Investigation of States Populated in the ^{102}Ru(p,t)^{100}Ru Two Neutron Transfer Reaction

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WNPPC : February 18, 2023

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Overview

Topics of Discussion

- Background
- Project Motivation
- Experiment
- Results & Discussion
- Summary

Background : Nuclear Models

Shell Model

- Independent particle model
- Designed to account for quantal properties of nuclei, such as spins, quantum states, magnetic moments, and magic numbers.
- Fundamental assumption that all the nucleons are different ; i.e. nucleons are fermions and must occupy different quantum states as a result of the Pauli exclusion principal

Collective Model

- Groups of nucleons act together
- Integration of both global properties and quantal properties of nuclei

- Two major types of collective motion:

1. Rotations: Rotations of a deformed shape
2. Vibrations: Surface oscillations

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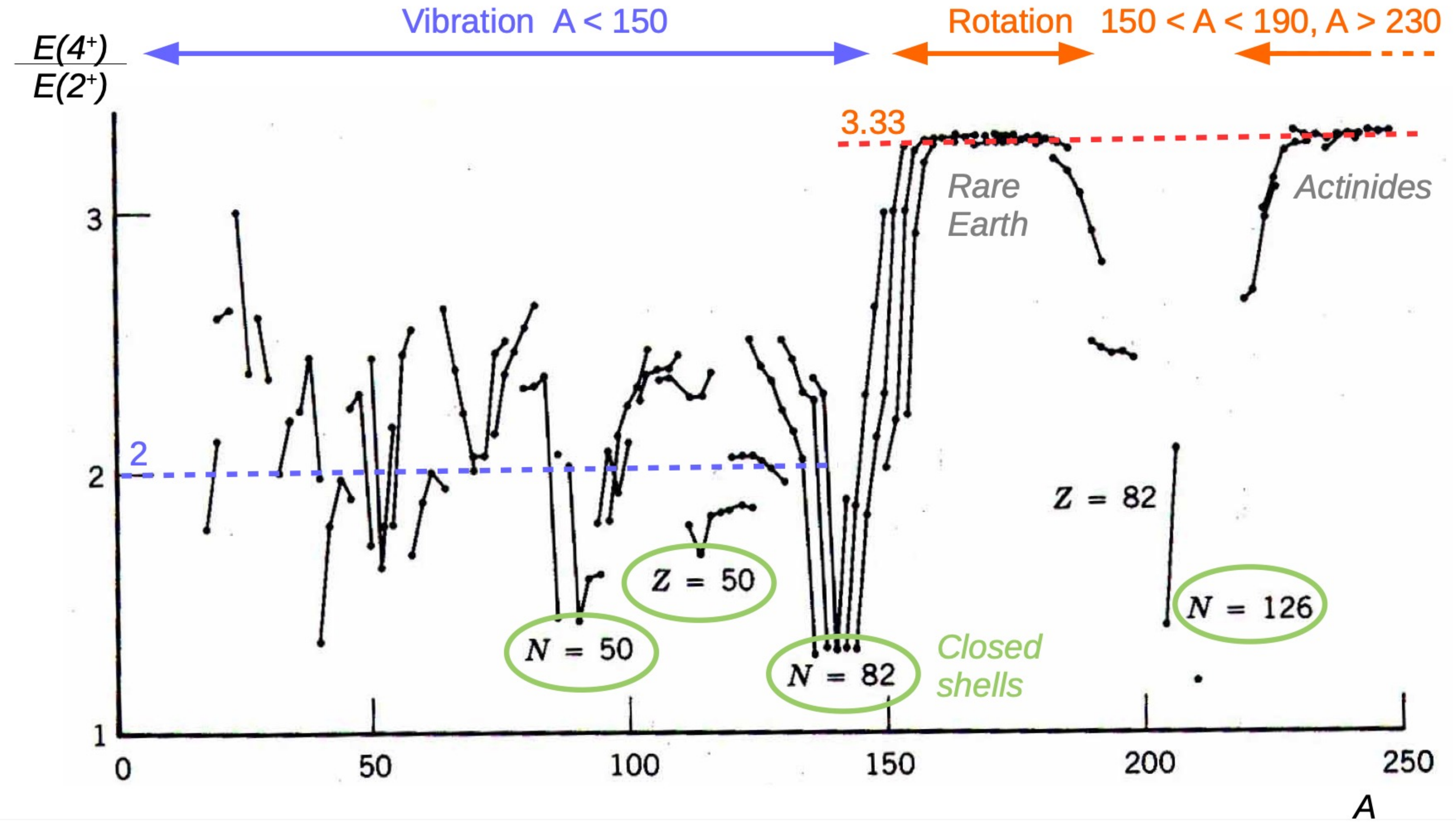
Background: Collective Model

In nuclear spectra, we can identify three kinds of excitations:

1) Single nucleon excited states
2) Vibrational excited states
3) Rotational excited states

$$\frac{E\left(4_1^+\right)}{E\left(2_1^+\right)}$$

For even-even ground state nuclei, the ratio of excitation energies $\frac{E(4^+)}{E(2^+)}$ is a diagnostic of the type of excitation.



