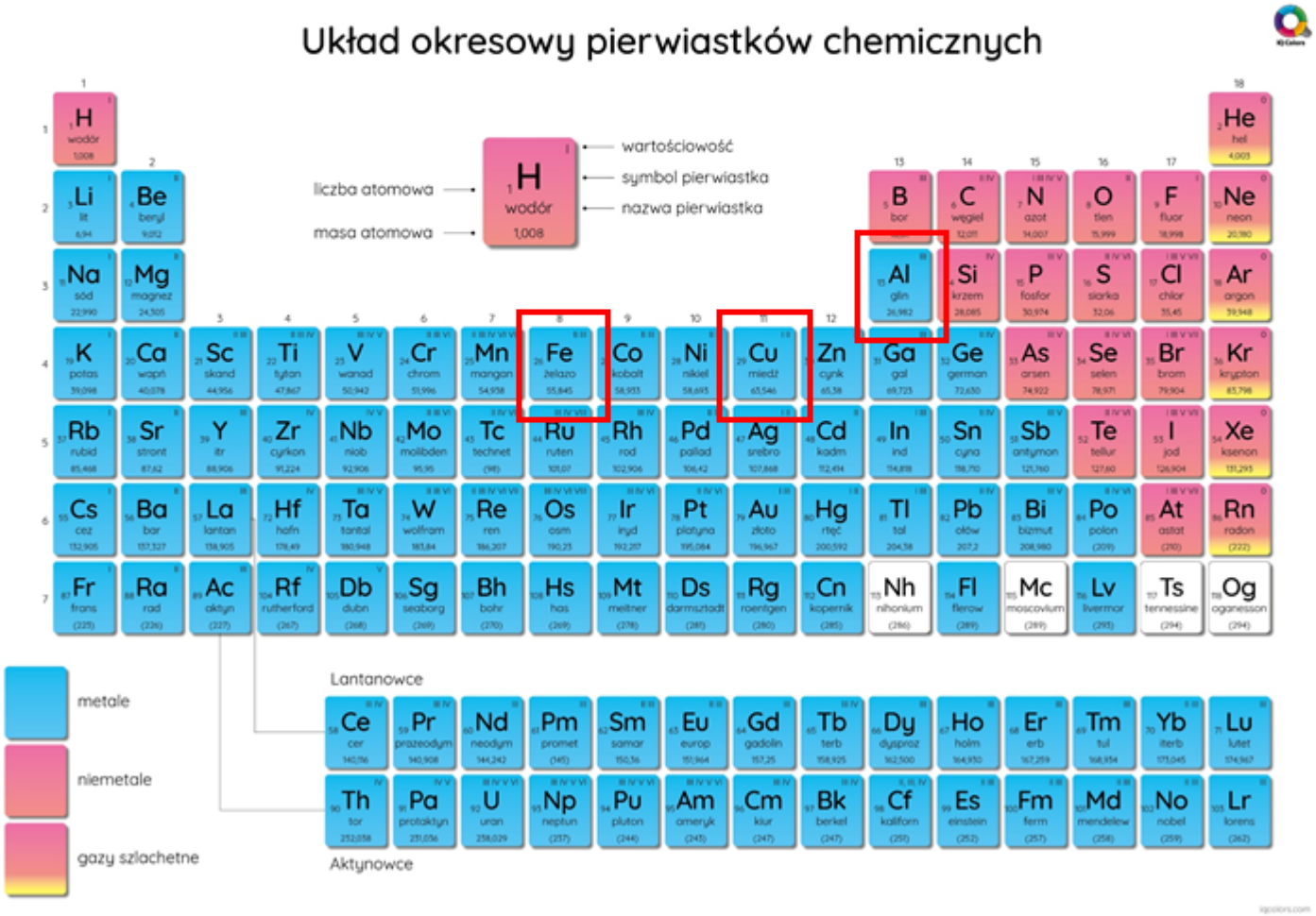
Badana próbka

- Badania nad AuGa(Gd, Tb)
- Ostateczny skład: $Au_{65}Ga_{20}Gd_{15}$, $Au_{65}Ga_{20}Tb_{15}$
- Stop przygotowano przy użyciu metody *melt spinning*,
- Badano skład w okolicach $e/a = 1.70$ (średnia liczba elektronów na atom),

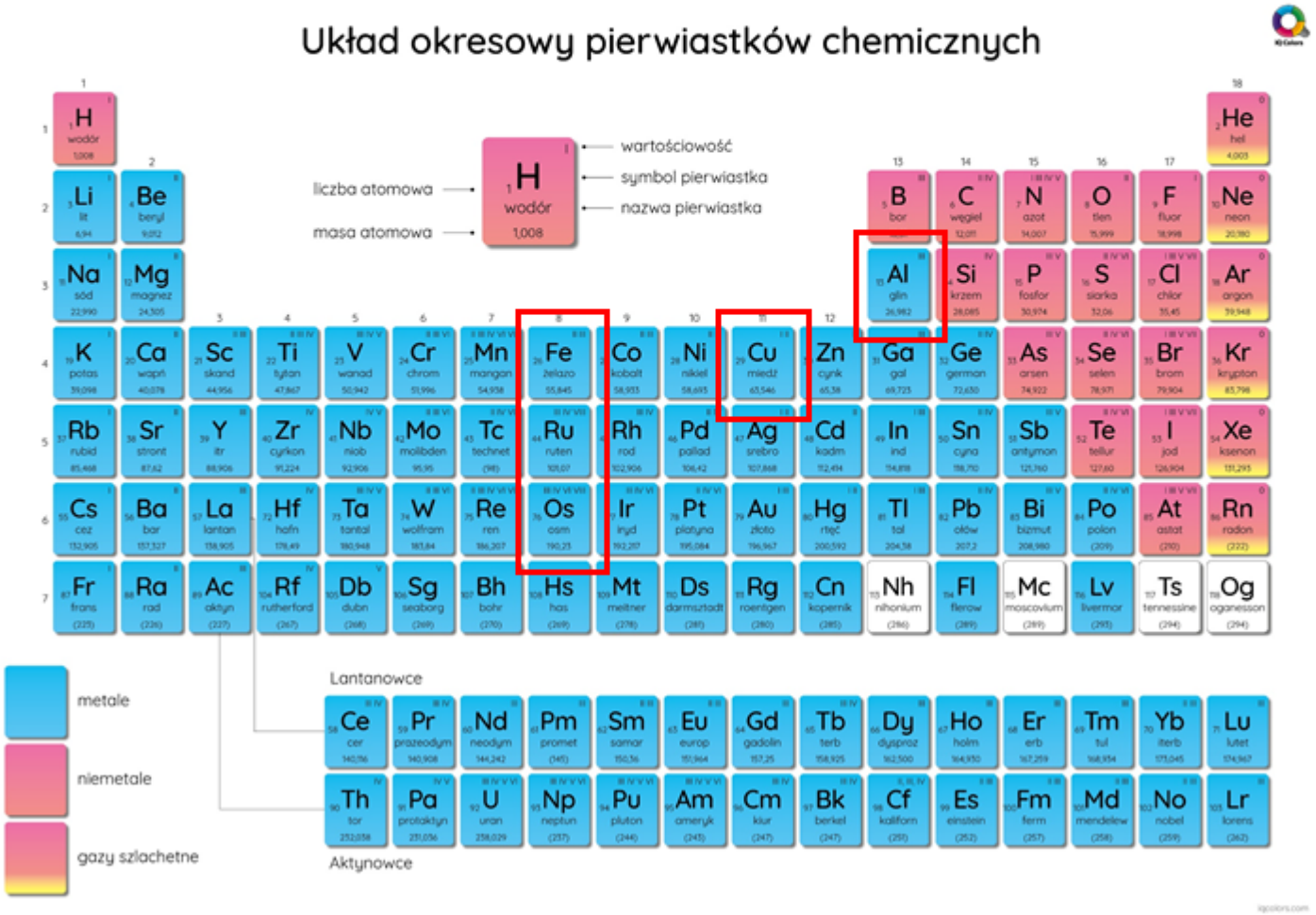


Idea metody *melt-spinning*

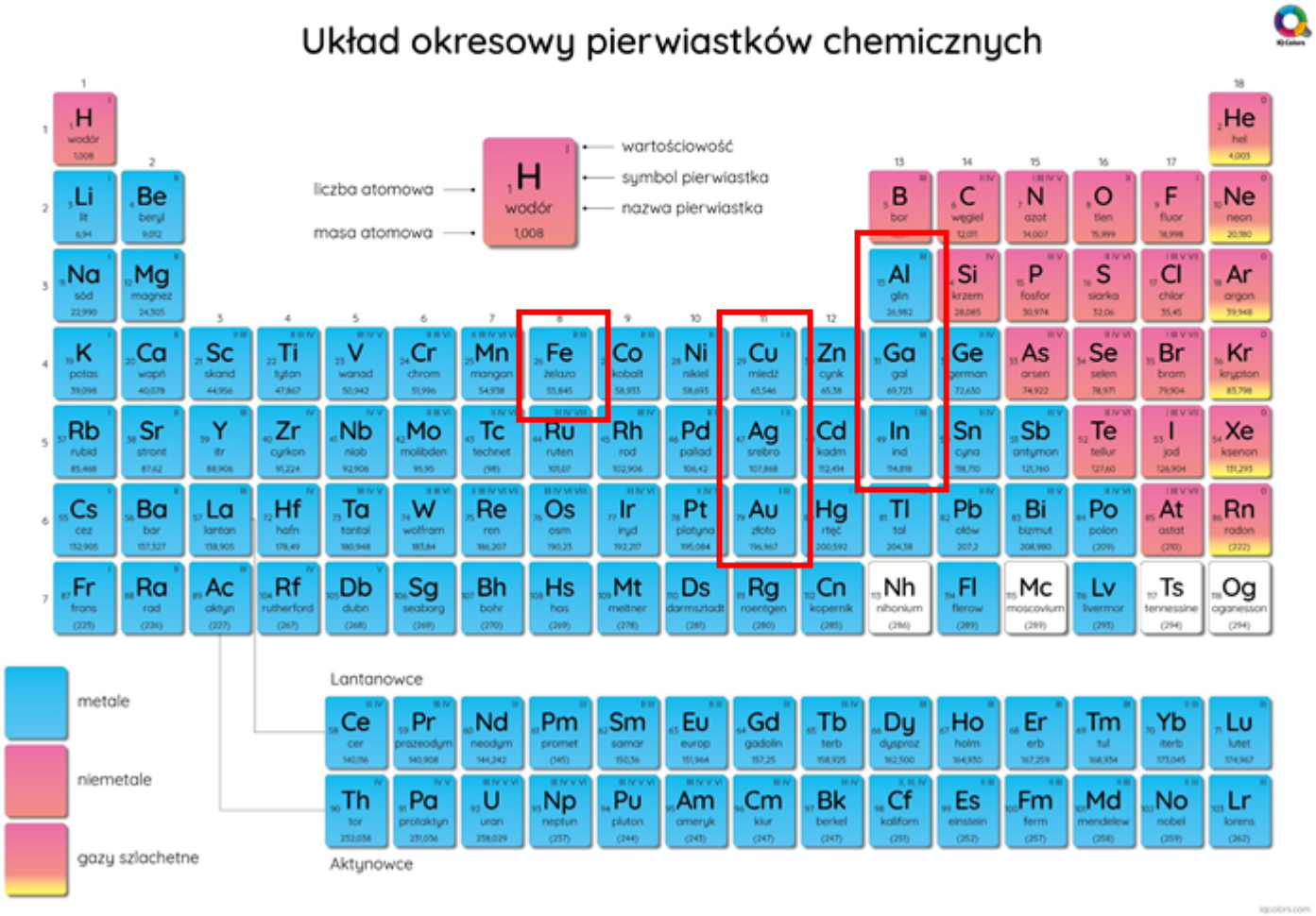
Dlaczego taki układ?



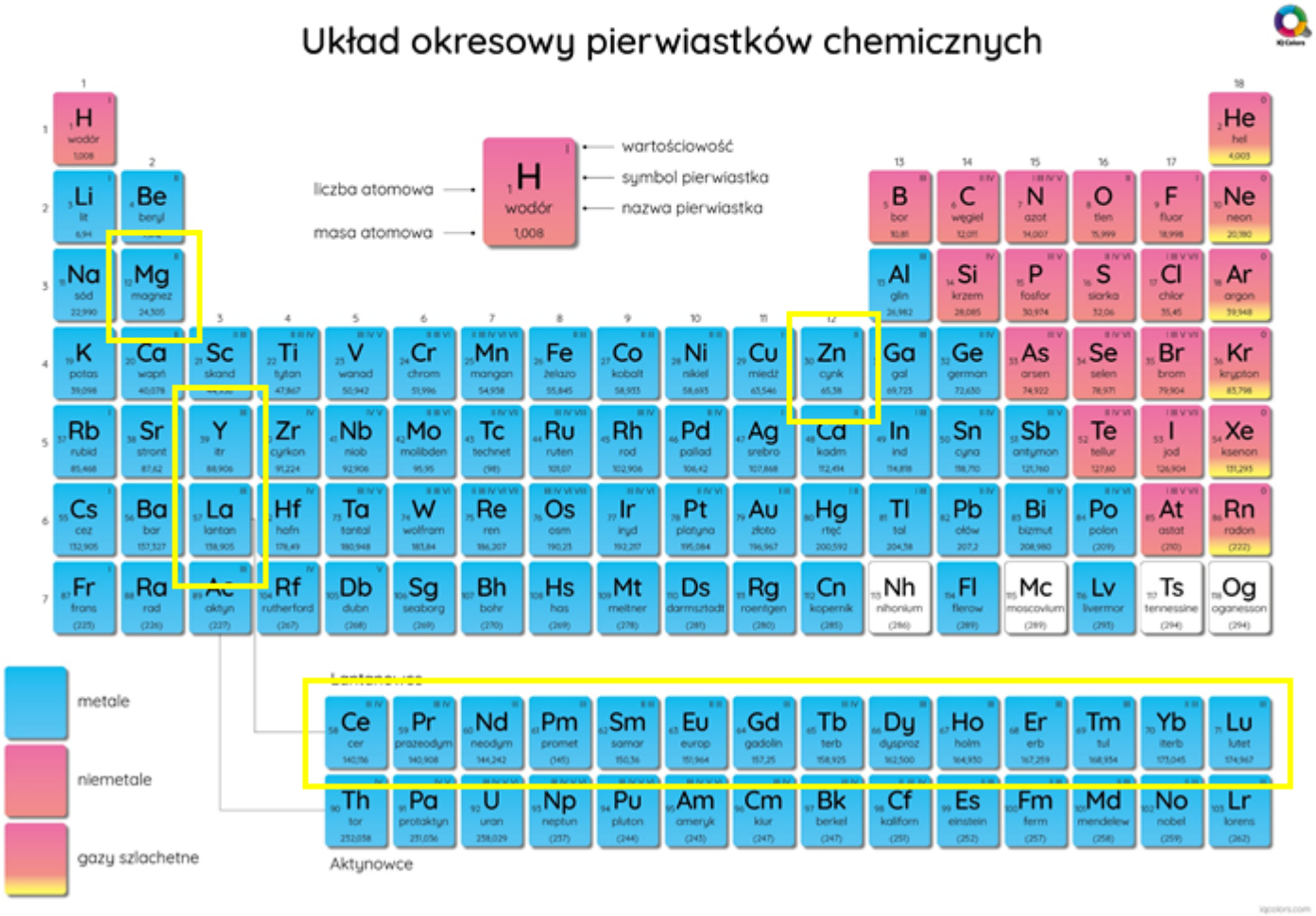
Dlaczego taki układ?



