EXOTIC BEAM SUMMER SCHOOL 2023



Nuclear Structure (Experiment)



Claus Müller-Gatermann





MOTIVATION

Why study nuclear structure using exotic beams? Necessary to understand nuclei far from stability!

Changes in nuclear shell structure Evolution of collectivity Phenomena which happen at extreme ratios of N/Z single or multiple nucleon decay nucleon skins, halos isospin symmetry breaking nuclear astrophysics

Primary Decay Mode Stable n e- capture Fission 2n p α β + 2p β - 2 β + 3p 2β - e+ Long-lived Estimated Unknown





NUCLEAR LANDSCAPE

255 stable isotopes 3100 observed isotopes 6000-8000 maybe particle stable





NUCLEAR LANDSCAPE



Heavy Elements shell stability island of SHE

Neutron drip-line Halos, skins pairing at low density new shell structure new collective modes r-process Stars, Supernovae



INGREDIENTS OF AN EXPERIMENT

Accelerator facility to provide beam

- stable/radioactive, pure/cocktail, intensity
- energies from keV to 100s MeV/A

A target

- solid/liquid/gaseous, density/thickness
- active targets

Instruments

- HPGe detectors
- Double-sided strip detectors (Si,Ge)
- scintillators
- magnetic spectrometers
- gaseous detectors
- ion traps
- ...

Theory

- interpretation of the data
- motivate experiments to validate theories



PRODUCTION OF BEAM/EXCITED STATES

6

Reactions

- Coulomb excitation (low and high energy)
- (deep-)inelastic scattering, (multi-nucleon) transfer reactions, incomplete fusion
- fusion-evaporation
- target/beam fragmentation
- nucleon knockout

Decay

DEPARTMENT OF

- alpha-decay
- beta-decay
- fission (spontaneous/induced)







NUCLEAR PROPERTIES

- Mass, half-life nuclear binding energy
- Level energy
- Electromagnetic matrix elements B(E2), B(M1), Q, lifetime, g-factor
- Reaction cross sections

transfer, knockout (need reaction model)





EVOLUTION OF LEVEL ENERGIES



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EVOLUTION OF LEVEL ENERGIES



12

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9

EVOLUTION OF DEFORMATION





SHELL STRUCTURE AND MAGIC NUMBERS



On Closed Shells in Nuclei. II

MARIA GORPPERT MAYER Argonne National Laboratory and Department of Physics, University of Chicago, Chicago, Illinois February 4, 1949

THE spins and magnetic moments of the even-odd nuclei have been used by Feenberg^{1,2} and Nordheim³ to determine the angular momentum of the eigenfunction of the odd particle. The tabulations given by them indicate that spin orbit coupling favors the state of higher total angular momentum. If strong spin-orbit coupling, increasing with angular momentum, is assumed, a level assignment different from either Feenberg or Nordheim is obtained. This assignment encounters a very few contradictions with experimental facts and requires no major crossing of the levels from those of a square well potential. The magic numbers 50, 82, and 126 occur at the place of the spin-orbit splitting of levels of high angular momentum.

Thanks are due to Enrico Fermi for the remark, "Is there any indication of spin-orbit coupling?" which was the origin of this paper.

.........

Physical Review 75 (1949)



SHELL STRUCTURE AND MAGIC NUMBERS





- j=l+1/2 orbitals from higher shells intrude into lower shell (f7/2, g9/2, h11/2,...)
- Increased stability for N,Z=2, 8, 20, 28, 50, 82... as energy difference to next shell is large
 - intruder states remain pure as strong interaction does not mix with opposite parity



SHELL STRUCTURE AND MAGIC NUMBERS



limits of existence:

neutron drip-line, island of SHE

- drip-lines are a benchmark for every nuclear model
- nuclear structure is different (Halo nuclei, skins, ...)
- sensitive to nuclear force

How about ²⁸O and ⁴⁰Mg?



NSCL @ MSU

⁴⁸Ca @140MeV/A on ^{nat}W 7.6d @ 5x10¹¹pps





SEARCH FOR ⁴⁰MG

dE proportional to Z^2 (diagonal lines for same Z) Time of flight proportional to A/Z x flight path/magnetic rigidity (vertical line for N=2Z)

3 events ⁴⁰Mg 1 event ⁴³Al 23 events ⁴²Al



SEARCH FOR ⁴⁰MG

- Existence of ⁴⁰Mg consistent with best global models
- The existence of odd-odd ⁴²Al contradicts the predictions to be unbound of both models
- Adding 1 proton to Mg has stabilizing effect
- Same for O to F?





