

Moments and Radii at $N \sim 40$

T.E. Cocolios

Region

Specific

Co

Ni

Beams

Ground-state properties in the vicinity of ⁶⁸Ni

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T.E. Cocolios

Region

Specifics

Fe

Со

Ni

Beams

1 Around ⁶⁸Ni

Outline I

- 2 Specific interest in Fe, Co and Ni
 - Deformation in the Fe isotopes
 - Intruder isomers and collectivity in the Co isotopes
 - The magic reference: the Ni isotopes



Beams of Fe and Co at DESIR



Outline

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Specifics Fe Co Ni

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1 Around ⁶⁸Ni

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Beams of Fe and Co at DESIR



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										Ga	Ga	Ga	Ga	Ga	Ga	Za	Ga	Ga	Ga	Ga	Ga	Ga	Ga	Ga
⁵⁷ Zn	⁵⁸ Zn	⁵⁰ Zn					⁶⁴ Zn	⁶⁵ Zn	⁶⁶ Zn	⁶⁷ Zn	^{68}Zn	⁶⁹ Zn	⁷⁰ Zn	71 Zn	72 Zn	⁷³ Zn	74 Zn	75 Zn	76 Zn	77Zn	78 Zn	79 Zn	80 Zn	⁸¹ Zn
⁵⁶ Cu	$^{57}\mathrm{Cu}$	⁵⁸ Cu					⁶³ Cu	⁶⁴ Cu	⁶⁵ Cu	⁶⁶ Cu	⁶⁷ Cu	⁶⁸ Cu	®Cu	юCu	71 Cu	⁷² Cu	⁷³ Cu	⁷⁴ Cu	$^{75}\mathrm{Cu}$	76Cu	77Cu	⁷⁸ Cu	⁷⁹ Cu	⁸⁰ Cu
⁵⁵ Ni	⁵⁶ Ni	⁵⁷ Ni	⁵⁸ Ni	⁵⁹ Ni	⁶⁰ Ni	⁶¹ Ni	⁶² Ni	⁶³ Ni	⁶⁴ Ni	65 Ni	⁶⁶ Ni	⁶⁷ Ni	⁶⁸ Ni	⁶⁹ Ni	⁷⁰ Ni	⁷¹ Ni	⁷² Ni	⁷³ Ni	$^{74}\mathrm{Ni}$	$^{75}\mathrm{Ni}$	⁷⁶ Ni	77Ni	⁷⁸ Ni	
⁵⁴ Co	⁵⁵ Co	⁵⁶ Co		58Co	⁵⁹ Co	^{.m} Co	⁶¹ Co	⁶² Co	⁶³ Co	⁶⁴ Co	⁶⁵ Co	⁶⁶ Co	€ZCo	⁶⁸ Co	⁶⁹ Co	⁷⁰ Co	⁷¹ Co	^{72}Co	⁷³ Co	^{74}Co	⁷⁵ Co			
- ⁵³ Fe	$^{54}\mathrm{Fe}$		56 Fe	57Fe	58 Fe	$^{59}\mathrm{Fe}$	$^{60}\mathrm{Fe}$	$^{61}\mathrm{Fe}$	$^{62}\mathrm{Fe}$	$^{63}\mathrm{Fe}$	$^{64}\mathrm{Fe}$	$^{65}\mathrm{Fe}$	66 Fe	$^{67}\mathrm{Fe}$	$^{68}\mathrm{Fe}$	∞Fe	$^{70}\mathrm{Fe}$	$^{71}\mathrm{Fe}$	$^{72}\mathrm{Fe}$					
⁵² Mn	⁵³ Mn	⁵⁴ Mn	⁵⁵ Mn	⁵⁶ Mn	⁵⁷ Mn	⁵⁸ Mn	⁵⁹ Mn	⁶⁰ Mn	^{61}Mn	⁶² Mn	⁶³ Mn	⁶⁴ Mn	⁶⁵ Mn	⁶⁶ Mn	⁶⁷ Mn	⁶⁸ Mn	⁶⁹ Mn							
⁵¹ Cr	⁵² Cr	⁵³ Cr	⁵⁴ Cr	^{55}Cr	^{56}Cr	$^{57}\mathrm{Cr}$	$^{58}\mathrm{Cr}$	⁵⁹ Cr	⁶⁰ Cr	⁶¹ Cr	⁶² Cr	⁶³ Cr	⁶⁴ Cr	^{65}Cr	^{66}Cr	^{67}Cr								
50 17	51 V	52 V	53 V	54 V	55 V	56 V	57 M	5817	5917	6017	6117	62 V	6317	6417										