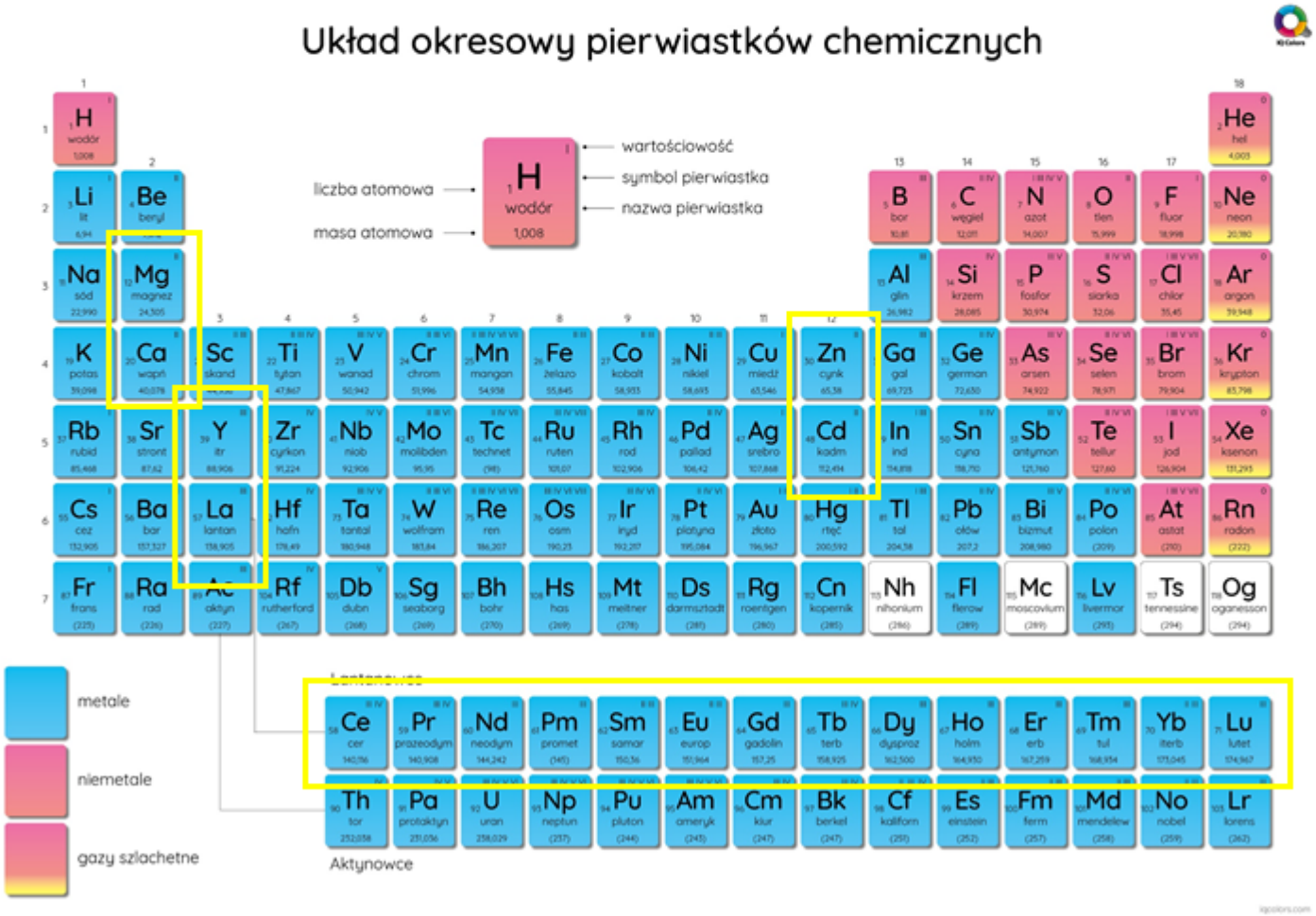
Dlaczego taki układ?



Dlaczego taki układ?



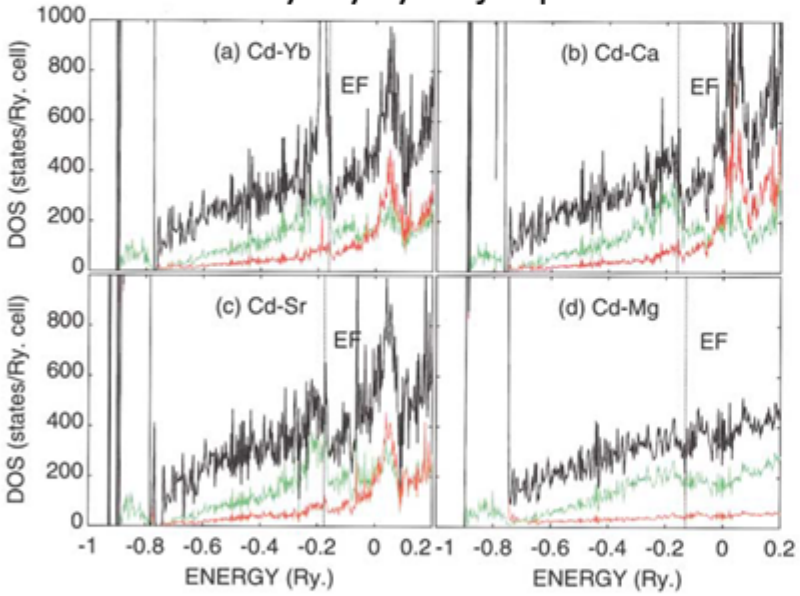
Dlaczego taki układ?



Stabilizacja Hume-Rothery

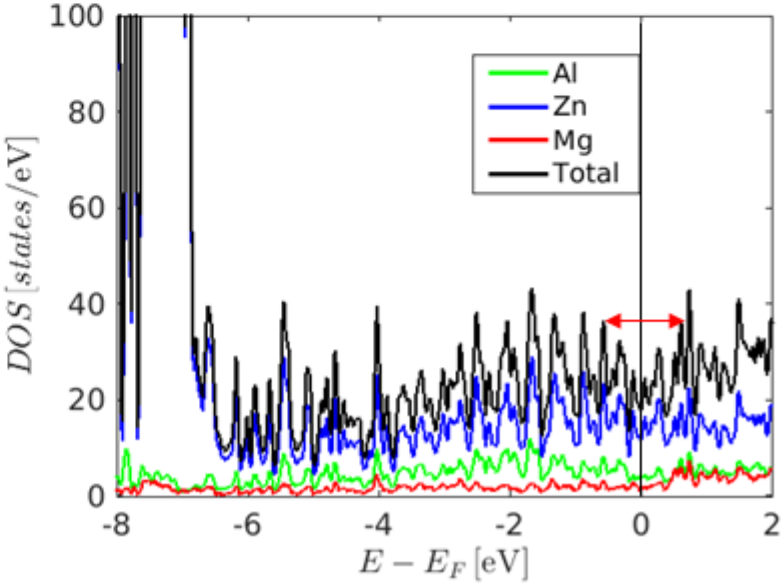
- Stabilizacja Hume-Rothery: Formowanie się pseudoprzerwy w okolicy energii Fermiego – kwazikryształy stabilne tylko dla określonych długości wektora Fermiego (określonej koncentracji elektronów swobodnych)
- Podstawienie pierwiastkiem o tej samej liczbie elektronów walencyjnych

Hybrydyzacja sp-d



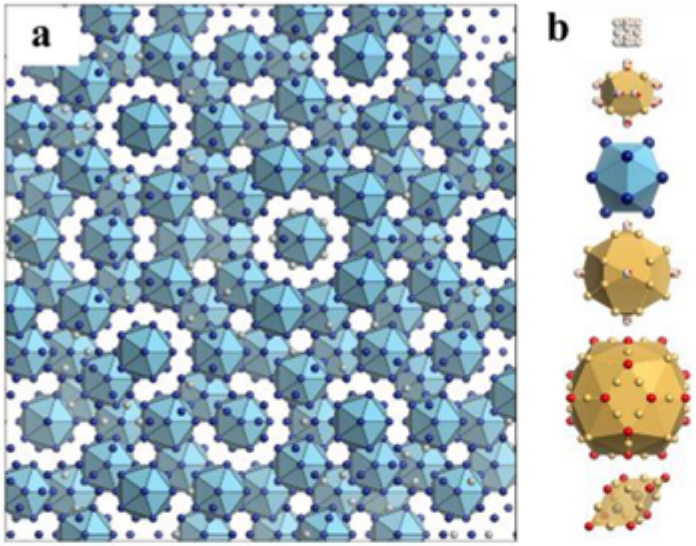
Y. Ishii, T. Fujjiwara, Phys. Rev. Lett. 87 (2001), 206408

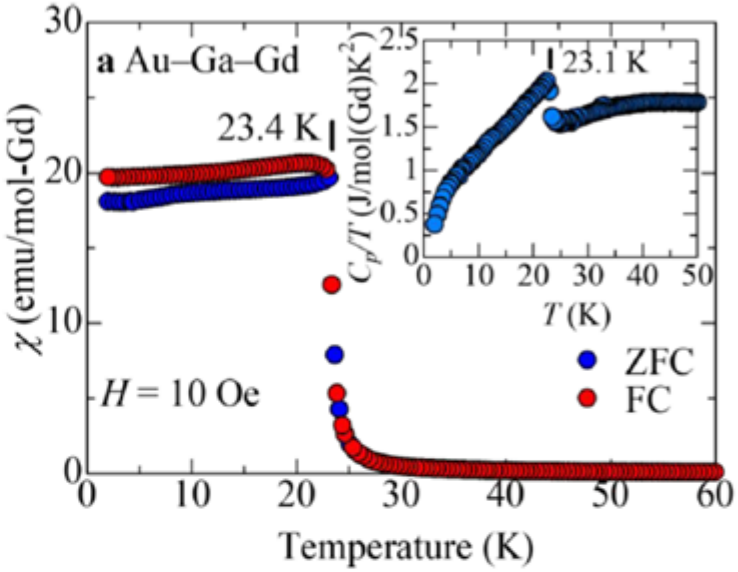
Dla AlCuLi czy ZnMgY nie zauważono relacji między brakiem pseudoprzerwy a usunięciem ze struktury pierwiastków z orbitalami d.

