Overview Lecture 2:

- Inverse Kinematics Lifetimes and g Factors – g - Plunger
  - „Troubles” in Inverse Kinematics, and how to use them
- Proof of principle: Pd Chain
- Next Projects ...

The femto-second regime – Nuclear Resonance Fluorescence

- Introduction to Photon-Scattering
- Example: Investigation of $^{76}$Se with Continuous and „Laser” Beams
(g-)Plunger Experiments

Recoil Distance Doppler Shift (RDDS) method

\[
\Delta d
\]

\[
E'_\gamma = E_o(1 + \frac{v}{c}\cos(\theta))
\]

\[
E_\gamma = E_o
\]

NYPD
Yale Plunger

Plunger: Recoil Distance Method

\[ E_{sh} = E_0 (1 + \frac{v}{c} \cos \theta) \]

\(^{166}\text{Hf}: 4^+ \rightarrow 2^+\)

Counts / 0.5 keV

Energy (keV)
Inverse Kinematics

Recoil Distance Method

\[ v/c \sim 5-10\% \]

High recoil velocity
- large separation of peaks
  (and some problems we didn't have before....)

All I show is Coulomb Excitation
- direct excitation, no feeding!

Important now, next order

\[ E_{sh} = E_0(1 + \frac{v}{c\cos\theta}) + \beta^2/2 \]

\[ 2^+_1 \rightarrow 0^+_1 \]
Inverse Troubles

Intensity correction of $\gamma$ rays

Attenuation coefficients (solid angle) of the detectors - $Q$

Solid angle of the particle detector – **attenuation of the angular distribution**

Lorentz boost

$$\frac{d\Omega}{d\Omega'} = \left(\frac{E_\gamma}{E_{\gamma_0}}\right)^2 = \left[1 + \frac{(E_\gamma-E_{\gamma_0})}{E_{\gamma_0}}\right]^2$$

Nuclear Deorientation

*Hyperfine Interaction:* Precession of the nuclear spin $I$ and the electron spin $J$ about the total spin $F$

$F = I + J$

$J$ electron spin randomly oriented

$I$ nuclear spin aligned by reaction
Nuclear Deorientation (RIV)

Make use of “Recoil Into Vacuum” (RIV)

\[ W(\theta) = 1 + \sum_{i=2,4} G_i(t) Q_i B_i F_i P_i(\cos \theta) \]

\[ G_i(t) = \alpha_k + (1 - \alpha_k) \cdot \exp\left[-(g \cdot d)/(v \cdot C_k)\right] \]

\[ \Rightarrow \text{3 parameters: } \alpha_k, g, C_k \]

Distance dependent angular distribution:

\[ \frac{A_{2/4}^{\text{exp}}}{A_{2/4}^{\text{coul}}(d = 0)} = G_{2/4} \]
Angular Distributions

\[ W_0(\Theta) = \sum_k A_k P_k(\cos \Theta) \]

\[ A_k = \sqrt{2I + 1} \rho_0^k R_k Q_k = B_k R_k Q_k \]

Initial alignment characterized by: \[ B_k = \sqrt{2I + 1} \rho_0^k \]

\[ \rho_0^k = \sum_{mm'} (-1)^{I+m'} \langle I - m'Im|kq\rangle \rho_{m'm} \]

„statistical tensor”

\[ \rho_{m,m'} = a_m a_{m'}^* \]

\[ R_k Q_k \]

stat. coefficients and attenuation due to solid angle... can be calculated analytically

Since we use Coulomb excitation, which is a well-known E-M process, all the above can be calculated from Coulex Theory.

\[ a_m \] is the \( m \) component of the nuclear WF, and \( m \) is the component of the spin along the z-axis.
Parameters going into HF

Charge state of the ion exiting the target.

Depends on velocity. Average charge state is reached while passing through the target foil. (Avg. charge state reached within a fraction of the target at these velocities.)