SEARCH FOR ²⁸O







MAY THE STRONG FORCE BE WITH YOU

Proton-neutron monopole interaction changes position of single particle orbits as a function of proton-neutron ratio Attractive p-n force between J_{c} and J_{s} orbitals

>: I+1/2

<: I-1/2





VANISHING OF THE N=20 SHELL GAP





SHELL STABILIZATION OF SHE

Existence of SHE owed to shell correction to the liquid drop model

e.g. fission barrier ²⁵⁴No:

LDM: 0.9MeV LDM + Shell: >5MeV

13 order of magnitude difference in $\rm T_{_{1/2}}$







Kinematic compression in inverse kinematics - resolution Strong angle dependence - broadening







Helios approach



<u>ntities</u>
T _{flight} =T _{cvc}
Z
E _{lab}

Derived quan	<u>itities</u>
Part. ID:	m/q
Energy:	E _{cm}
Angle:	$\theta_{\sf cm}$

B=2T	
D-21	

Particle	T _{cyc} (ns)
р	34.2
³ He ²⁺	51.4
d , α	68.5
t	102.7



















Thank you for your attention!



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HELIOS









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Claus Müller-Gatermann





NUCLEAR SHAPES



Argonne

NUCLEAR SHAPES & COEXISTENCE







SHAPE COEXISTENCE IN HG ISOTOPES



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SHAPE COEXISTENCE IN HG ISOTOPES







DEFORMATION FROM LIFETIME

$$B(E2; J_i \to J_f) = 8.197 \cdot 10^{-2} \frac{b_{ij}}{1 + \alpha_{ic}(E_{\gamma})} E_{\gamma}^{-5} \tau^{-1}$$

$$Q_{t} = \sqrt{\frac{16\pi}{5} \frac{B(E2; J \to J - 2)2(2J - 1)(2J + 1)}{3J(J - 1)}}$$
$$\beta = 0.625(-5a + \frac{\sqrt{25a^{2} + 16aQ_{t}}}{a})$$
$$a = \frac{3}{\sqrt{5\pi}ZR_{0}^{2}}$$

Transition strength can be calculated model independent from lifetime

Quadratic dependence of the wavefunction (linear for energies)

Initial and final states are considered (Selection rules)

Absolute values of quadrupole moments, deformation... (model dependent)





THE RDDS METHOD







FEEDBACK SYSTEM







BATEMAN EQUATIONS





DIFFERENTIAL DECAY CURVE METHOD Gamma singles

$$\frac{d}{dt}n_i(t) = -\lambda_i \cdot n_i(t) + \sum_{k=i+1}^N \lambda_k \cdot n_k(t) \cdot b_{ki}$$

$$R(t) = \frac{I_u(t)}{I_u(t) + I_s(t)}$$

$$\tau_{i}(t) = \frac{-R_{i}(t) + \sum_{k} R_{k}(t) b_{ki} \alpha_{ki}}{\frac{d}{dt} R_{i}(t)}$$
$$\alpha_{ki} = \frac{\omega_{k}(\theta) \cdot \epsilon_{k}(E_{\gamma,k})}{\omega_{i}(\theta) \cdot \epsilon_{i}(E_{\gamma,i})}$$





DIFFERENTIAL DECAY CURVE METHOD

Gamma-Gamma coincidences

$$\frac{d}{dt}n_i(t) = -\lambda_i \cdot n_i(t) + \sum_{k=i+1}^N \lambda_k \cdot n_k(t) \cdot b_{ki}$$

$$\boldsymbol{R}(t) = \frac{\boldsymbol{I}_u(t)}{\boldsymbol{I}_u(t) + \boldsymbol{I}_s(t)}$$

$$\tau_{i}(\mathbf{x}) = \frac{I_{u}^{A}(\mathbf{x}) - \alpha(\mathbf{x})I_{u}^{B}(\mathbf{x})}{\frac{d}{dx}I_{s}^{A}(\mathbf{x}) \cdot \mathbf{v}}$$

$$\alpha_{x} = \frac{I_{u}^{A}(x) + I_{s}^{A}(x)}{I_{u}^{B}(x) + I_{s}^{B}(x)}$$

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GAMMA-RAY SINGLES EXPERIMENT





ANALYSIS OF 178HG





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SHAPE COEXISTENCE IN HG ISOTOPES