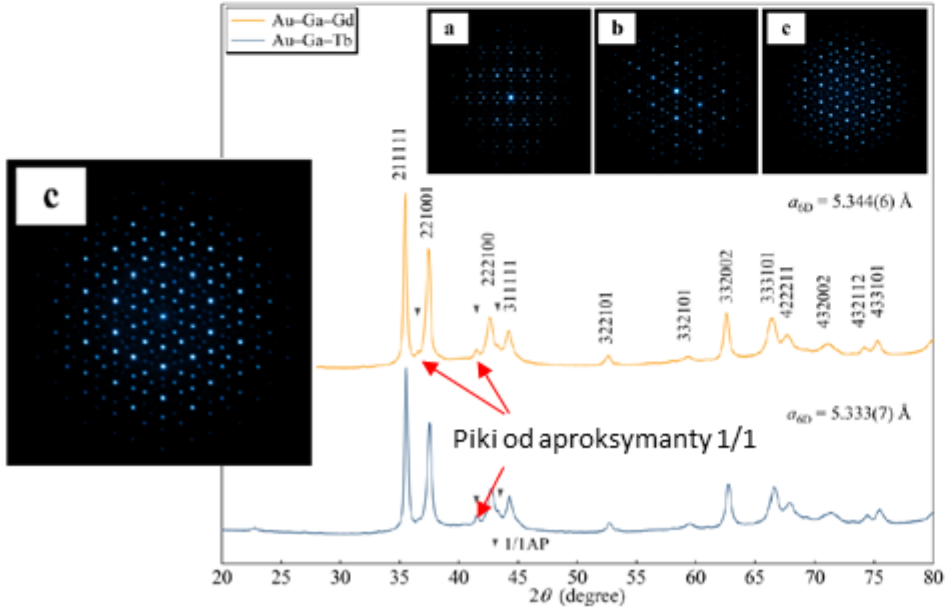


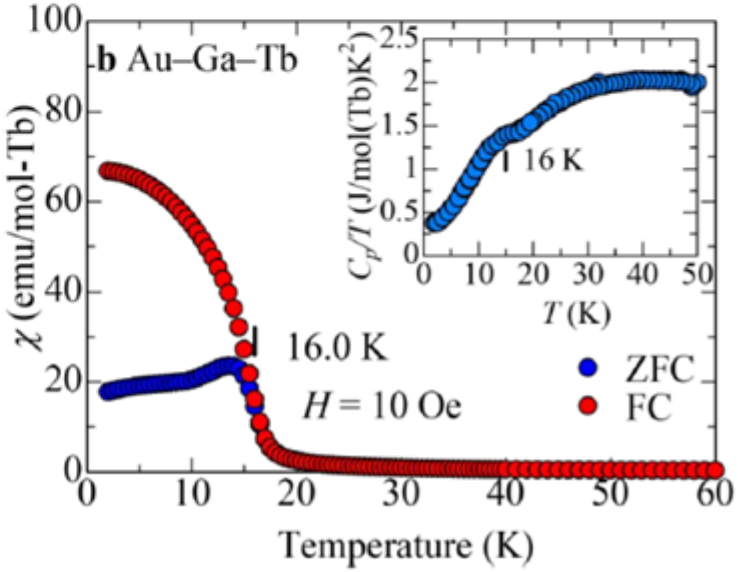
$Au_{65}Ga_{20}(Gd, Tb)_{15}$

Struktura atomowa (tylko Gd, Tb). Niebieski – atomy na ikozaedrze (85%), srebrny – w romboedrze





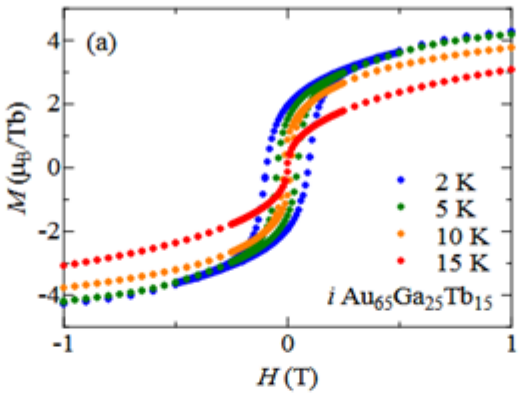


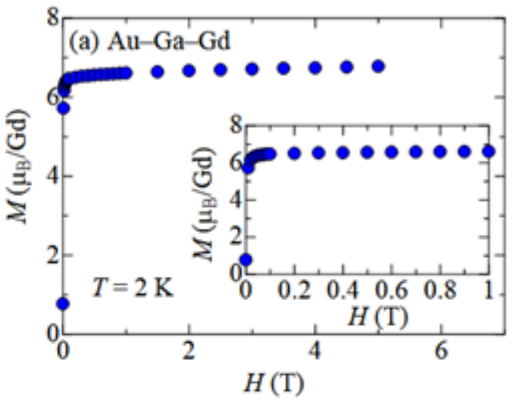


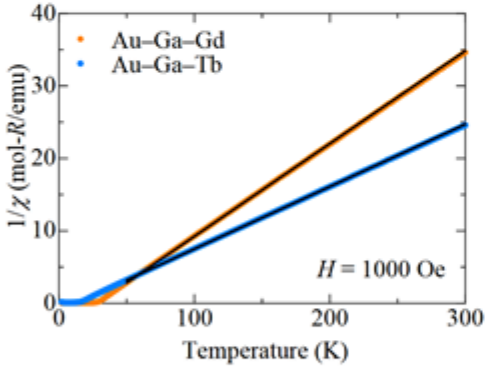
R. Tamura, et al. J. Am. Chem. Soc. 143 (2021), 19938

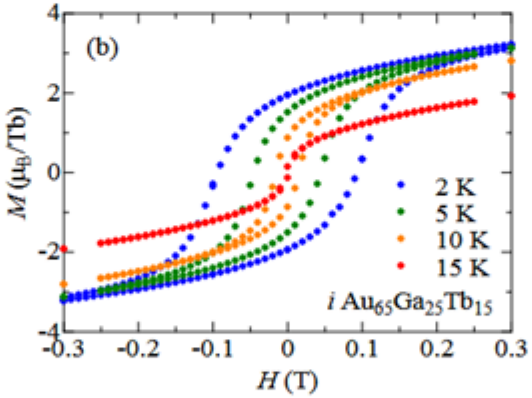
$Au_{65}Ga_{20}(Gd, Tb)_{15}$ – pomiary magnetyczne

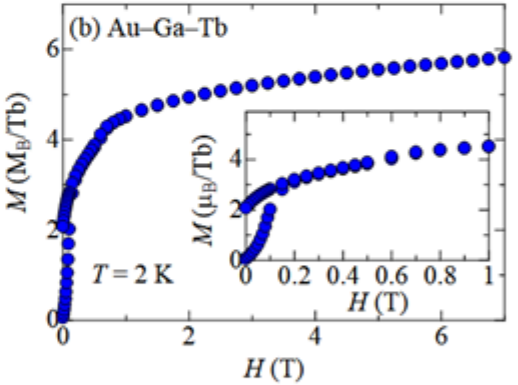
Histereza M-H – Remanencja i pole koercji maleją wraz ze wzrostem temperatury do temperatury krytycznej











$$\chi = \frac{N_A \mu_{eff}^2}{3k_B(T-\theta)}$$

Gd - $\mu_{eff} = 7.90\mu_B$ (teoretyczna wartość dla RE^{3+} - $7.94\mu_B$)
Tb - $\mu_{eff} = 9.64\mu_B$ (teoretyczna wartość dla RE^{3+} - $9.72\mu_B$)
Temperatura Weisse'a: $\theta_{Gd} = 27.9\,\mathrm{K}, \theta_{Tb} = 12.9\,\mathrm{K}$

Dla Gd M szybko osiąga stan nasycenia w okolicach $7\mu_B/Gd^{3+}$ - oznaka słabej anizotropii magnetycznej. Gla Tb M osiąga ok. $6\mu_B/Tb^{3+}$ (ok. 2/3 momentu swobodnego jonu) – wpływ anizotropii jednoosiowej.

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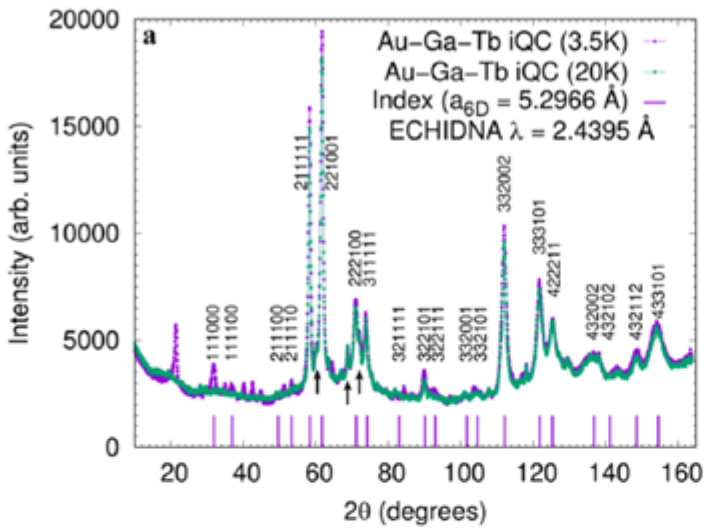
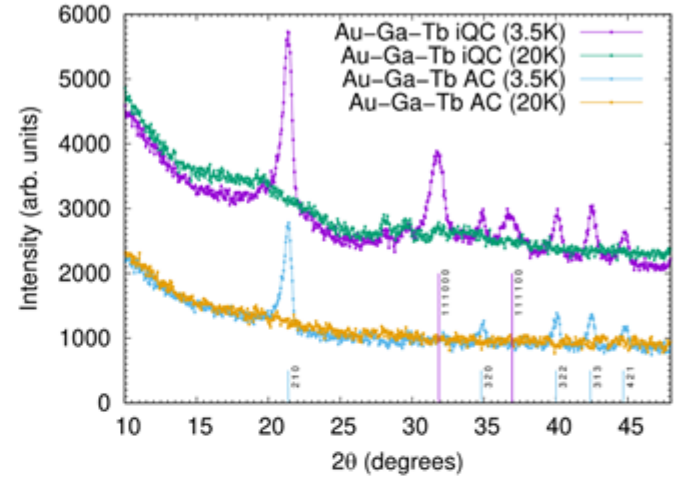
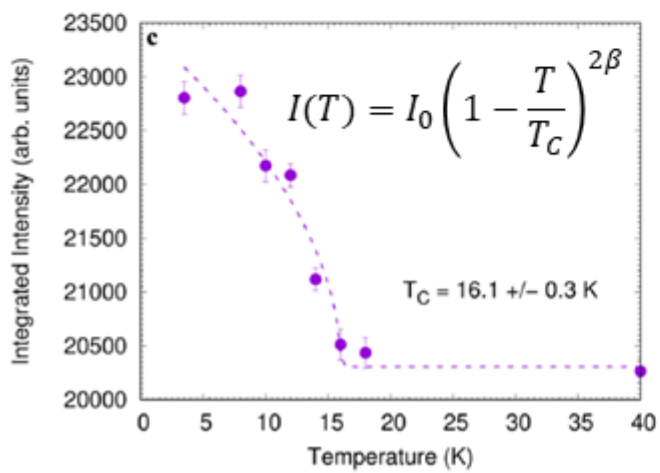
$Au_{65}Ga_{20}(Gd, Tb)_{15}$ – dyfrakcja neutronów





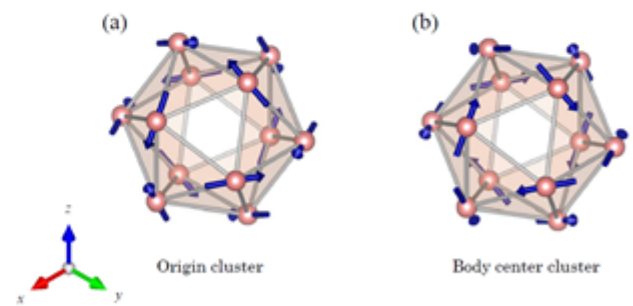
Poniżej temperatury krytycznej pojawiają się nowe piki struktury magnetycznej lub wzmacniające piki w temperaturze struktury paramagnetycznej (np. 211111).

Niektóre piki pochodzą od aproksymanty 1/1. Występuje tam uporządkowanie antyferromagnetyczne.



R. Tamura, et al. J. Am. Chem. Soc. 143 (2021), 19938

Wyznaczona wartość T_C na podstawie dopasowania empirycznej funkcji $I(T)$ do scałkowanego natężenia piku 111000 wynosi 16.1 K.



Klastry atomowe z orientacją spinów uporządkowanych antyferromagnetycznie (AuAlTb)

T.J. Sato, et al. Phys. Rev. B 100 (2019) 054417.

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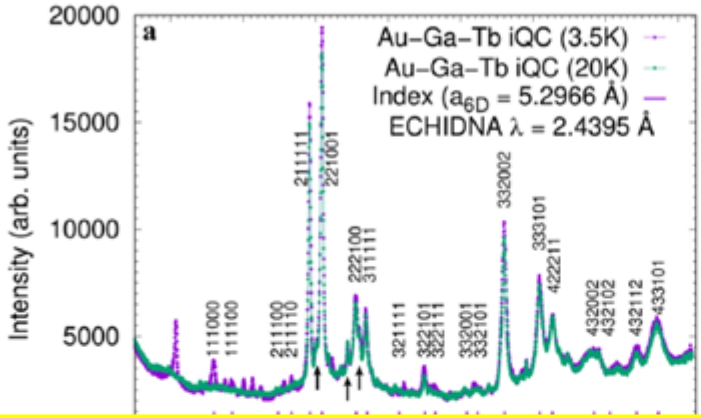

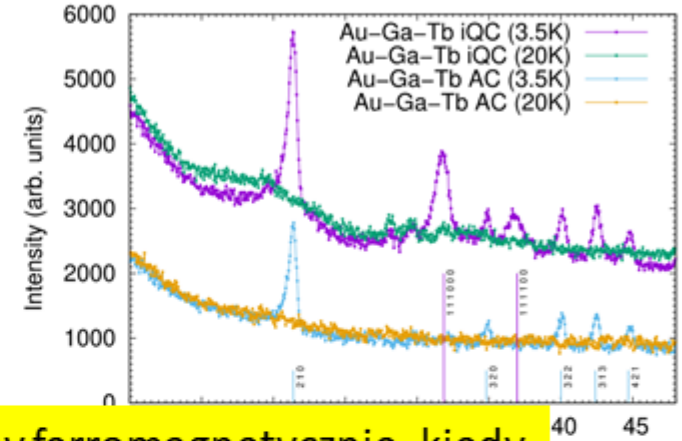

Dlaczego kwazikryształ AuGaTb jest uporządkowany ferromagnetycznie, kiedy aproksymanta jest antyferromagnetykiem?