-> Avg. charge state determines atomic physics (electron-configurations)

H. Betz, Rev. Mod. Phys. 44, 465 (1972)
Parameters going into HF

\[ E_{\text{HF}} = -\vec{\mu} \cdot \vec{B}_{\text{HF}} \]
\[ \vec{B}_{\text{HF}} \propto \vec{J} \]
\[ \vec{\mu} = g_i \vec{J} \mu_N \]

\[ E_{\text{HF}} = A \frac{\vec{I} \cdot \vec{J}}{\hbar^2} \]

\[ \vec{F} = \vec{I} + \vec{J} \]
\[ \langle \vec{I} \cdot \vec{J} \rangle = \frac{1}{2} \hbar^2 [F(F+1) - I(I+1) - J(J+1)] \]

Typical values: HF – splittings $10^{-6} – 10^{-7}$ eV ; $B_{\text{HF}} \sim 2-3$ kT

We don't quite know the atomic physics (values of $I$).
Since the nuclear ensemble is deorienting with time, we need a factor (function) to take this into account:

\[ W(\Theta, t) = \sum_k G_k(t) A_k P_k(\cos \Theta) \]

If there is no stopper (that is „normal” Recoil Into Vacuum – RIV):

\[ W_p(\Theta) = \langle W(\Theta, t) \rangle = \frac{1}{\tau} \int_0^\infty e^{-t/\tau} W(\Theta, t) dt = \sum_k A_k G_k(\infty) P_k(\cos(\Theta)) \]

\[ G_k(\infty) = \langle G_k(t) \rangle = \frac{1}{\tau} \int_0^\infty e^{-t/\tau} G_k(t) dt \]

with excited state lifetime \( \tau \)

If we would know the electron configurations (but we don’t)

\[ G_k(t) = \sum_{F,F'} C^{F,F'}_{I,J}(k) \cos(\omega_{F,F'} t) \]

\[ C^{F,F'}_{I,J}(k) = \frac{(2F + 1)(2F' + 1)}{2J + 1} \left( \begin{array}{ccc} F & F' & k \\ I & I & J \end{array} \right)^2 \]

\[ \omega_{F,F'} = g \frac{\mu_N}{\hbar} B_{HF} \frac{F(F + 1) - F'(F' + 1)}{2J} \]

(for each electron configuration)
Too Complicated!

We need a more empirical approach:

\[ G_k(t) = \sum_i q(J_i) \sum_{F,F'} C_{IJ}^{F,F'}(k) \cos(\omega_{FF'}t) \]

\( q(J) \) is a distribution of electron configurations.

Let us assume that electronic configurations (states) are much \textit{longer-lived} than the excited nuclear state -> Static Limit!

If the electronic states have a broad distribution, then the Larmor frequencies of the precessions are also broadly distributed.

-> Broad distribution of Larmor frequencies with some Lorentzian distribution width \( \Gamma_k \), which depends on the nuclear magnetic moment.

Broad distribution leads to exponential behavior of \( G_k \), and the initial orientation will never \textit{completely} be destroyed -> „hard-core” parameter \( \alpha_k \)

\[ G_k(t) = \alpha_k + (1 - \alpha_k) \cdot \exp(-\Gamma_k t) \]

\[ \alpha_k = \sum_F \frac{(2F + 1)^2}{2J + 1} \left( \begin{array}{ccc} F & F' & K \\ I & I & J \end{array} \right)^2 \]

we use as a parameter, since \( F, J \) unknown
Nuclear Deorientation (RIV)

Make use of “Recoil Into Vacuum” (RIV)

\[ W(\theta) = 1 + \sum_{i=2,4} G_i(t) Q_i B_i F_i P_i(\cos \theta) \]

\[ G_k(t) = \alpha_k + (1-\alpha_k) \cdot \exp[-(g \cdot d)/(v \cdot C_k)] \]

\[ A_{2/4}^{\text{exp}} / A_{2/4}^{\text{coul ex}}(d = 0) = G_{2/4} \]

\( F = I + J \)

J electron spin randomly oriented

I nuclear spin aligned by reaction

\( \Rightarrow \) Angular distribution is attenuated!

By precession of the nuclear spin due to the hyperfine interaction

\( \rightarrow \) deorientation coefficients.

\( \Rightarrow \) 3 parameters: \( \alpha_k, g, C_k \)

Distance dependent angular distribution:

A. Stuchbery et al., PRC 76, 034307 (2007)
High recoil velocity \((v/c \sim 6\%)\) 
-> large Doppler shift allows precise lifetime measurement

\[ ^{10}\text{Pd} \]

\[ ^{24}\text{Mg} \, 0.6 \, \text{mg/cm}^2 \text{ target} \]

\[ ^{nat}\text{Cu} \, 15 \, \text{mg/cm}^2 \text{ stopper} \]
T-Dependent Angular Distribution (or: TDRIV)

\[ W(\theta) = 1 + \sum_{i=2,4} G_i(t) Q_i B_i F_i P_i(\cos \theta) \]