Single nucleon excited states may, to some extent, be predicted from the simple Shell Model. Most likely to be successful for lowest-lying excitations of odd A nuclei near closed shells.

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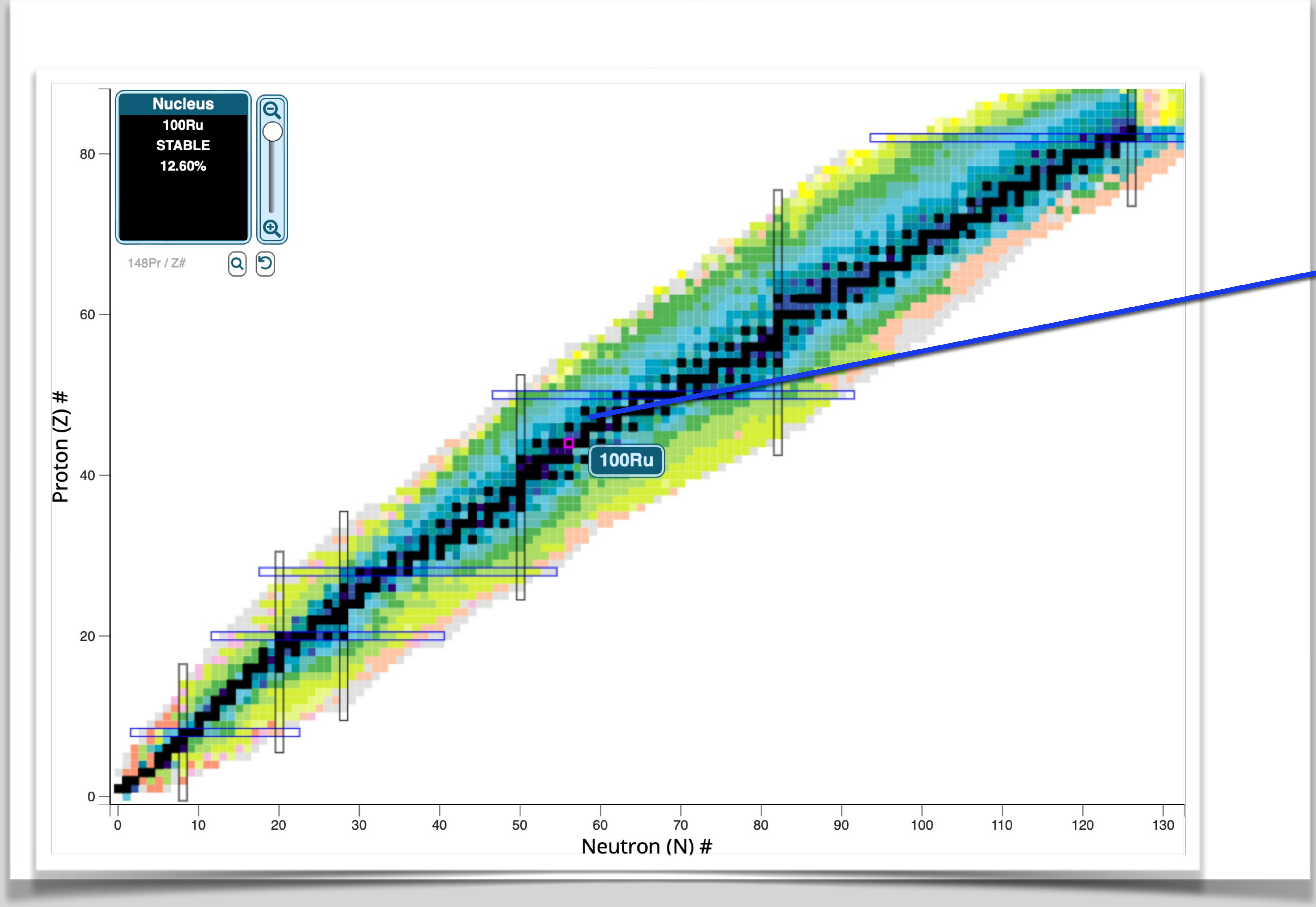
Project Motivation

Significance of Studying ^{100}Ru:



Project Motivation : Probing Pairing Content via Two-Nucleon Transfer Reactions

- Pairing correlations are important for calculations of the nuclear matrix elements:

  Do the correlations follow a normal BCS scheme or not?