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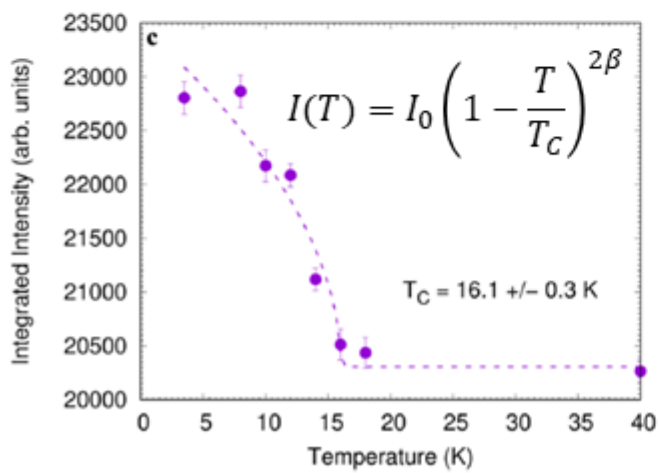

R. Tamura, et al. J. Am. Chem. Soc. 143 (2021), 19938

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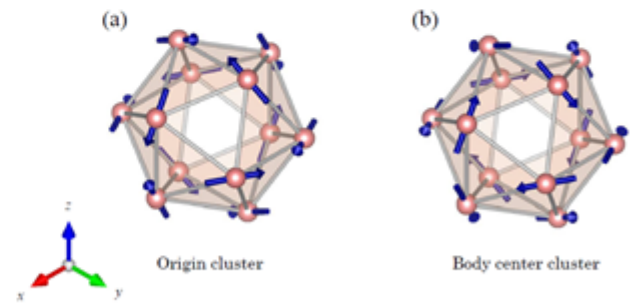
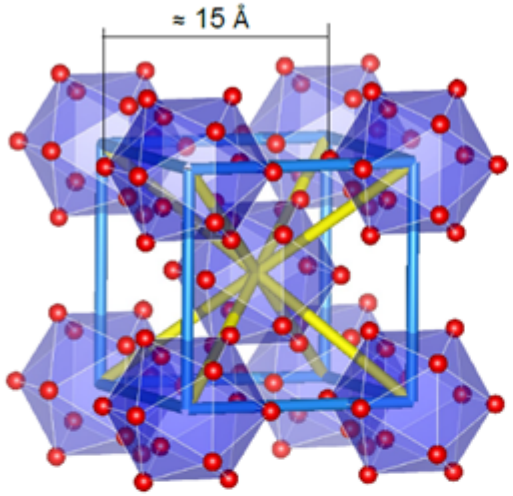


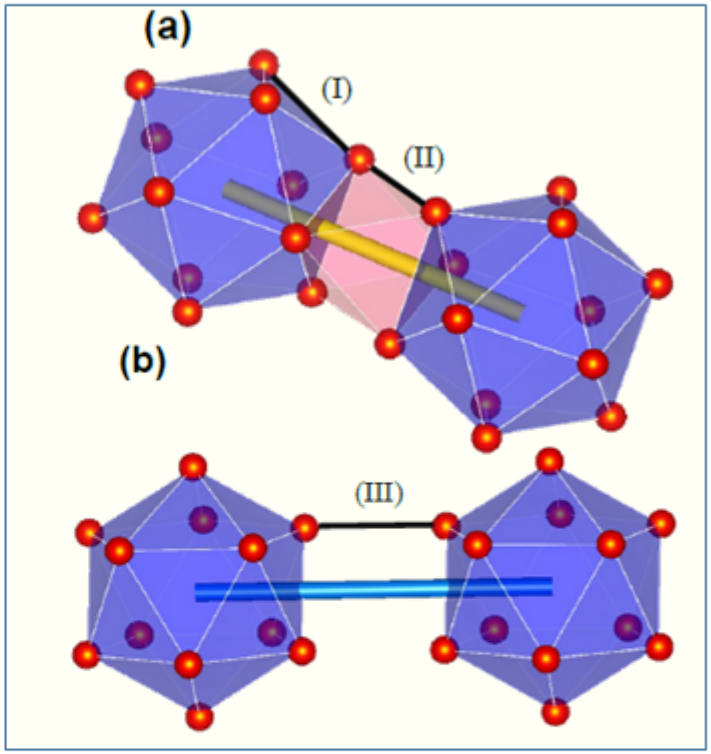
Klastry atomowe z orientacją spinów uporządkowanych antyferromagnetycznie (AuAlTb)

T.J. Sato, et al. Phys. Rev. B 100 (2019) 054417.

Lokalne uporządkowanie RE

1/1





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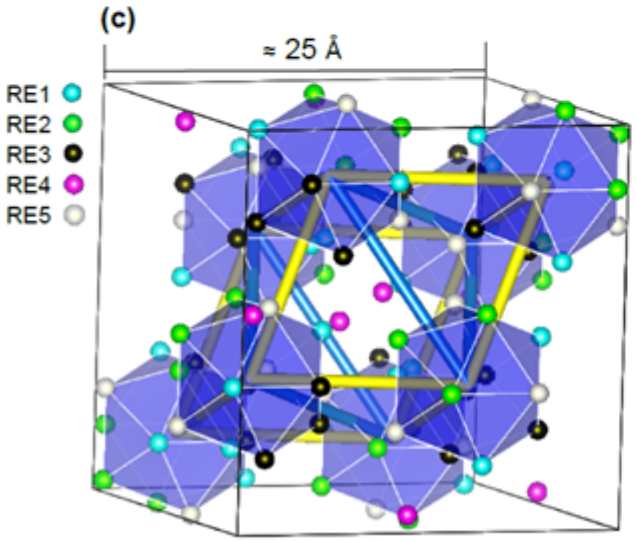
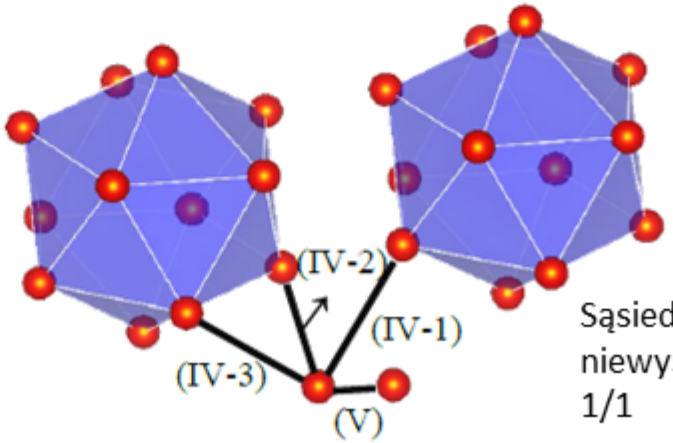


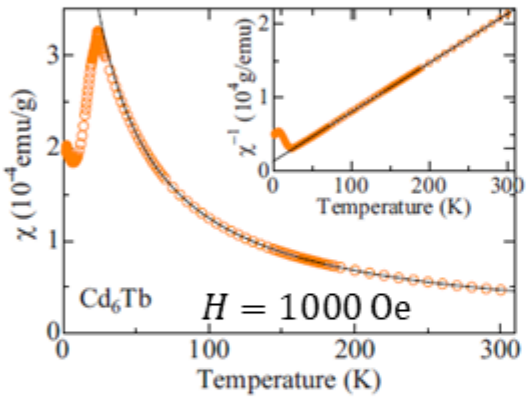


Sąsiedztwo atomów ziem rzadkich niewystępujące w aproksymancie 1/1

F. Labib, et al. J. Phys.: Condens. Matter 32 (2020), 415801

Pierwsza magnetyczna aproksymanta

- Bogata rodzina faz Cd_6(Ca, Sr, Y, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu)
- Komórka przestrzennie centrowana $I\bar{3}m$
- Brak nieporządku chemicznego
- Próbka Cd-Tb wygrzewana przez 100h w 770 K.

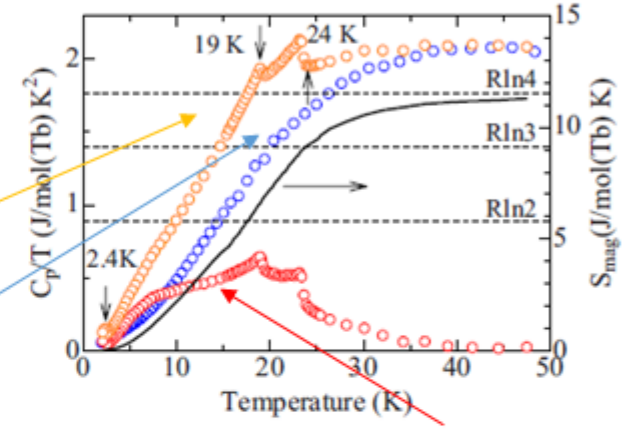


$$\chi = \frac{N_A \mu_{eff}^2}{3k_B(T-\theta)}$$

$$\mu_{eff} = 9.8\mu_B,\ \theta = -17\ \mathrm{K}$$

CdTb

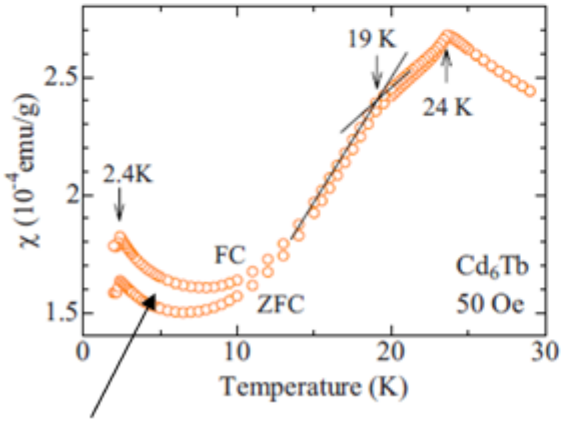
CdYb



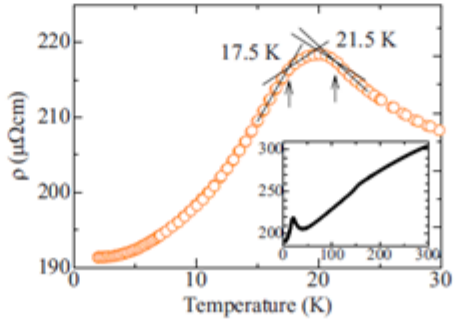
CdTb (wkład od magnetyzmu)

Entropia magnetyczna $S = R\ln(2J+1) = R\ln(13)$ - w rzeczywistości zbieżność do $R\ln(4)$ - 4 zdegenerowane singlety poprzez pole krystaliczne

Niezerowa entropia magnetyczna powyżej $T_N = 24$ K– krótkozasięgowe uporządkowanie magnetyczne



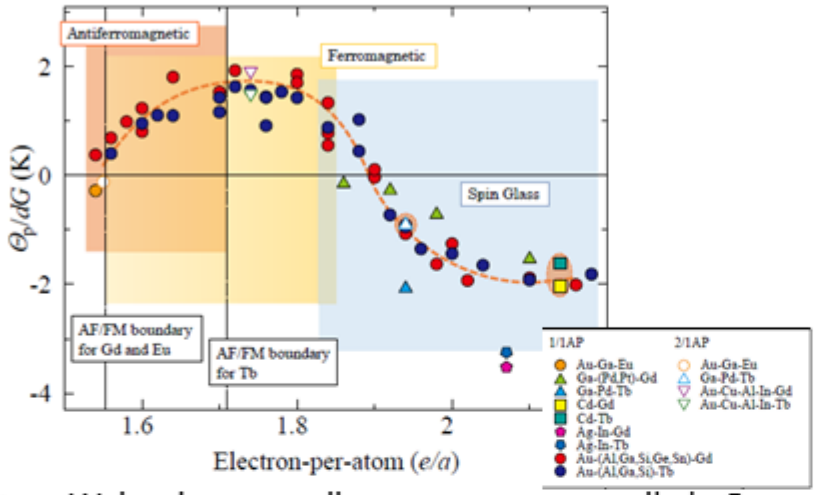
Histereza między FC i ZFC (najprawdopodobniej wpływ pola krystalicznego)



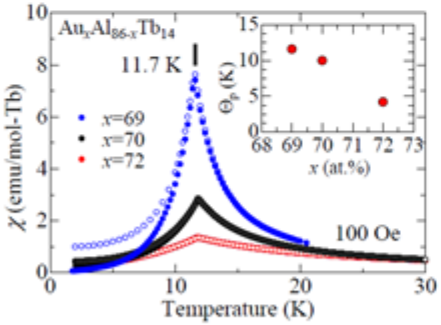
Opór właściwy w funkcji temperatury

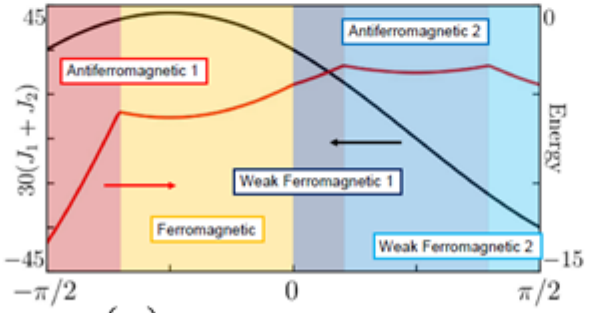
R. Tamura, et al. Phys. Rev. B82, (2010), 220201

Magnetyzm Aproksymant 1/1



- Temperatura Weisse'a znormalizowana przez czynnik de Gennes jest funkcją koncentracji elektronów walencyjnych
- Obszary Antyferromagnetyczny/Ferromagnetyczny/Szkło Spinowe zależą od anizotropii jednoosiowej