Example of experimental and theoretical calculation of angular distribution for the stopped and the Doppler shift component.
G - Plunger TDRIV analysis

\[ G_k(t) = \alpha_k + (1-\alpha_k) \cdot \exp \left[ - \left( g \cdot (d-d_0)/(v \cdot C_k) \right) \right] \]

A. Stuchbery et al., PRC 76, 034307 (2007)

“calibrate” \( C_k \) of in one isotope with known \( g \) factor (\(^{106}\text{Pd}\))

- measure the time dependent attenuation
- “calibrate” an isotopic chain

\[ g(2^+_1,^{106}\text{Pd})^{\text{NNDC}} = +0.398(21) \]

\[ C_2 = 32.3(6.4) \mu\text{m} \]
\[ \alpha_2 = 0.23(5) \]

\[ C_4 = 16.0(2.2) \mu\text{m} \]
\[ \alpha_4 = 0.07(3) \]
We have 2 Peaks - use them!

\[ W(\Theta, t) = \sum_k G_k(t) A_k P_k(\cos \Theta) \]

**stopped peak:**
\[ G_k(t) = \alpha_k + (1 - \alpha_k) \cdot \exp(-\Gamma_k t) \]

**flight peak (decayed somewhere on the way):**
\[
G_k^{(\tau)}(d) = \frac{\int_0^d \left( \alpha_k + (1 - \alpha_k) \exp\left(-\Gamma_k \frac{x - d_0}{v}\right) \right) \cdot \exp\left(-\lambda \frac{x - d_0}{v}\right) \, dx}{\int_0^d \exp\left(-\lambda \frac{x - d_0}{v}\right) \, dx} \\
= \alpha_k + (1 - \alpha_k) \cdot \exp\left(-\Gamma_k - \lambda \right) \frac{d - d_0}{v} \cdot \frac{\lambda}{\Gamma_k + \lambda} \cdot \frac{\lambda}{1 - \exp\left(-\lambda \frac{d - d_0}{v}\right)}
\]
Simultaneous fit for each Isotope

96Ru

$G_2(d), \tilde{G}_2(d)$

relative distance [μm]

$G_4(d), \tilde{G}_4(d)$

relative distance [μm]

$G_2(d)$, $\tilde{G}_2(d)$

time [ps]

104Ru

$G_2(d), \tilde{G}_2(d)$

relative distance [μm]

$G_4(d), \tilde{G}_4(d)$

relative distance [μm]

$G_2(d)$, $\tilde{G}_2(d)$

time [ps]

104Ru

$G_2(d), \tilde{G}_2(d)$

relative distance [μm]

$G_4(d), \tilde{G}_4(d)$

relative distance [μm]

$G_2(d)$, $\tilde{G}_2(d)$

time [ps]
Negligible feeding => simple decay curve: \( P(d) = \frac{I_{\gamma}^{\text{doppler-shift}}}{I_{\gamma}^{\text{total}}} \)

\[ P(d) = 1 - \exp[- \lambda (d-d_0)] ; \quad \lambda = \frac{1}{(v \cdot \tau)} \]

\( \tau = 19.87(14) \text{ ps} \)

\( ^{106}\text{Pd} \)

Diagram showing probability of decay in-flight versus relative target-stopper distance (\( \mu \text{m} \)). Two curves are shown: one without deorientation correction and one with deorientation correction. The graph also shows mean lifetimes with different corrections applied.
Relative g-Factor Measurements

(The method does not give the sign of the g factor!)  

<table>
<thead>
<tr>
<th>Adopted value $^1$</th>
<th>$g(2_{1}^+)$</th>
<th>$^{104}$Pd</th>
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<tr>
<td>This work</td>
<td>+0.46(4)</td>
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<td></td>
<td>$</td>
<td>0.52(10)</td>
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<td>0.40(2)</td>
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| IBM-2 $^2$        | 0.42         | 0.392      | 0.366      |
| Shell-Model       |              | 0.5        |            |

$^1$Evaluated Nuclear Structure Data File


$^3$G. Gurdal et al., Phys. Rev. C 82, 064301 (2010); SM-int: JJ45PN (Hjorth-Jensen), Ni-core, fpg, dg
Relative $g$-Factor Measurements

(The method does not give the sign of the $g$ factor !)

| Adopted value $^1$ & +0.46(4) & +0.398(21) & +0.36(3) |
|---------------------|-----------|-----------|-----------|
| $g(2_1^+)$          | $^{104}$Pd | $^{106}$Pd | $^{108}$Pd |