- Shape co-existence may disrupt the normal BCS distributions:

  Shape coexistence is known to occur approximately in the Z=40 N=60 region of the nuclear chart

- Reactions that involve the transfer of two alike particles, such as the (p,t) two-neutron transfer reactions, specifically probe such pairing correlations:

  We are probing the pairing correlations in ^{100}Ru via the ^{102}Ru(p,t)^{100}Ru reaction

- To a high degree of accuracy, when both transferred nucleons are of the same type, they couple to total spin S = 0, so J = L:

  As such, when the target S=0, the final states have J=L

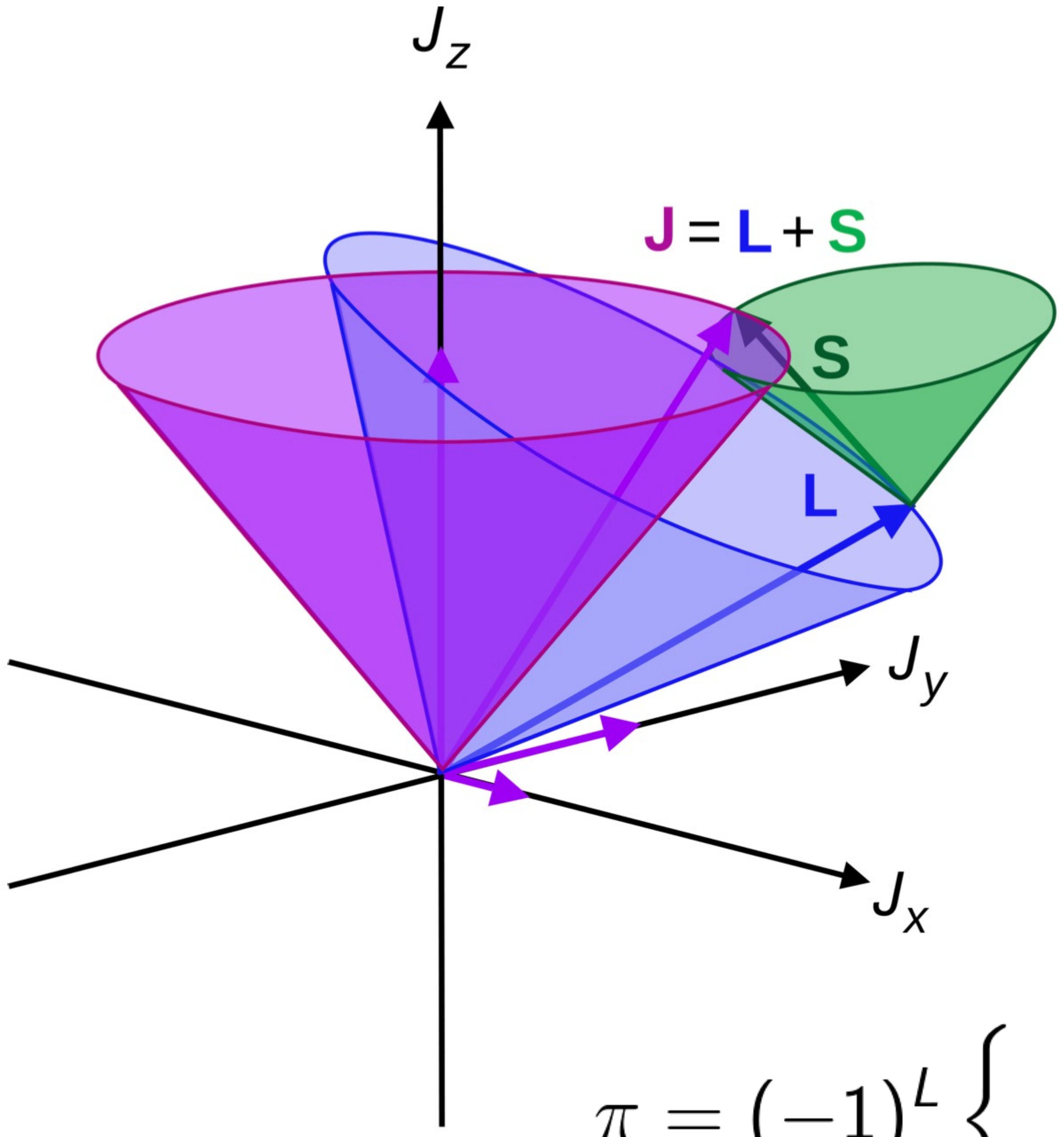
Project Motivation

Significance of Studying ^{100}Ru:

$$\vec{J} = \sum_{i=1}^{A} \vec{j_i} \;\Rightarrow\; \vec{J} = \vec{j}_1 + \vec{j}_2$$

$$\boxed{\vec{L} = \vec{\ell}_1 + \vec{\ell}_2}$$

$$\boxed{\begin{aligned} \vec{S} &= \vec{s}_1 + \vec{s}_2 \\ &= \uparrow + \downarrow \\ &= 0 \end{aligned}}$$



$$\boxed{\begin{aligned} \vec{J} &= \vec{S} + \vec{L} \\ \vec{J} &= 0 + \vec{L} \\ \vec{J} &= \vec{L} \end{aligned}}$$

$$\pi = (-1)^L \begin{cases} \text{odd } L = \text{ negative parity state} \\ \text{even } L = \text{ positive parity state} \end{cases}$$

Project Motivation: ^{102}Ru(p,t)^{100}Ru

- The advantageous feature that this transfer reaction provides is the spin parities of the nuclear states for an even-even target.