Neutron-rich nickel region

- Z = 28: magic shell closure
- N = 40: sub-shell closure with parity change to the $\nu g_{9/2}$



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- Evidence for magic behaviour;
- Understood from the parity change accross the N = 40 shell gap;
- the νg_{9/2} orbital still gives headaches to our community...



A moment on magicity

Nailing the structure of the neutron-rich Cu isotopes.



Pieter Vingerhoets, Ph.D. work



Limited knowledge

Moments and Radii at $N \sim 40$

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Region

Specifics Fe Co

Reams



http://www.gsi.de/forschung/ap/projects/laser/survey_e.html

Laser spectroscopy

Nothing but the Cu isotopes have been done!

- Note that the Mn isotopes are currently under investigation at IGISOL and ISOLDE -



Limited knowledge

Moments and Radii at $N \sim 40$

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Beams

1		- Ga	Ga	-Ca	Ga	Ga	Ca	Ga	- Ga	- Ga	Ga	Ga	Ga	Ga	Ga	∕~ª	Ga	Ga	- Ga	Ga	Ga	Ga	Ga	Ga
$^{57}\mathrm{Zn}$	⁵⁸ Zn	^{so} Zn	60 Zn				⁶⁴ Zn	⁶⁵ Zn	⁶⁶ Zn	⁶⁷ Zn	⁶⁸ Zn	⁶⁹ Zn	70 Zn	71 Zn	72 Zn	⁷³ Zn	74 Zn	75 Zn	⁷⁶ Zn	⁷⁷ Zn	⁷⁸ Zn	$^{79}\mathrm{Zn}$	⁸⁰ Zn	⁸¹ Zn
⁵⁶ Cu		⁵⁸ Cu			⁶¹ Cu	^{62}Cu	⁶³ Cu	64 Cu	⁶⁵ Cu	⁶⁶ Cu		[⊛] Cu	®Cu	⁷⁰ Cu		^{72}Cu	⁷³ Cu	⁷⁴ Cu	⁷⁵ Cu	^{76}Cu	77Cu	78 Cu	⁷⁹ Cu	⁸⁰ Cu
	⁵⁶ Ni	⁶⁷ Ni	⁵⁸ Ni	⁵⁹ Ni	⁶⁰ Ni	⁶¹ Ni	⁶² Ni	⁶³ Ni	⁶⁴ Ni	65 Ni	⁶⁶ Ni		⁶⁸ Ni	⁶⁹ Ni	⁷⁰ Ni	⁷¹ Ni	$^{72}\mathrm{Ni}$	⁷³ Ni	⁷⁴ Ni	$^{75}\mathrm{Ni}$	⁷⁶ Ni	$^{77}\mathrm{Ni}$	⁷⁸ Ni	
⁵⁴ Co		⁵⁶ Co		^{rs} Co	⁵⁹ Co	en Co	⁶¹ Co	⁶² Co	⁶³ Co	⁶⁴ Co	⁶⁵ Co	⁶⁶ Co	⁶⁷ Co	⁶⁸ Co	⁶⁹ Co	⁷⁰ Co	⁷¹ Co	⁷² Co	⁷³ Co	^{74}Co	⁷⁵ Co			
⁵³ Fe	⁵⁴ Fe	55 Fe	⁵⁶ Fe	⁵⁷ Fe	⁵⁸ Fe	⁵⁰ Fe	∞Fe	⁶¹ Fe	$^{62}\mathrm{Fe}$	⁶³ Fe	$^{64}\mathrm{Fe}$	65 Fe	⁶⁶ Fe	$^{67}\mathrm{Fe}$	⁶⁸ Fe	∞Fe	⁷⁰ Fe	⁷¹ Fe	72 Fe					
⁵² Mn	⁵³ Mn	⁵⁴ Mn	⁵⁵ Mn		⁵⁷ Mn	⁵⁸ Mn	⁵⁹ Mn	⁶⁰ Mn	⁶¹ Mn	⁶² Mn	⁶³ Mn	⁶⁴ Mn	⁶⁵ Mn	⁶⁶ Mn	⁶⁷ Mn	⁶⁸ Mn	⁶⁹ Mn							
⁵¹ Cr	⁵² Cr	⁵³ Cr	⁵⁴ Cr	⁵⁵ Cr	$^{56}\mathrm{Cr}$	⁵⁷ Cr	$^{58}\mathrm{Cr}$	⁵⁹ Cr	⁶⁰ Cr	⁶¹ Cr	⁶² Cr	⁶³ Cr	⁶⁴ Cr	^{65}Cr	^{66}Cr	$^{67}\mathrm{Cr}$								
5017	51 V	5217	53 V	54 V	55 V	5617	57 V	58 V	5917	60 17	6117	62 17	63 V	6417										