This work       | 0.52(10) | 0.40(2)   | 0.32(5)   |
Ref $^3$              |          | 0.48(1)(?)|          |
This w. Rescaled | 0.62(10) | 0.48(1)   | 0.38(5)   |
IBM-2 $^2$            | 0.42     | 0.392     | 0.366     |
Shell-Model          | 0.5      |           |           |

$^1$ Evaluated Nuclear Structure Data File
$^3$ G. Gurdal et al., Phys. Rev. C 82, 064301 (2010); SM-Int: JJ45PN (Hjorth-Jensen), Ni-core, fpg, dg
Relative $g$-Factor Measurements

(The method **does not give the sign** of the $g$ factor !)

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<table>
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<tr>
<th>Adopted value $^1$</th>
<th>14.9(9)</th>
<th>17.6(6)</th>
<th>34.6(18)</th>
</tr>
</thead>
<tbody>
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<td>$\tau(2_{1}^+)$</td>
<td>$^{104}$Pd</td>
<td>$^{106}$Pd</td>
<td>$^{108}$Pd</td>
</tr>
<tr>
<td>This work</td>
<td>15.64(18)</td>
<td>19.87(14)</td>
<td>39.05(67)</td>
</tr>
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**Even worse:** This change in $\tau$ will affect the $g$ factor as well!

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August 6-10, 2012
Volker Werner, Exotic Beam Summer School 2012
G - Plunger Experiments so far

Use of stable beams at the WNSL Tandem accelerator.

Restricted to stable beams, understaffed

-> ceased operation in 2011.

Used the YRAST-Ball array – work to be continued at other facilities with stable AND unstable beams!

$^{104-108}$Pd: G. Ilie, in preparation & CGS 14

$^{96,98,104}$Ru: D. Radeck, PRC 85, 014301 (2012)

$^{92,94}$Zr: Matt Hinton, MPhys U. Surrey (UK)
First g-plunger experiment device at ATLAS / Gammsphere: $^{138,142}$Ce

*October 2011* – analysis with F. Naqvi

Plan: use radioactive CARIBU beams in future experiments. Later: ReA3 Beams at NSCL.

New plunger to be built for experiments with Re-accelerated radioactive beams.

New approach to test the g-plunger technique with relativistic beams. Has to overcome one complication!
First Estimates from HF Simul.

\[ v/c \approx 6\%, \text{Charge State} \approx 8-12 + \]

\[ \rightarrow \text{nice exponential behavior...} \]

\[ v/c \approx 40\%, \text{Charge State} \approx Z - 1 + \]

\[ \rightarrow \text{fast oscillations, details depend on atomic orbits} \]

Needs understanding and testing with stable beams first.
Region 1

fs - regime

(One way to get there is similar to plunger, but by looking at the stopping process leading to a Doppler-Lineshape – we saw this. Alternative: cross-section measurements!)
Low-Lying Dipole Strength

- Giant Dipole Resonance: $E_x \sim 10 - 20$ MeV, $B(E1) \sim 5 - 10$ W.u.
- Orbital “Scissors” mode: $E_x \sim 3$ MeV, $B(M1) \sim 3 \mu_N^2$
- Two Phonon Excitation: $E_x \sim 4$ MeV, $B(E1) \sim 10^{-3}$ W.u.
- Pygmy Dipole Resonance ?
N/Z Dependence

**Experiment**

- $^{136}\text{Xe}$, N/Z = 1.52
- $^{138}\text{Ba}$, N/Z = 1.46
- $^{140}\text{Ce}$, N/Z = 1.41
- $^{142}\text{Nd}$, N/Z = 1.37
- $^{144}\text{Sm}$, N/Z = 1.32

**Quasiparticle-Phonon-Model (QPM)**

- $^{136}\text{Xe}$
- $^{138}\text{Ba}$
- $^{140}\text{Ce}$
- $^{142}\text{Nd}$
- $^{144}\text{Sm}$


V. Yu. Ponomarev
PDR <-> Neutron Skin

Clear dependence on neutron skin!
Possible influence of the PDR on the r-process:

Reliable extrapolation to exotic nuclei requires a detailed understanding of the PDR

Structural Motivation: Evolution of the PDR toward deformed nuclei!

“Side Motivation”:

An odd situation:
Learn about a weakly interacting particle by look at a strongly interacting system.