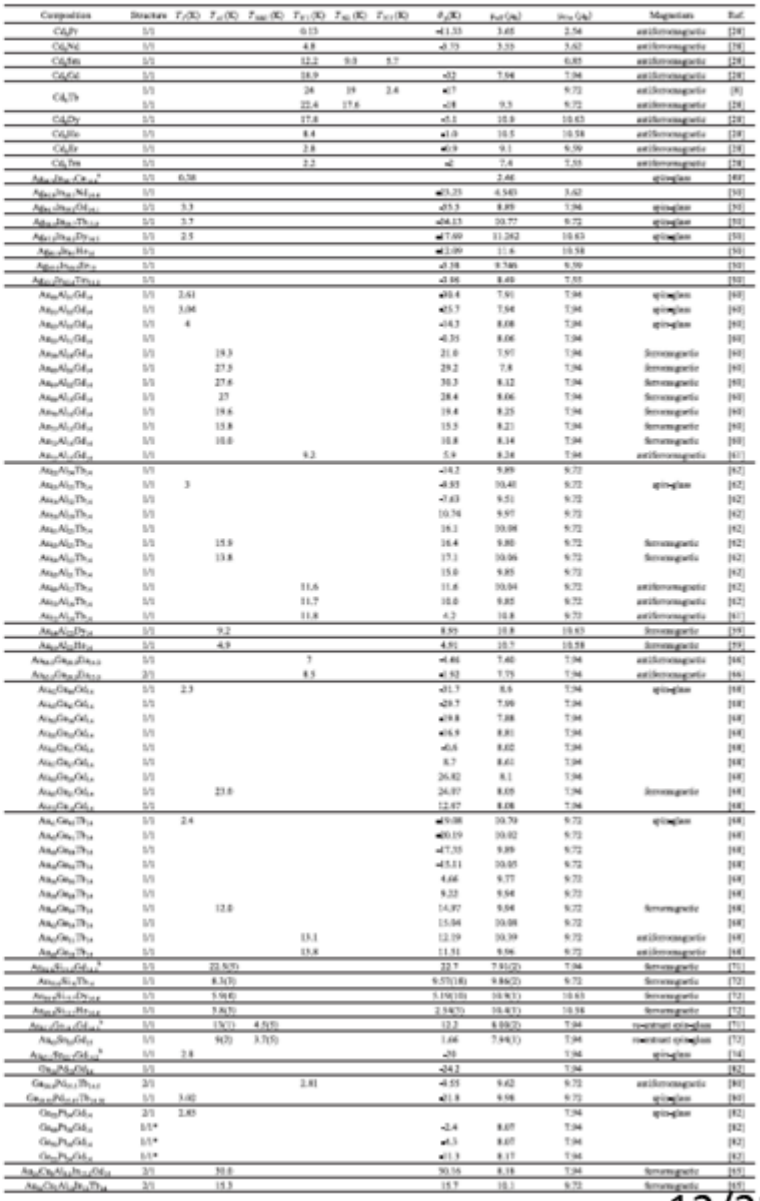


$$J_1 = \cos(\alpha_J)$$
$$J_2 = \sin(\alpha_J)$$

$$\mathcal{H} = -J_1 \sum_{\langle i,j \rangle_1} \boldsymbol{S}_i \cdot \boldsymbol{S}_j - J_2 \sum_{\langle i,j \rangle_2} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

Dla rosnącej koncentracji Au temperatura Weisse'a maleje (podatność maleje) – wzrost udziału oddziaływań antyferromagnetycznych (w obszarze antyferromagnetycznym)

Stabilizacja antyferromagnetyczna w obszarze dodatniej temperatury Weisse'a



Composition	Structure	T_c(K)	T_N(K)	T_{SG}(K)	T_{N1}(K)	T_{N2}(K)	T_{N3}(K)	θ_p(K)	μ_{eff}(μ_B)	μ_{sat}(μ_B)	Magnetism	Ref.
CdA_1Dy	1/1				0.13			-11.33	3.65	2.54	antiferromagnetic	[28]
Cd_1NdC	1/1				4.8			-0.75	3.55	3.62	antiferromagnetic	[28]
Cd_1Sm	1/1				12.2	9.0	5.7			0.85	antiferromagnetic	[28]
Cd_1Gd	1/1				18.9			-12	7.94	7.94	antiferromagnetic	[28]
Cd_1Tb	1/1				24	19	2.4	-17		9.72	antiferromagnetic	[8]
	1/1				22.4	17.6		-18	9.5	9.72	antiferromagnetic	[28]
Cd_1Dy	1/1				17.8			-5.1	10.8	10.63	antiferromagnetic	[28]
Cd_1Ho	1/1				8.4			-1.0	10.5	10.58	antiferromagnetic	[28]
Cd_1Er	1/1				2.8			-0.9	9.1	9.59	antiferromagnetic	[28]
Cd_1Tm	1/1				2.2			-2	7.4	7.55	antiferromagnetic	[28]
$Au_{64.5}Dy_{18.5}Cu_{16.5}$*	1/1	0.38							2.48		spinglass	[40]
$Au_{63.5}Dy_{18.5}Ni_{17.5}$	1/1							-15.25	4.540	3.62		[50]
$Au_{63.5}Dy_{18.5}Gd_{17.5}$	1/1	5.3						-15.3	8.89	7.94	spinglass	[50]
$Au_{63.5}Dy_{18.5}Tb_{17.5}$	1/1	3.7						-14.13	10.77	9.72	spinglass	[50]
$Au_{63.5}Dy_{18.5}Dy_{17.5}$	1/1	2.5						-17.69	11.282	10.63	spinglass	[50]
$Au_{63.5}Dy_{18.5}Ho_{17.5}$	1/1							-12.09	11.6	10.58		[50]
$Au_{63.5}Dy_{18.5}Er_{17.5}$	1/1							-5.38	9.546	9.59		[50]
$Au_{63.5}Dy_{18.5}Tm_{17.5}$	1/1							-3.86	8.49	7.55		[50]
$Au_{56}Al_{32}Gd_{12}$	1/1	2.61						-10.4	7.91	7.94	spinglass	[40]
$Au_{57}Al_{31}Gd_{12}$	1/1	3.04						-15.7	7.94	7.94	spinglass	[40]
$Au_{58}Al_{30}Gd_{12}$	1/1	4						-14.3	8.08	7.94	spinglass	[40]
$Au_{59}Al_{29}Gd_{12}$	1/1							-8.35	8.06	7.94		[40]
$Au_{60}Al_{28}Gd_{12}$	1/1		19.3					21.0	7.97	7.94	ferromagnetic	[40]
$Au_{61}Al_{27}Gd_{12}$	1/1		27.3					29.2	7.8	7.94	ferromagnetic	[40]
$Au_{62}Al_{26}Gd_{12}$	1/1		27.6					30.3	8.12	7.94	ferromagnetic	[40]
$Au_{63}Al_{25}Gd_{12}$	1/1		27					28.4	8.06	7.94	ferromagnetic	[40]
$Au_{64}Al_{24}Gd_{12}$	1/1		19.6					19.4	8.25	7.94	ferromagnetic	[40]
$Au_{65}Al_{23}Gd_{12}$	1/1		15.8					15.5	8.21	7.94	ferromagnetic	[40]
$Au_{66}Al_{22}Gd_{12}$	1/1		10.0					10.8	8.14	7.94	ferromagnetic	[40]
$Au_{67}Al_{21}Gd_{12}$	1/1				4.2			5.9	8.24	7.94	antiferromagnetic	[41]
$Au_{56}Al_{32}Tb_{12}$	1/1							-14.2	9.89	9.72		[42]
$Au_{57}Al_{31}Tb_{12}$	1/1	3						-8.55	10.40	9.72	spinglass	[42]
$Au_{58}Al_{30}Tb_{12}$	1/1							-7.63	9.51	9.72		[42]
$Au_{59}Al_{29}Tb_{12}$	1/1							-10.74	9.97	9.72		[42]
$Au_{60}Al_{28}Tb_{12}$	1/1							16.1	10.08	9.72		[42]
$Au_{61}Al_{27}Tb_{12}$	1/1		15.9					16.4	9.80	9.72	ferromagnetic	[42]
$Au_{62}Al_{26}Tb_{12}$	1/1		13.8					17.1	10.06	9.72	ferromagnetic	[42]
$Au_{63}Al_{25}Tb_{12}$	1/1							15.0	9.85	9.72		[42]
$Au_{64}Al_{24}Tb_{12}$	1/1				11.6			11.6	10.04	9.72	antiferromagnetic	[42]
$Au_{65}Al_{23}Tb_{12}$	1/1				11.7			10.0	9.85	9.72	antiferromagnetic	[42]
$Au_{67}Al_{21}Tb_{12}$	1/1				11.8			4.2	10.8	9.72	antiferromagnetic	[41]
$Au_{56}Al_{32}Dy_{12}$	1/1		9.2					8.95	10.8	10.63	ferromagnetic	[39]
$Au_{57}Al_{31}Dy_{12}$	1/1		4.9					4.91	10.7	10.58	ferromagnetic	[39]
$Au_{64.5}Cu_{16.5}Al_{18.5}$	1/1				7			-4.46	7.40	7.94	antiferromagnetic	[44]
$Au_{62.5}Cu_{16.5}Al_{21.5}$	2/1				8.5			-4.52	7.75	7.94	antiferromagnetic	[44]
$Au_{56}Cu_{26}Gd_{18}$	1/1	2.3						-11.7	8.6	7.94	spinglass	[48]
$Au_{57}Cu_{25}Gd_{18}$	1/1							-29.7	7.99	7.94		[48]
$Au_{58}Cu_{24}Gd_{18}$	1/1							-29.8	7.88	7.94		[48]
$Au_{59}Cu_{23}Gd_{18}$	1/1							-16.9	8.81	7.94		[48]
$Au_{60}Cu_{22}Gd_{18}$	1/1							-6.6	8.02	7.94		[48]
$Au_{61}Cu_{21}Gd_{18}$	1/1							8.7	8.61	7.94		[48]
$Au_{62}Cu_{20}Gd_{18}$	1/1							26.82	8.1	7.94		[48]
$Au_{63}Cu_{19}Gd_{18}$	1/1		23.0					24.97	8.05	7.94	ferromagnetic	[48]
$Au_{64}Cu_{18}Gd_{18}$	1/1							12.67	8.08	7.94		[48]
$Au_{56}Cu_{26}Tb_{18}$	1/1	2.4						-19.08	10.70	9.72	spinglass	[48]
$Au_{57}Cu_{25}Tb_{18}$	1/1							-20.19	10.02	9.72		[48]
$Au_{58}Cu_{24}Tb_{18}$	1/1							-17.35	9.89	9.72		[48]
$Au_{59}Cu_{23}Tb_{18}$	1/1							-15.11	10.05	9.72		[48]
$Au_{60}Cu_{22}Tb_{18}$	1/1							4.66	9.77	9.72		[48]
$Au_{61}Cu_{21}Tb_{18}$	1/1							9.22	9.94	9.72		[48]
$Au_{62}Cu_{20}Tb_{18}$	1/1		12.0					14.97	9.94	9.72	ferromagnetic	[48]
$Au_{63}Cu_{19}Tb_{18}$	1/1							15.04	10.08	9.72		[48]
$Au_{64}Cu_{18}Tb_{18}$	1/1				13.1			12.19	10.39	9.72	antiferromagnetic	[48]
$Au_{65}Cu_{17}Tb_{18}$	1/1				13.8			11.51	9.96	9.72	antiferromagnetic	[48]
$Au_{64.5}Si_{17.5}Gd_{18}$*	1/1		22.5(5)					22.7	7.91(2)	7.94	ferromagnetic	[71]
$Au_{63.5}Si_{17.5}Tb_{18}$	1/1		8.3(5)					9.57(18)	9.86(2)	9.72	ferromagnetic	[72]
$Au_{63.5}Si_{17.5}Dy_{18}$	1/1		5.9(4)					5.19(10)	10.9(1)	10.63	ferromagnetic	[72]
$Au_{63.5}Si_{17.5}Ho_{18}$	1/1		3.8(5)					2.54(5)	10.4(1)	10.58	ferromagnetic	[72]
$Au_{63.5}Si_{17.5}Gd_{18}$*	1/1		13(1)	4.5(5)				12.2	8.09(2)	7.94	reentrant spinglass	[71]
$Au_{63}Si_{19}Gd_{18}$	1/1		9(2)	3.7(5)				1.66	7.94(1)	7.94	reentrant spinglass	[72]
$Au_{64.5}Sn_{17.5}Gd_{18}$*	1/1	2.8						-20		7.94	spinglass	[74]
$Cu_{56}Pd_{26}Gd_{18}$	1/1							-24.2		7.94		[82]
$Cu_{55}Pd_{25.5}Tb_{19.5}$	2/1				2.81			-4.55	9.62	9.72	antiferromagnetic	[80]
$Cu_{54.5}Pd_{25.5}Tb_{19.5}$	1/1	3.02						-11.8	9.98	9.72	spinglass	[80]
$Cu_{56}Pd_{26}Gd_{18}$	2/1	2.85								7.94	spinglass	[82]
$Cu_{56}Pd_{26}Gd_{18}$	1/1*							-2.4	8.07	7.94		[82]
$Cu_{56}Pd_{26}Gd_{18}$	1/1*							-4.3	8.07	7.94		[82]
$Cu_{56}Pd_{26}Gd_{18}$	1/1*							-11.3	8.17	7.94		[82]
$Au_{47}Cu_{19}Al_{12}Ga_{12}Gd_{10}$	2/1		30.0					30.16	8.18	7.94	ferromagnetic	[65]
$Au_{47}Cu_{19}Al_{12}Ga_{12}Tb_{10}$	2/1		15.3					15.7	10.1	9.72	ferromagnetic	[65]

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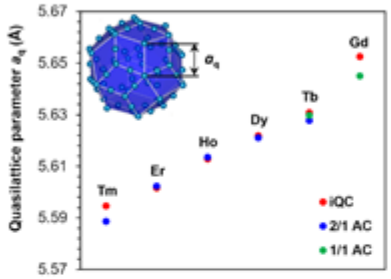
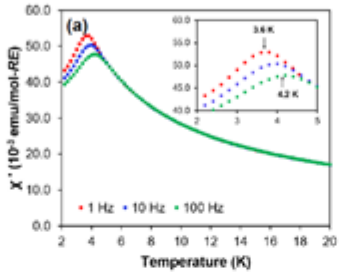
Magnetyzm Aproksymant 2/1 i 1/1 CdMgRE