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CRITICAL POINT SYMMETRIES

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EVOLUTION OF COLLECTIVITY

				1 a d a															a	a	a	a	-
	Stabl	le le	ecay Ν β-	Node												¹⁹⁷ Fr	¹⁹⁸ Fr	¹⁹⁹ Fr	200 Fr	²⁰¹ Fr	²⁰² Fr	203 Fr	204
	2p 2n β+		e+ 2β+										¹⁹³ Rn	¹⁹⁴ Rn	¹⁹⁵ Rn	¹⁹⁶ Rn	¹⁹⁷ Rn	¹⁹⁸ Rn	¹⁹⁹ Rn	²⁰⁰ Rn	²⁰¹ Rn	²⁰² Rn	203
p 2p a Fission													¹⁹² At	¹⁹³ At	¹⁹⁴ At	¹⁹⁵ At	¹⁹⁶ At	¹⁹⁷ At	¹⁹⁸ At	¹⁹⁹ At	200 At	²⁰¹ At	202 ß
e- capture								¹⁸⁶ Po	¹⁸⁷ PO			¹⁹⁰ Po	¹⁹¹ Po	¹⁹² PO	¹⁹³ Po	¹⁹⁴ Po	¹⁹⁵ Po	¹⁹⁶ Ро	¹⁹⁷ Ρο _{β+}	¹⁹⁸ Po	¹⁹⁹ Ро _{в+}	²⁰⁰ Ρο _{β+}	201 β
							¹⁸⁴ Bi		¹⁸⁶ Bi	¹⁸⁷ Bi	¹⁸⁸ Bi	¹⁸⁹ Bi	¹⁹⁰ Bi	¹⁹¹ Bi	¹⁹² Βi β+	¹⁹³ Ві _{β+}	¹⁹⁴ Ві _{β+}	¹⁹⁵ Ві _{β+}	¹⁹⁶ Ві _{β+}	¹⁹⁷ Βi _{β+}	¹⁹⁸ Βi _{β+}	¹⁹⁹ Ві _{β+}	200 β
			¹⁷⁹ Pb	¹⁸⁰ Pb					¹⁸⁵ Pb	¹⁸⁶ Ρb	¹⁸⁷ Ρb	¹⁸⁸ Ρb _{β+}	¹⁸⁹ Ρb	¹⁹⁰ Ρb	¹⁹¹ Ρb	¹⁹² Ρb		¹⁹⁴ Ρb	¹⁹⁵ Ρb	¹⁹⁶ Ρb	¹⁹⁷ Ρb	¹⁹⁸ Ρb	199 β
	¹⁷⁶ TI P	¹⁷⁷ ΤΙ α	¹⁷⁸ ΤΙ α	¹⁷⁹ ΤΙ α	¹⁸⁰ ΤΙ β+	¹⁸¹ ΤΙ β+	¹⁸² ΤΙ β+	¹⁸³ ΤΙ β+	¹⁸⁴ ΤΙ β+	¹⁸⁵ ΤΙ β+		¹⁸⁷ ΤΙ β+	¹⁸⁸ ΤΙ β+	¹⁸⁹ ΤΙ β+	¹⁹⁰ ΤΙ β+		¹⁹² ΤΙ β+	¹⁹³ ΤΙ _{β+}	¹⁹⁴ ΤΙ β+	¹⁹⁵ ΤΙ _{β+}	¹⁹⁶ ΤΙ _{β+}	¹⁹⁷ ΤΙ β+	198 β
<mark>-</mark> lg	¹⁷⁵ Hg	¹⁷⁶ Hg	¹⁷⁷ Hg	¹⁷⁸ Hg	¹⁷⁹ Hg	¹⁸⁰ Ηg	¹⁸¹ Ηg	¹⁸² Ηg	¹⁸³ Нд _{β+}	¹⁸⁴ Ηg	¹⁸⁵ Ηg	¹⁸⁶ Hg β+	¹⁸⁷ Ηg	¹⁸⁸ Нд _{β+}	¹⁸⁹ Ηg	¹⁹⁰ Hg e- capture	¹⁹¹ Ηg	¹⁹² Hg e- capture	¹⁹³ Ηg	¹⁹⁴ Hg e- capture	¹⁹⁵ Ηg	¹⁹⁶ Hg _{Stable}	197 e- ca
Au	¹⁷⁴ Au	¹⁷⁵ Au	¹⁷⁶ Au	¹⁷⁷ Au	¹⁷⁸ Αu ^{β+}	¹⁷⁹ Αu _{β+}	¹⁸⁰ Αu	¹⁸¹ Αu _{β+}	¹⁸² Αu _{β+}	¹⁸³ Αu	¹⁸⁴ Αu	¹⁸⁵ Αu	¹⁸⁶ Αu _{β+}	¹⁸⁷ Αu _{β+}	¹⁸⁸ Αu _{β+}	¹⁸⁹ Αu	¹⁹⁰ Αu	¹⁹¹ Αu _{β+}	¹⁹² Αu _{β+}	¹⁹³ Αu	¹⁹⁴ Au _{β+}	¹⁹⁵ Au e- capture	196 β
Pt	¹⁷³ Pt	¹⁷⁴ Pt	¹⁷⁵ Pt	¹⁷⁶ Ρt β+	¹⁷⁷ Ρt _{β+}	¹⁷⁸ Ρt β+	¹⁷⁹ Ρt _{β+}	¹⁸⁰ Ρt β+	¹⁸¹ Ρt β+	¹⁸² Ρt β+	¹⁸³ Ρt β+	¹⁸⁴ Ρt β+	¹⁸⁵ Ρt β+	¹⁸⁶ Ρt β+	¹⁸⁷ Ρt β+	¹⁸⁸ Pt e- capture	¹⁸⁹ Ρt β+	¹⁹⁰ Pt _{Stable}	¹⁹¹ Pt e- capture	¹⁹² Pt _{Stable}	¹⁹³ Pt e- capture	¹⁹⁴ Pt _{Stable}	195 Sta