Why nuclear structure?
First claim on the observation of $0\nu2\beta$ decay $^{76}\text{Ge} \to ^{76}\text{Se}$ has been made (Heidelberg-Moscow)
New experiments just started or are about to start (GERDA / MAJORANA)
Observation of the decay rate is not sufficient to extract masses
Need: Nuclear Matrix Elements!!
Can only be extracted from nuclear theory
=> scrutinize involved theories

Some selected experiments going that way:
Schiffer et al.: ground state wave functions from transfer reactions
WNSL: gamma-spectroscopy on intermediate nuclei
HIGS/TUNL/Darmstadt(GER): dipole response of $0\nu2\beta$ candidates
UK Lexington: $\gamma$-spectroscopy after neutron scattering
ANU (Australia): electron spectroscopy
TRIUMF: in-trap spectroscopy => EC decay branchings
$\Pi \lambda$ strengths
$\Delta J = 1,2$
high energy resolution

Nuclear Resonance Fluorescence
Connection to Lifetimes

In a nutshell – description of resonance: Breit-Wigner

\[ \frac{d^2 \sigma_{abs}(E)}{d\Omega dE} = \pi \chi^2 \cdot \frac{2j + 1}{2(2j_0 + 1)} \cdot \frac{\Gamma_0 \Gamma_f}{(E - E_r)^2 + \frac{1}{4} \Gamma^2} \cdot \frac{W(\theta)}{4\pi} \]

Integrate that over solid angle and the resonance:

\[ I_{s,f} = \pi^2 \chi^2 \cdot \frac{2J + 1}{2J_0 + 1} \cdot \frac{\Gamma_0 \Gamma_f}{\Gamma} \]

Integrated cross-section from size of the observed peak to "f"inal state.
Measurement of x-sections always relative to a standard! For example, $^{27}\text{Al} / ^{11}\text{B}$ have well-known cross-sections.

Measure Al/B states, measure / simulate detector efficiency
=> Photon Flux / Cross-section calibration
Connection to Lifetimes

Extract:

Resonance width:

\[
\frac{\Gamma_0^2}{\Gamma} = \frac{2j_0 + 1}{2j + 1} \cdot \left( \frac{E_\gamma}{\pi \hbar c} \right)^2 \cdot I_{s,0}
\]

\[
\Gamma = \frac{\Gamma_0^2}{\Gamma} \cdot \left( 1 + \sum_{f>0} \frac{\Gamma_f}{\Gamma_0} \right)^2
\]

(if branchings known)

And the relation to lifetimes is:

\[
\frac{1}{\tau} = \Gamma = \sum_{f \geq 0} \Gamma_f
\]

Typical lifetimes for strongly dipole-excited states: \textit{femto- / attoseconds}!

\textit{NRF is a model-independent way to measure lifetimes!}
Continuous Bremsstrahlung beams allow to identify dipole-excited states! Parity determination is possible via polarimetry, but difficult. (Figures of merit of polarimeters are not favorable, especially at high energies.)

Target ~ 4 g enriched 76Se
Continuous Bremsstrahlung beams allow to identify dipole-excited states!
Parity determination is possible via polarimetry, but difficult.
(Figures of merit of polarimeters are not favorable, especially at high energies.)

Target ~ 4 g enriched 76Se
Continuous Bremsstrahlung beams allow to identify dipole-excited states! Parity determination is possible via polarimetry, but difficult. (Figures of merit of polarimeters are not favorable, especially at high energies.)

Target ~ 4 g enriched 76Se
Spin Determination

\[ \frac{W(90^\circ)}{W(130^\circ)} \]

Diagram showing the relationship between energy and spin determination, with labels for different transitions and detector orientations.
Absolute X-Sections

Strength concentrations – E1?
HIGS (Free Electron Laser)

H.R. Weller et al.  
Progress in Particle and Nuclear Physics  

100% polarized, near-monoenergetic gammas

Precollimator (x, y) = (32, 20) mm

Primary Collimator

BEAM SPECTRA
6.6 MeV
6.85 MeV
7.1 MeV

Counts

Energy (keV)

6000  6200  6400  6600  6800  7000  7200  7400
Actually beam profile derived from $0^\circ$ HPGe spectrum and GEANT simulation.
Polarization => Parity

Clear (and easy) identification of E1 excited states through asymmetry horizontal/vertical

\[ P_{\text{ana}} = \frac{W_{\text{hor}} - W_{\text{ver}}}{W_{\text{hor}} + W_{\text{ver}}} \]

Close lying E1 M1 – irresolvable at TUD

Almost all: E1

Positive Parity

Negative Parity

Energy (MeV)
Combined HIGS & TUD Data

Between ~ 4-9 MeV: Cross sections from TU Darmstadt, parities from HIGS

Nathan Cooper, Yale
submitted to PRC

Phil Goddard, Yale/Surrey
MPhys thesis, in prep. for PRC

Deformation splitting of the GDR (oscillations with respect to two ellipsoid axes)

E1 strength distribution suggests that Pygmy strength is split. Splitting due to $\beta$-deformation?