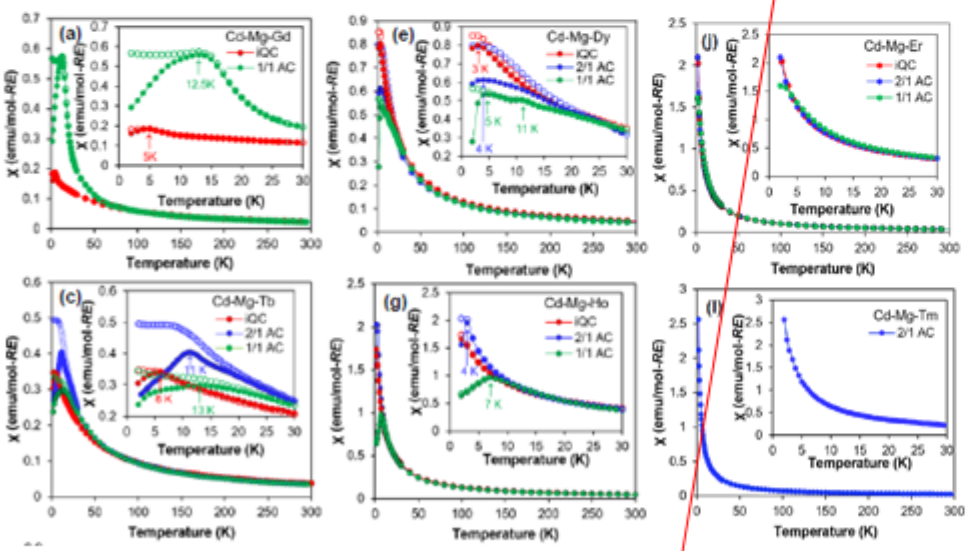
- Badania różnic struktury magnetycznej w zależności od rzędu aproksymanty
- Utrzymana jest ta sama koncentracja Mg



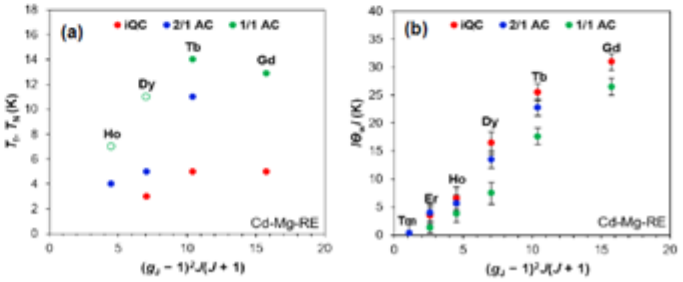


iQC/AC	System	μ_{eff} (μ_B/RE_{ion})	μ_{calc} (μ_B/RE_{ion})	Θ_w (K)	T_f (K)	T_{N1} (K)	T_{N2} (K)	T_{N3} (K)	T_{N4} (K)
i-QC	Cd-Mg-Gd	7.24		-37.8	4.3	–	–	–	–
i-QC	$Cd_{7.88}Gd$	–	7.94	-41	4.6	–	–	–	–
1/1 AC	Cd_6Gd	7.94		-32	–	18.9	13.2	7.3	2.5
i-QC	Cd-Mg-Tb	9.74		-24.5	5.9	–	–	–	–
i-QC	$Cd_{7.60}Tb$	–	9.72	-21	5.3	–	–	–	–
1/1 AC	Cd_6Tb	9.8		-17	–	24	19	2.4	
i-QC	Cd-Mg-Dy	10.59		-18.4	3.2	–	–	–	–
i-QC	$Cd_{7.58}Dy$	–	10.63	-11	3	–	–	–	–
1/1 AC	Cd_6Dy	10.9		-5.1	–	17.8	–	–	–
i-QC	Cd-Mg-Ho	10.42		-7	12.5	–	–	–	–
i-QC	$Cd_{7.60}Ho$	–	10.60	-6	1.76	–	–	–	–
1/1 AC	Cd_6Ho	10.5		-1	–	8.4	6.8	3.4	–
i-QC	Cd-Mg-Er	9.71		-6	4.4	–	–	–	–
i-QC	$Cd_{7.54}Er$	–	9.59	-4	1.11	–	–	–	–
1/1 AC	Cd_6Er	9.1		-0.9	–	2.8	–	–	–
i-QC	Cd-Mg-Tm	7.08		-2	–	–	–	–	–
i-QC	$Cd_{7.28}Tm$	–	7.57	-2	0.63	–	–	–	–
1/1 AC	Cd_6Tm	7.4		-3.1	–	2.2	–	–	–

Stała sieci kryształu w zależności od pierwiastka RE



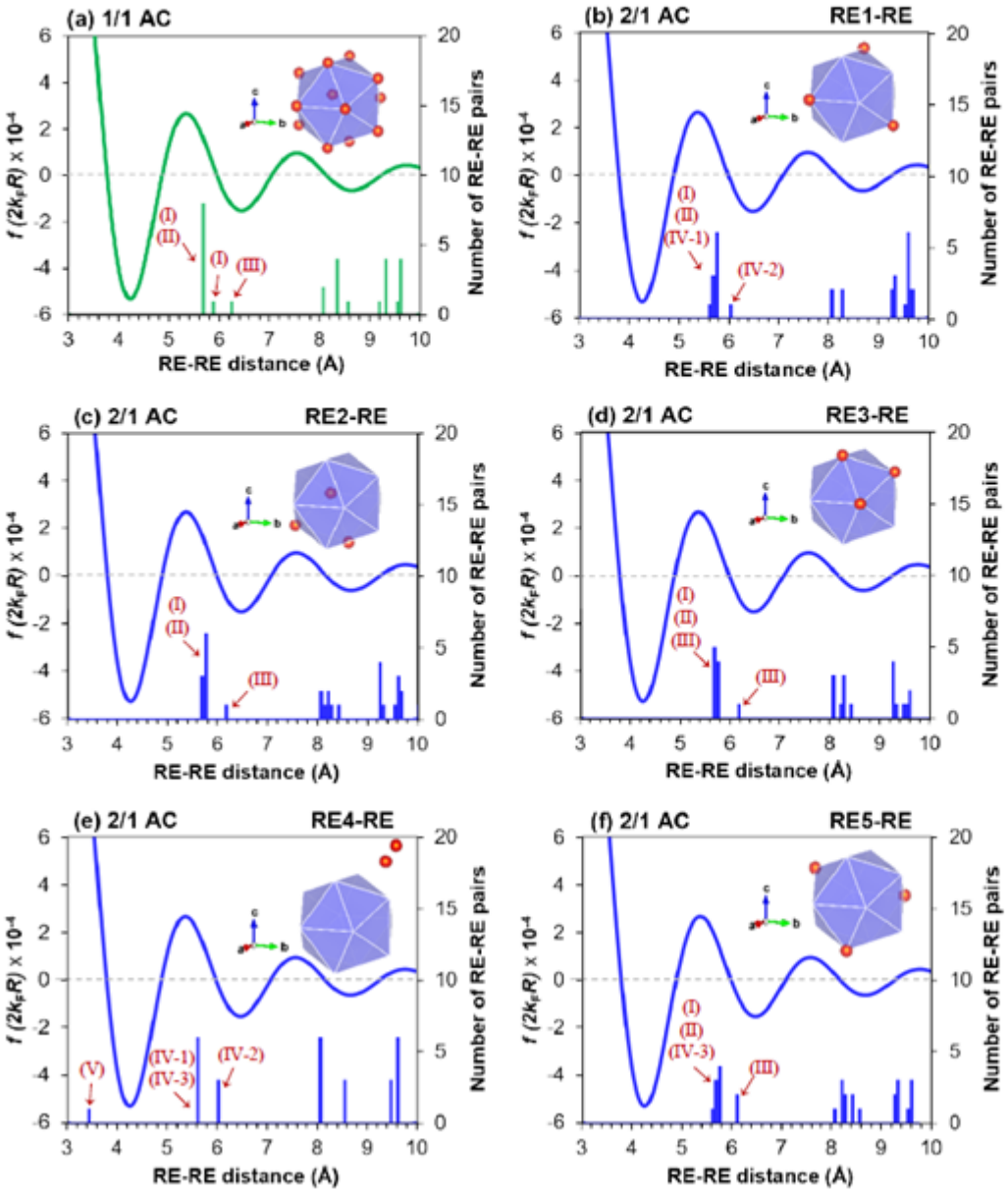
iQC/AC	Composition	μ_{eff} (μ_B/RE_{ion})	μ_{calc} (μ_B/RE_{ion})	Θ_w (K)	T_f (K)	T_N (K)	$\lvert\Theta_w / T_f\rvert$
i-QC	$Cd_{65}Mg_{22.5}Gd_{12.5}$	7.8±0.2	7.94	-31.0±1.5	5.0±0.5	–	6.2±1.5
1/1 AC	$Cd_{65}Mg_{25}Gd_{13}$	7.6±0.2		-26.5±1.5	12.5±0.5	–	2.0±1.5
i-QC	$Cd_{65}Mg_{22.5}Tb_{12.5}$	9.8±0.2		-25.5±1.5	6.0±0.5	–	5.1±1.5
2/1 AC	$Cd_{62}Mg_{25}Tb_{13}$	9.6±0.2	9.72	-23.0±1.5	11.0±0.5	–	2.0±1.5
1/1 AC	$Cd_{65}Mg_{20}Tb_{15}$	9.7±0.2		-17.5±1.5	13.0±0.5	–	1.3±1.5
i-QC	$Cd_{65}Mg_{22.5}Dy_{12.5}$	10.8±0.2		-17.0±2.0	3.0±0.5	–	5.5±1.5
2/1 AC	$Cd_{62}Mg_{25}Dy_{13}$	10.6±0.2	10.63	-13.5±1.5	4.0±0.5	–	2.7±1.5
1/1 AC	$Cd_{75}Mg_{10}Dy_{15}$	10.0±0.2		-8.0±2.0	–	11.0±0.5	0.8±1.5
i-QC	$Cd_{65}Mg_{22.5}Ho_{12.5}$	10.7±0.2		-7.0±2.0	–	–	–
2/1 AC	$Cd_{62}Mg_{25}Ho_{13}$	10.5±0.2	10.60	-5.5±1.5	4.0±0.5	–	1.7±1.5
1/1 AC	$Cd_{75}Mg_{10}Ho_{15}$	10.2±0.2		-4.0±1.5	–	7.0±0.5	0.8±1.5
i-QC	$Cd_{65}Mg_{22.5}Er_{12.5}$	9.6±0.2		-3.5±1.5	–	–	–
2/1 AC	$Cd_{62}Mg_{25}Er_{13}$	9.5±0.2	9.59	-4.0±1.5	–	–	–
1/1 AC	$Cd_{75}Mg_{10}Er_{15}$	9.3±0.2		-1.5±1.5	–	2.5±0.5	0.5±1.5
2/1 AC	$Cd_{62}Mg_{25}Tm_{13}$	7.2±0.2	7.57	-0.5±1.5	–	–	–



- Formacja szkła spinowego potwierdzona badaniami ac podatności dla iQC i 2/1
- Antyferromagnetyzm dla 1/1 Ho (mniejsza koncentracja magnezu 10%)

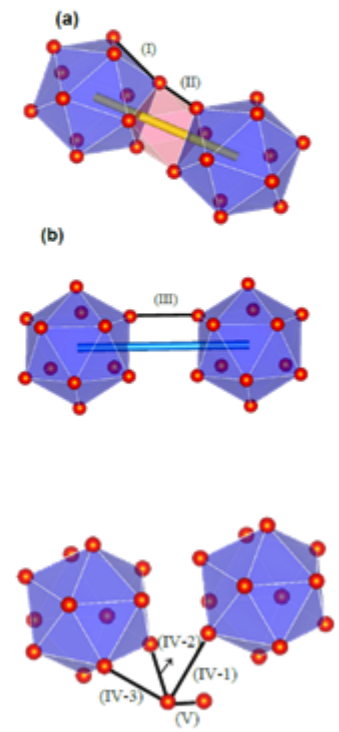
F. Labib, et al. J. Phys.: Condens. Matter 32 (2020), 415801

Magnetyzm Aproksymant 2/1 i 1/1 (RKKY)