Moments and radii

All in all, only isotopes very close to stability have been studied.



Limited knowledge

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3 Beams of Fe and Co at DESIR



Ra

Fe Co Ni

Deformation?

ents and t $N \sim 40$	⁶⁶ ₃₀ Z n ₃₆ -0.20	⁶⁷ ₃₀ Zn ₃₇ -0.16	68 Zn 38 -0.17	⁶⁹ ₃₀ Zn ₃₉ -0.17	⁷⁰ ₃₀ Zn ₄₀	⁷¹ ₃₀ Zn ₄₁	⁷² ₃₀ Z n ₄₂ 0.23	⁷³ ₃₀ Zn ₄₃ 0.23	⁷⁴ ₃₀ Zn
ocolios	0.22 ⁶⁵ ₂₉ Cu ₃₆ -0.17	⁶⁶ ₂₉ Cu ₃₇ -0.16	0.21 ⁶⁷ ₂₉ Cu ₃₈ -0.16	⁶⁸ ₂₉ Cu ₃₉ -0.16	0.23 ⁶⁹ C u ₄₀ 0.08	⁷⁰ Cu ₄₁ 0.11	0.23 ⁷¹ ₂₉ Cu ₄₂ 0.12	⁷² ₂₉ Cu ₄₃ 0.12	0.25 73 29 0.14
	⁶⁴ ₂₈ N i ₃₆ -0.17	⁶⁵ ₂₈ N i ₃₇ -0.12	66 Ni ₃₈ -0.12	⁶⁷ N i ₃₉ -0.08	⁶⁸ N i 40 0.01	⁶⁹ N i ₄₁ -0.05	⁷⁰ Ni ₄₂ 0.01	⁷¹ ₂₈ N i ₄₃ 0.05	⁷² ₂₈ N i ₄ 0.05
	⁶³ ₂₇ Co ₃₆ 0.15	⁶⁴ C 0 ₃₇ 0.14	65 27 C 0 38 0.14	⁶⁶ 27 C 0 39 0.09 ?	⁶⁷ ₂₇ Co ₄₀ 0.14 ?	⁶⁸ ₂₇ Co ₄₁ ^{0.13} ?	⁶⁹ ₂₇ C o ₄₂ 0.16	⁷⁰ ₂₇ Co ₄₃ _{0.17}	⁷¹ ₂₇ Co ₄ 0.16
	⁶² ₂₆ F e ₃₆ 0.18	⁶³ ₂₆ F e ₃₇ 0.15	⁶⁴ ₂₆ F e ₃₈ 0.24	${}^{65}_{26}$ F e $_{39}$ 0.30	⁶⁶ ₂₆ Fe ₄₀ 0.27	⁶⁷ ₂₆ F e ₄₁ 0.30	⁶⁸ ₂₆ F e ₄₂ 0.26	⁶⁹ ₂₆ F e ₄₃ 0.27	⁷⁰ ₂₆ F e ₄
	⁶¹ ₂₅ Mn ₃₆ 0.23	⁶² ₂₅ Mn ₃₇ 0.24	⁶³ ₂₅ Mn ₃₈ 0.26	⁶⁴ ₂₅ Mn ₃₉ 0.30	⁶⁵ ₂₅ Mn ₄₀ 0.28	⁶⁶ ₂₅ Mn ₄₁ 0.29	⁶⁷ ₂₅ Mn ₄₂ 0.28	⁶⁸ ₂₅ Mn ₄₃ 0.28	⁶⁹ ₂₅ Mn ₄ 0.24
	⁶⁰ ₂₄ C r ₃₆ 0.17	⁶¹ ₂₄ C r ₃₇ 0.14	⁶² ₂₄ C r ₃₈ 0.28	⁶³ ₂₄ C r ₃₉ 0.31	⁶⁴ ₂₄ C r ₄₀ 0.28	⁶⁵ ₂₄ C r ₄₁ 0.30	⁶⁶ 24 C r ₄₂ 0.27	⁶⁷ ₂₄ C r ₄₃ 0.29	⁶⁸ ₂₄ C r ₄ , 0.26
	Abs quad	olute va rupole d parame	lue of tl eformat ter β ₂	ne ion	0.00 - 0.11 - 0.21 - 0.31 - stable	0.10 0.20 0.30 0.40			