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![Graph showing cross sections from 4 to 9 MeV with isotopes $^{154}$Sm and $^{144}$Sm.]

![Graph showing $B(E1)$ values for $^{76}$Se.]

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August 6-10, 2012
Volker Werner, Exotic Beam Summer School 2012
Anything on the GDR Tail ??

Data from Bremsstrahlung only!
Two Lorentzians fitted because $^{76}$Se is deformed ($\beta \sim 0.31$)

Overpredicts low-energy data

$$\sigma_{SLO} \propto \frac{E^2 \Gamma^2}{(E^2 - E_0^2)^2 + E^2 \Gamma^2}$$

$$\sigma_{GLO} \propto E \Gamma \left[ \frac{E \Gamma(E)}{(E^2 - E_0^2)^2 + E^2 \Gamma(E)^2} \right]$$
Much E1 Strength is Hidden

Higher-lying states decay stronger to excited states – corrections to total E1 excitation strength!

- Could be an effect of structure of the higher (> 7 MeV) states -> GDR
- In Pygmy region: affects sum strength by a factor of 2 or more

Now including HIGS Data:

Add observed decays from 2+ back into excitation cross section

Usually observed

many unobserved branchings

Can only come from feeding from 1−
Another way of splitting the PDR

Higher lying states not excited in $\alpha$-scattering
⇒ Different underlying structure
(isoscalar / isovector part)
Switch from PDR to GDR?

Sn isotopes:
Calculated proton / neutron densities
-> neutron skin

Transition densities:
Isoscalar, n-oscillation on surface

Tsonева / Lenske, PRC 77, 024321 ('08)
HFB + QPM

Isovector -> GDR
What's next?

First: finish all corrections from HIGS data and refit Lorentzians!

Comparison to $2\beta$-decay partner $^{76}\text{Ge}$

We need a means of observing the intermediate transitions, *Directly*!

Same holds for other excitation modes, few examples follow...
First Glimpse $^{76}$Ge

Pete Humby, Yale/Surrey, very first plot
Q-O Phonon Schemes

\[ (2^+_1 \otimes 2^+_{\text{ms}}) \]

Mixed-symmetry

\[ 1^+_{\text{sc}} \]

\[ 2^+_{\text{ms}} \]

\[ 2^+_2 \]

\[ 2^+_1 \]

E2

M1

Octupole

\[ (2^+_1 \otimes 3^-) \]

\[ 1^- \]

\[ 3^- \]

\[ 2^+_2 \]

\[ 2^+_1 \]

\[ 0^+_1 \]

sdf–IBM–2
Q-O MS Coupling Scheme

$Q-O$ MS Coupling Scheme

$\left( \begin{array}{c} 2^+_{ms} \\ 3^- \end{array} \right)$

$1^-_{ms}$

$1^-_{ms}$

$1^+_{sc}$

$2^+_{ms}$

$0^+_{1}$

$3^-$

$1^-$

$\left( \begin{array}{c} 2^+ \\ 3^- \end{array} \right)$

$2^+_{1}$

$2^+_{ms}$

$E1$

$E2$

$E3$

$E1$

$E1$

$E1$

$M1$

$M1$

$M1$

$Smirnova et al., NPA 678, 235 (2000)$

Missing so far: $3^-_{ms} \rightarrow M. Scheck$
A new project coming up: Extreme Light Infrastructure (ELI) in Europe (Collide highly-intense electron beam high-power lasers)

First time γ-coincidences after photo-excitation -> 2012

Complemented by α-scattering (KVI / Texas A&M)

Study of the Pygmy Dipole Resonance -> Neutron Skins
Study of Multi-Phonon States
A new project coming up: Extreme Light Infrastructure (ELI) in Europe (Collide highly-intense electron beam high-power lasers)
Thank you!

The Yale Nuclear Structure Group 2012

Farheen Naqvi, PD
Nathan Cooper, GS
Rick Casten, Prof.
Christian Bernards, PD
Volker Werner, PI

+ Peter Humby (MPhys Surrey) !!