ļr	¹⁷² Ιr _{β+}	¹⁷³ Ιr _{β+}	¹⁷⁴ lr _{β+}	¹⁷⁵ Ιr _{β+}	¹⁷⁶ lr _{β+}	¹⁷⁷ lr β+	¹⁷⁸ lr β+	¹⁷⁹ lr β+	¹⁸⁰ lr β+	¹⁸¹ lr _{β+}	¹⁸² lr β+	¹⁸³ lr β+	¹⁸⁴ lr β+	¹⁸⁵ lr β+	¹⁸⁶ lr β+	¹⁸⁷ lr _{β+}	¹⁸⁸ lr β+	¹⁸⁹ Ir e- capture	¹⁹⁰ lr β+	191 1 Stable	¹⁹² lr β-	193 Stable	194 β
₽s	¹⁷¹ Οs β+	¹⁷² Οs β+	¹⁷³ Οs _{β+}	¹⁷⁴ Οs β+	¹⁷⁵ Οs β+	¹⁷⁶ Οs β+	¹⁷⁷ Οs _{β+}	¹⁷⁸ Οs β+	¹⁷⁹ Οs β+	¹⁸⁰ Οs β+	¹⁸¹ Οs _{β+}	182 Os e- capture	¹⁸³ Οs β+	¹⁸⁴ Os _{Stable}	¹⁸⁵ Os e- capture	186 OS Stable	187 OS Stable	188 OS Stable	189 OS Stable	¹⁹⁰ Os _{Stable}	¹⁹¹ Οs β-	¹⁹² Os _{Stable}	¹⁹³ (
Ŗe	¹⁷⁰ Re β+	¹⁷¹ Re β+	¹⁷² Re β+	¹⁷³ Re _{β+}	¹⁷⁴ Re β+	¹⁷⁵ Re β+	¹⁷⁶ Re _{β+}	¹⁷⁷ Re β+	¹⁷⁸ Re β+	¹⁷⁹ Re β+	¹⁸⁰ Re β+	¹⁸¹ Re β+	¹⁸² Re β+	¹⁸³ Re e- capture	¹⁸⁴ Re β+	¹⁸⁵ Re _{Stable}	¹⁸⁶ Rе _{β-}	187 Re Stable	¹⁸⁸ Re β-	¹⁸⁹ Re β-	¹⁹⁰ Re β-	¹⁹¹ Re β-	192 β
ŵ	¹⁶⁹ ₩ _{β+}	¹⁷⁰ ₩ _{β+}	¹⁷¹ ₩ _{β+}	¹⁷² ₩ _{β+}	¹⁷³ ₩ _{β+}	¹⁷⁴ ₩ _{β+}	¹⁷⁵ ₩ _{β+}	¹⁷⁶ W e- capture	¹⁷⁷ ₩ _{β+}	¹⁷⁸ W e- capture	¹⁷⁹ ₩ _{β+}	180W Stable	181 W e- capture	182 W Stable	183 W Stable	184W Stable	¹⁸⁵ ₩ β-	186 W Stable	¹⁸⁷ ₩ β-	¹⁸⁸ ₩ β-	¹⁸⁹ ₩ β-	¹⁹⁰ ₩ β-	
Тэ	168 T a	169 T a	170 Ta	171 Ta	172 T a	173 Ta	174 T a	175 T a	176 Ta	177 T a	178 T a	179 Ta	180 T a	181 T a	182 Ta	183 Ta	184 T a	185 Ta	186 T a		188 T a		190

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7









A CHARGED PLUNGER







A CHARGED PLUNGER







A CHARGED PLUNGER



1.00

(a) $4_1^+ \rightarrow 2_1^+$

PLUNGER WITH 3 FOILS







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PLUNGER WITH 3 FOILS









PLUNGER WITH 1 FOIL?







PLUNGER WITH 1 FOIL?





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