Y. Aboussir, J.M. Pearson, A.K. Dutta, and F. Tondeur. ADNDT 61(1995)127.

The changes in the mean square charge radii of the even-even Fe isotopes would directly reveal whether this picture holds.



Fe

Shape coexistence



- The lowering 2^+ energy is a sign of collectivity in the Fe isotopes;
- The close vicinity of an excited 0^+ energy level may lead to mixing of different configurations and shapes.

68Ee



Intruder states in the Co isotopes The $1/2\mathchar`-$ isomer in $^{67}{\rm Co}$



- When the (1/2⁻) level goes below the (3/2⁻) level, it becomes isomeric;
- Confirmation of the spin is required;
- What happens beyond N = 40?



Intruder states in the Co isotopes

... and beyond?



Dieter Pauwels, Ph.D. work

The comparison to the intruding $7/2^-$ energy level in the odd-*A* Cu isotopes suggests that the intruding $1/2^-$ level in the odd-*A* Co isotopes may become the ground state beyond N = 40.



Magic nuclei are our fundations

Mor	ner	nts	an	d
Radii	at	Ν	\sim	40

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- The nickel nuclei should remain spherical;
- There are hints of shape coexistence;
- They shall become the reference, like Sn at $Z\sim 50$ or Pb at $Z\sim 82$.



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Beams of Fe and Co at DESIR



In-trap decay of Mn

A target-free secondary reaction

Moments and Radii at $N \sim 40$

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Region

Specifics

Fe

Co

IN I

Beams

Intense beams of Mn are achievable with a laser ion source (GISELE);

- The half-lives are short-enough (T_{1/2} < 1s for A ≤ 60) that trapped ions can decay to Fe...and Co;
- The extracted beam can be sent to your favorite setup...





In-trap decay of Mn

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Region

Ni Beams

Proof of principle Coulomb excitation of ⁶¹Fe at ISOLDE

Moments and Radii at $N \sim 40$ T.E. Cocolios REX-Trai



Region

Ni Beams

Proof of principle Coulomb excitation of ⁶¹Fe at ISOLDE

Moments and Radii at $N \sim 40$ T.E. Cocolios EBIS REX-Tran



Region

Ni Beams

Proof of principle Coulomb excitation of ⁶¹Fe at ISOLDE

Moments and Radii at $N \sim 40$ T.E. Cocolios EBIS REX-Tran



Moments and

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Proof of principle Coulomb excitation of ⁶¹Fe at ISOLDE



J. Van de Walle et al., EPJA 42(2009)401.

Ni



Typical case

A = 67

Moments and Radii at *N* ~ 40

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Region

Specific

Fe

Co Ni







Typical case

A = 67

Moments and Radii at $N \sim 40$

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Region

Specific

Fe

Co Ni







Conclusion

Mor	ner	nts	an	d
Radii	at	Ν	\sim	40

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Region

Specifics

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Co

- Ground-state properties of neutron-rich Fe, Co, and Ni isotopes can bring valuable information to the understanding of the $N \sim 40$, $Z \leq 28$ region;
- The knowledge is very limited due to the difficulty of producing those beams;
- In-trap decay of Mn at DESIR is a possible solution up to A = 69.