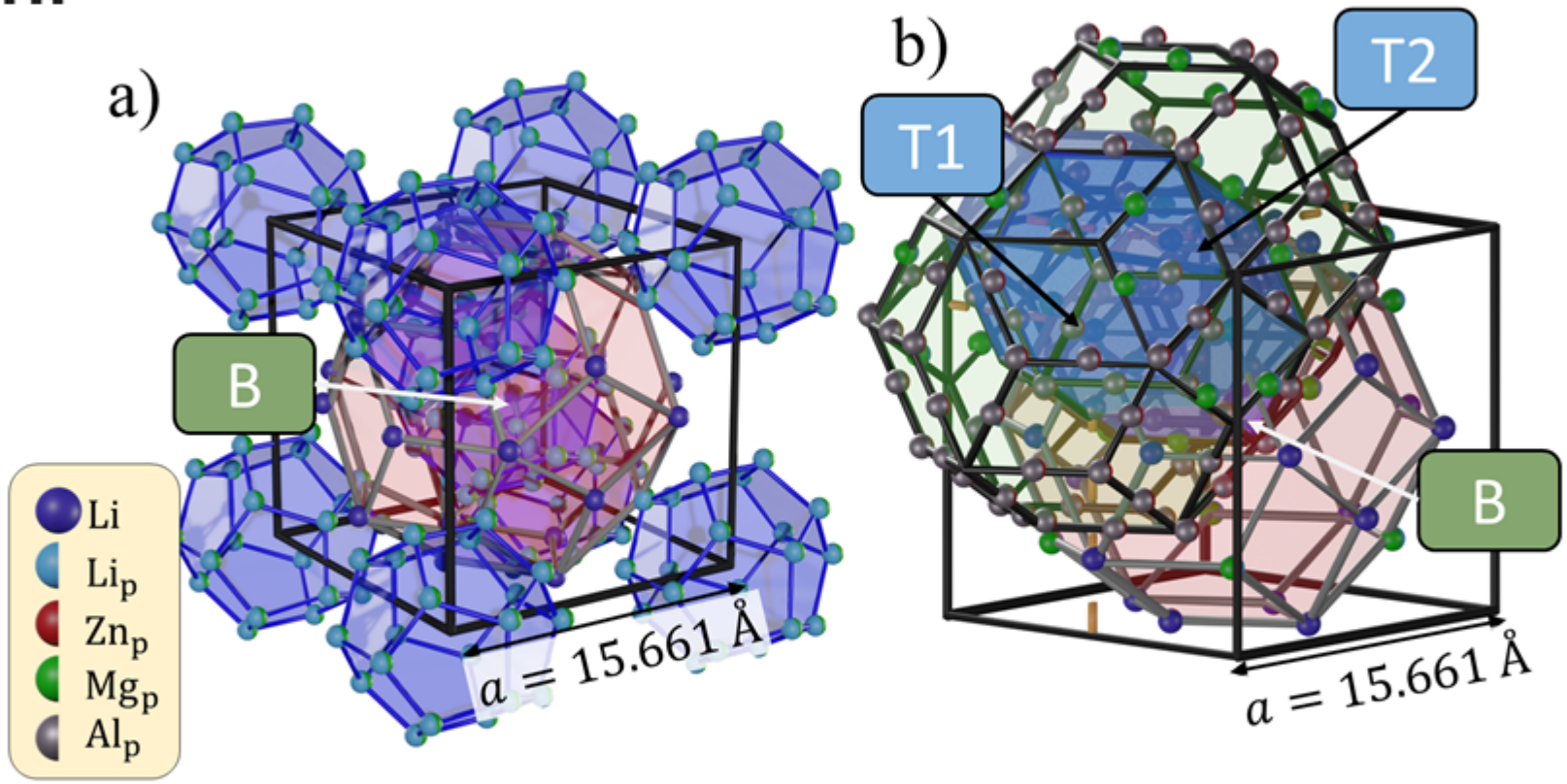


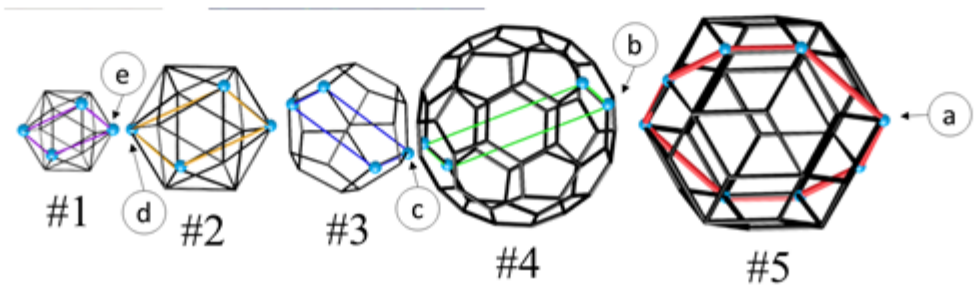
$$J(r) = -9\pi\left(\frac{N}{V}\right)^2 \frac{j_0{}^2}{\varepsilon_F} f(2k_F r_{ij}),$$

$$f(x) = (-x\cos x + \sin x)/x^4$$

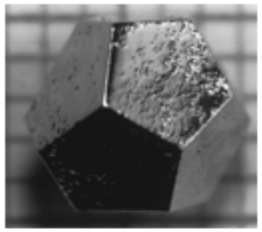


Faza Bergmana





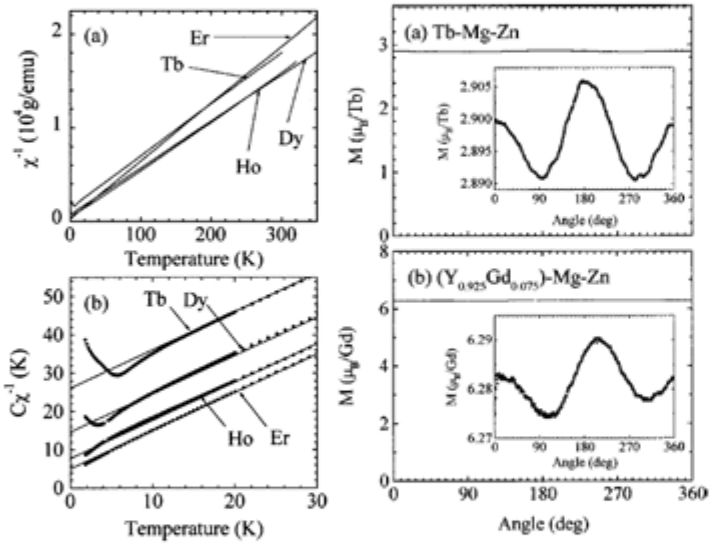
Magnetyzm faz Bergmana

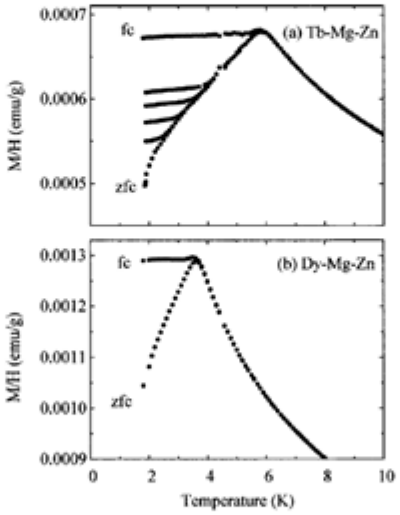


- Badania faz $Zn_{50}Mg_{42}RE_8, RE = Y, Dy, Ho, Er, (Gd), Zn_{57}Mg_{34}Tb_9$
- Badania na monokryształach

System	C (g/emu K)	RMM (g/mol R)	θ (K)	T_f (K)
Tb-Mg-Zn	0.0180 ± 0.0001	655 ± 1	-26.3 ± 0.4	5.80 ± 0.05^a
Dy-Mg-Zn	0.0201 ± 0.0001	705 ± 1	-14.8 ± 0.4	3.60 ± 0.05^a
Ho-Mg-Zn	0.0195 ± 0.0001	720 ± 1	-7.8 ± 0.4	1.95 ± 0.05^b
Er-Mg-Zn	0.0163 ± 0.0001	704 ± 1	-5.1 ± 0.4	1.30 ± 0.05^b

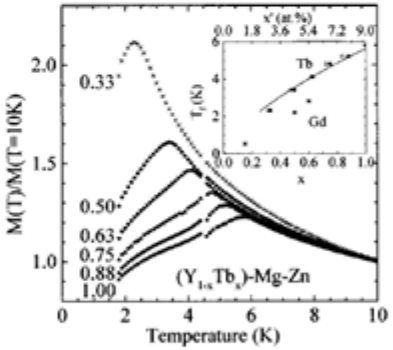
[a]Position of the maximum in zfc $\chi_{dc}(T)$.
[b]Position of the maximum in $\chi'_{ac}(T)$.





Brak uporządkowania dalekiego zasięgu (szkło spinowe)

Dla próbki z Tb domieszkowanej Y również widać szkło spinowe



- Negatywna temperatura Weisse'a (oddziaływania antyferromagnetyczne)
- Wzrost podatności przed temperaturą przejścia szkła spinowego – formowanie się klastra magnetycznego
- Brak zależności magnetyzacji od kąta wektora pola magnetycznego dla $T > T_f$

ZnMgTbY x	θ (K)	T_f[a] (K)
0.075	-2.1 ± 0.7	
0.15	-4.3 ± 0.2	
0.33	-9.2 ± 0.2	2.30 ± 0.05
0.50	-13.4 ± 0.2	3.40 ± 0.05
0.63	-16.9 ± 0.2	4.10 ± 0.05
0.75	-19.2 ± 0.2	4.80 ± 0.05
0.88	-22.7 ± 0.2	5.20 ± 0.05
1.00	-26.3 ± 0.2	5.80 ± 0.05

[a]Position of the maximum in zfc $\chi_{dc}(T)$.

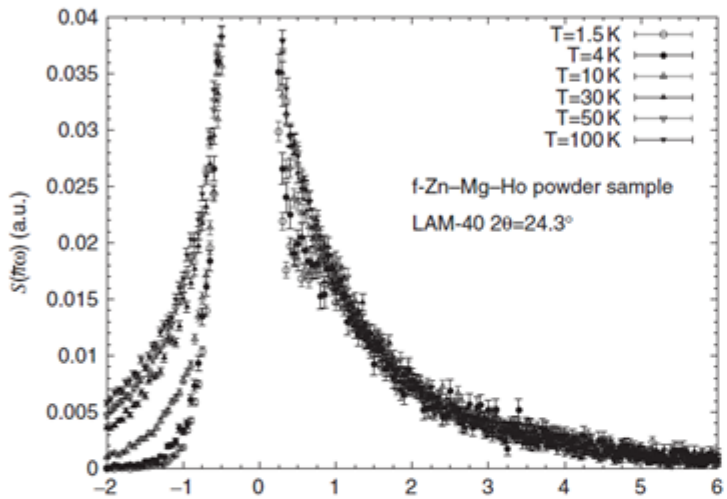
ZnMgGdY x	θ (K)	T_f (K)
0.075	-2.0 ± 0.9	
0.15	-5.8 ± 0.2	0.54 ± 0.05^a
0.50	-21.0 ± 0.2	2.20 ± 0.05^b
0.60	-23.6 ± 0.2	2.80 ± 0.05^b

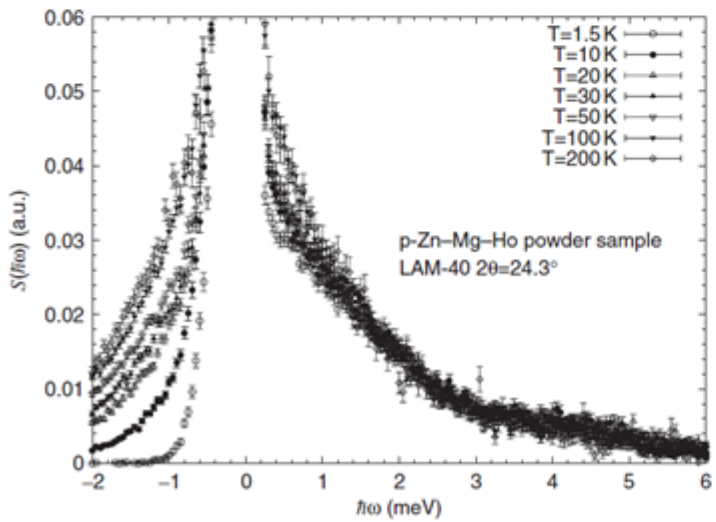
[a]Position of the maximum in zfc $\chi_{dc}(T)$.
[b]Position of the maximum in $\chi'_{ac}(T)$.

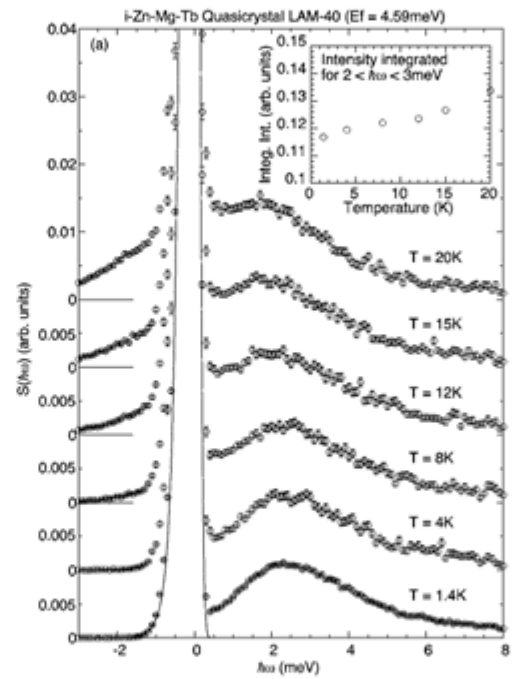
I. R. Fisher, et al. Phys. Rev. B59 (1999), 308

Magnetyzm faz Bergmana (rozpraszanie neutronów)

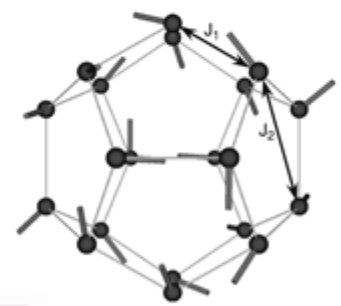
- Brak zależności temperaturowej dla ZnMgHo
- Brak zależności od wektora rozpraszania ZnMgHo (brak korelacji między momentami sąsiednich atomów)
- Obecność piku rozpraszania nieelastycznego neutronów dla ZnMgTb – lokalne korelacje spinowe

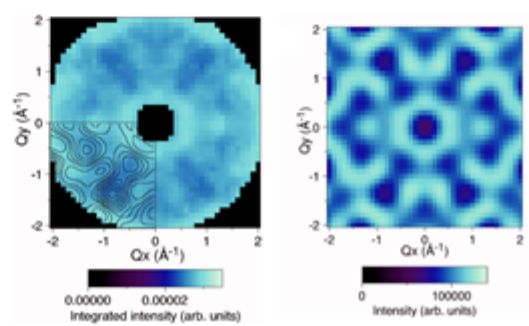






- Korelacje spinowe nawet dla $T > T_f$
- Dla $T > T_f$ klastry fluktuują niezależnie
- Dla $T = T_f$ indywidualne fluktuacje klastrów zamierają (zachowanie inne niż w klasycznych szkłach spinowych)





$$E_{cl} = -\sum_{\langle NNN \rangle} J_{ij} \boldsymbol{J}_i \cdot \boldsymbol{J}_j.$$

T. J. Sato & A. P. Tsai, Phil. Mag. 87 (2007), 2939

T. J. Sato, et al. Phys. Rev. B73 (2006), 0544417

Struktura atomowa P-ZnMgRE

research papers

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The atomic structure of the Bergman-type icosahedral quasicrystal based on the Ammann–Kramer–Neri tiling

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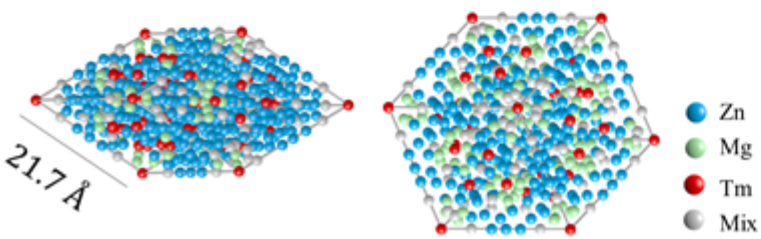
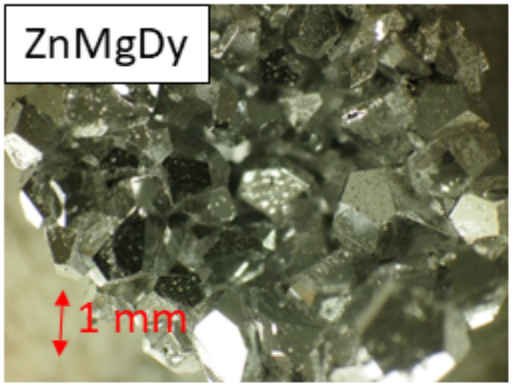
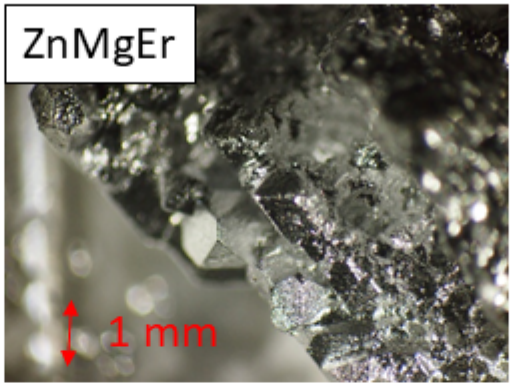
In this study, the atomic structure of the ternary icosahedral ZnMgTm quasicrystal (QC) is investigated by means of single-crystal X-ray diffraction. The structure is found to be a member of the Bergman QC family, frequently found in Zn–Mg–rare-earth systems. The *ab initio* structure solution was obtained by the use of the *Superflip* software. The infinite structure model was founded on the atomic decoration of two golden rhombohedra, with an edge length of 21.7 Å, constituting the Ammann–Kramer–Neri tiling. The refined structure converged well with the experimental diffraction diagram, with the crystallographic *R* factor equal to 9.8%. The Bergman clusters were found to be bonded by four possible linkages. Only two linkages, *b* and *c*, are detected in approximant crystals and are employed to model the icosahedral QCs in the cluster approach known for the CdYb Tsai-type QC. Additional short *b* and *a* linkages are found in this study. Short interatomic distances are not generated by those linkages due to the systematic absence of atoms and the formation of split atomic positions. The presence of four linkages allows the structure to be pictured as a complete covering by rhombic triacontahedral clusters and consequently there is no need to define the interstitial part of the structure (*i.e.* that outside the cluster). The 6D embedding of the solved structure is discussed for the final verification of the model.

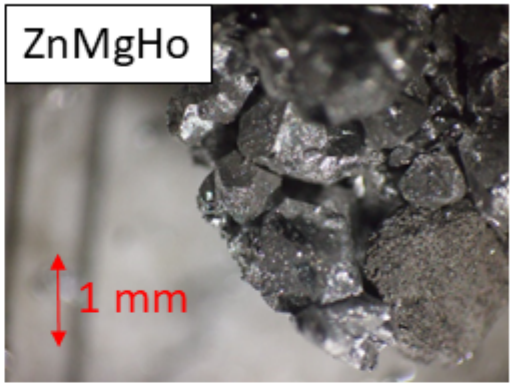
$Zn_{69.5}Mg_{20.9}Tm_{9.6}$

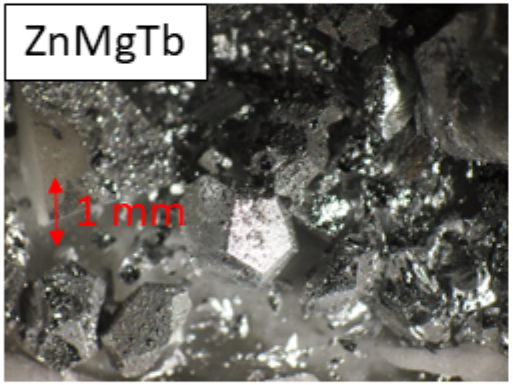


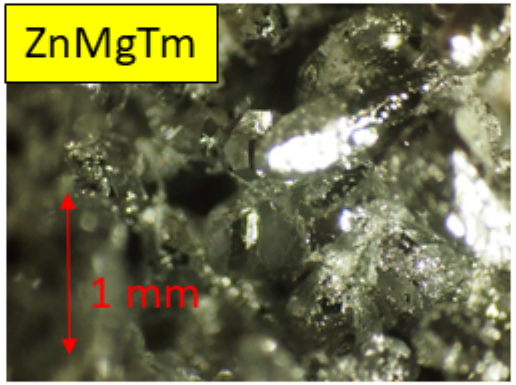
Hodowla próbek ZnMgRE

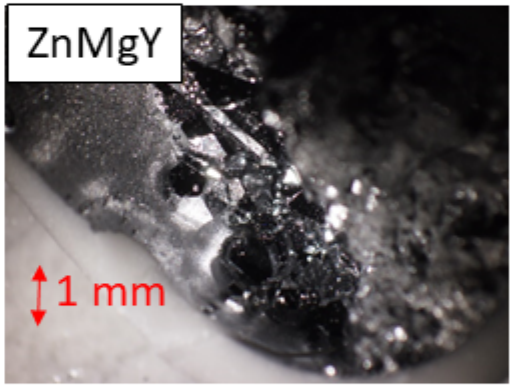


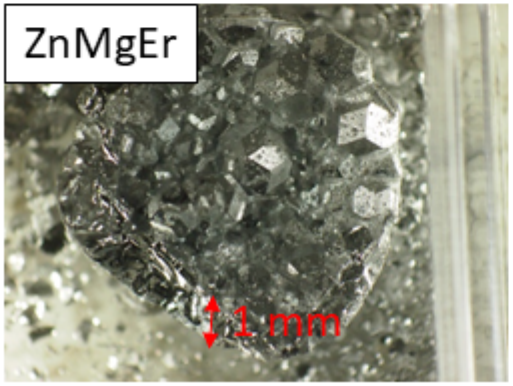


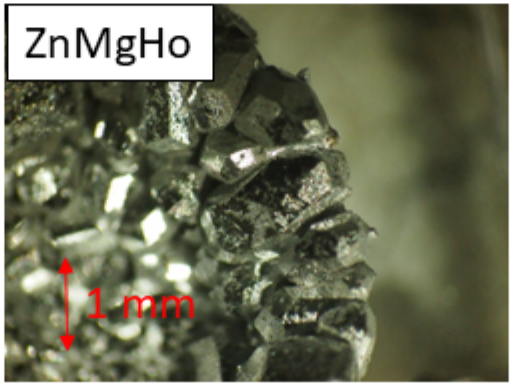


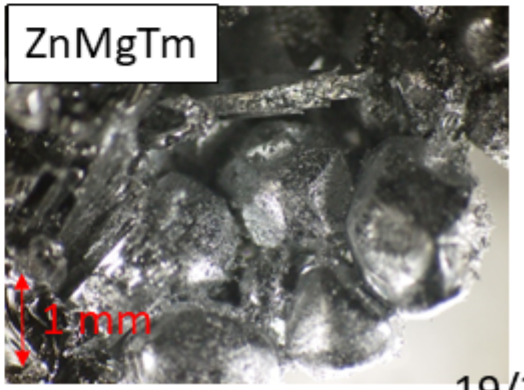




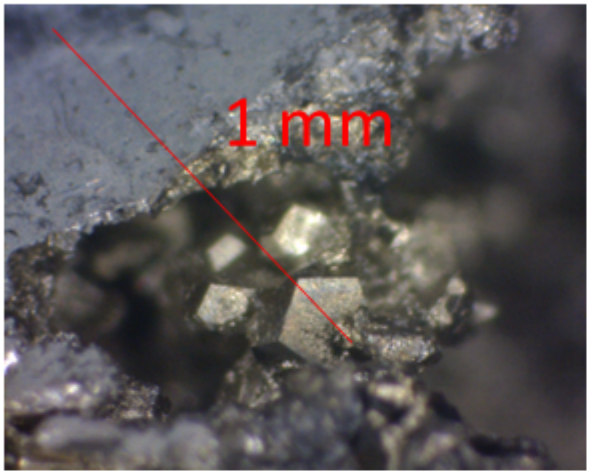


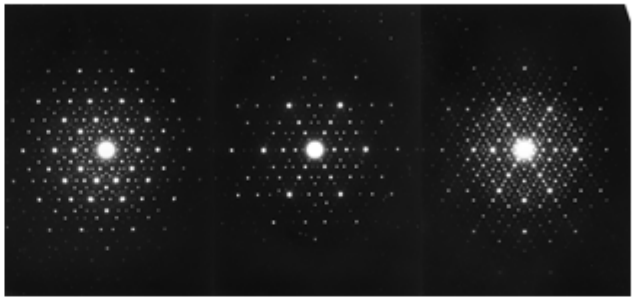






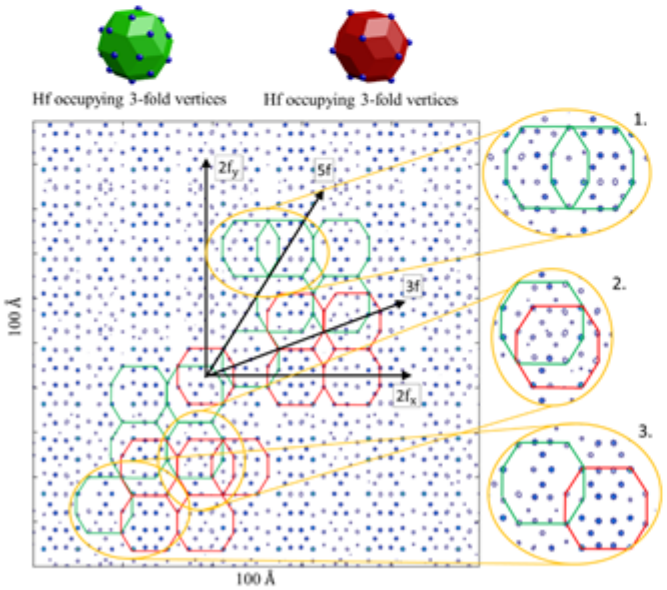
Pomiary ZnMgHf

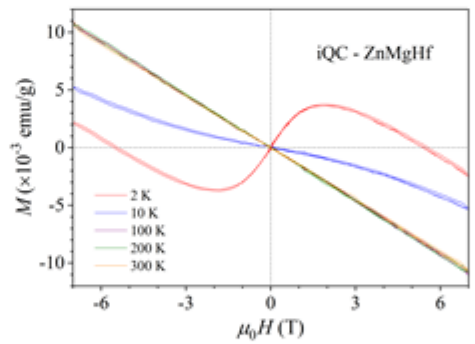


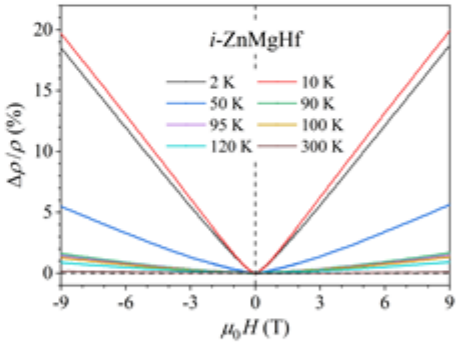


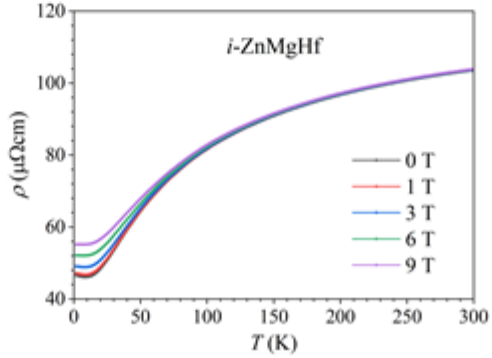
Kompozycja eksperymentalna:

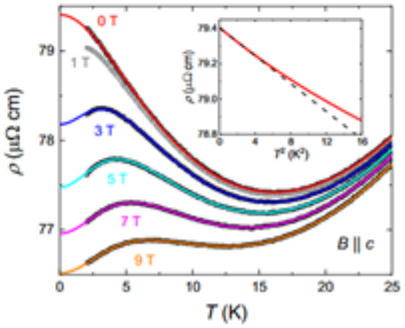
$Zn_{80,715(78)}Mg_{11,751(70)}Hf_{7,532(24)}$











Podsumowanie

- Pierwsza obserwacja dalekozasięgowego uporządkowania magnetycznego (ferromagnetyzmu) w kwazikryształach $Au_{65}Ga_{20}(Tb, Gd)_{15}$
- Oddziaływanie magnetyczne poprzez mechanizm RKKY – charakterystyczny, oscylacyjny charakter temperatury Weisse'a od koncentracji elektronów walencyjnych
- Sterowanie typem oddziaływania magnetycznego poprzez kontrolę koncentracji elektronów walencyjnych
- Przesunięcie zakresu ferromagnetycznego w zależności od typu atomu ziem rzadkich (wpływ pola krystalicznego)
- W fazach Bergmana brak uporządkowania dalekozasięgowego (lokalne korelacje w ramach klastra)

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