- We perform the ^{102}Ru(p,t) reaction, locate the natural spin parity states in ^{100}Ru, and examine the relative strengths of the excited 0+ states.

- Using normal BCS pairing, the strength to excited 0+ states is expected to be a few percent. However, when we see strengths ~10 percent or greater, this is considered a significant enhancement in the transition strength, and therefore would reflect a very special characteristic of the excited state in question.

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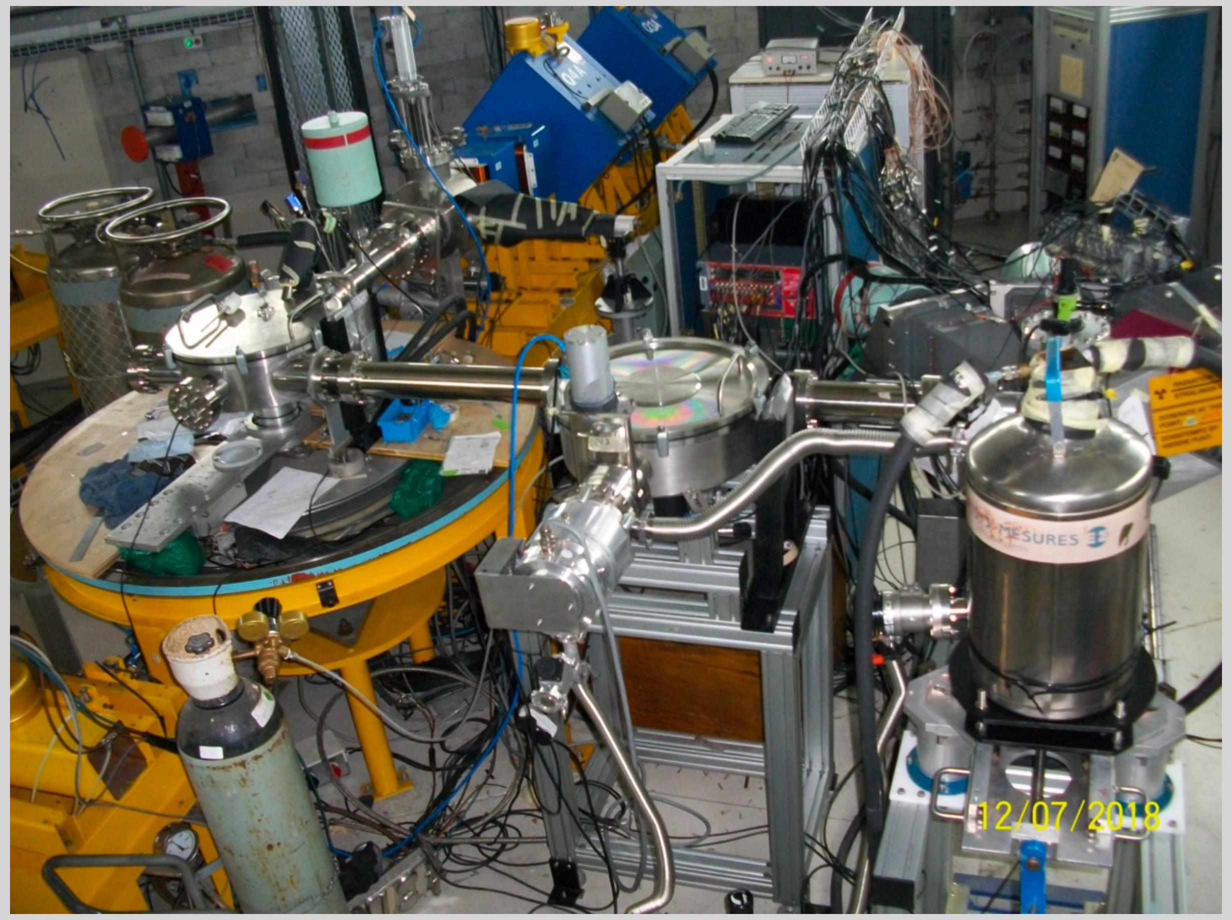
Experiment: ^{102}Ru(p,t)^{100}Ru

Purpose: ***Part of a multi-prong campaign aimed at investigating the structure of ^{100}Ru***

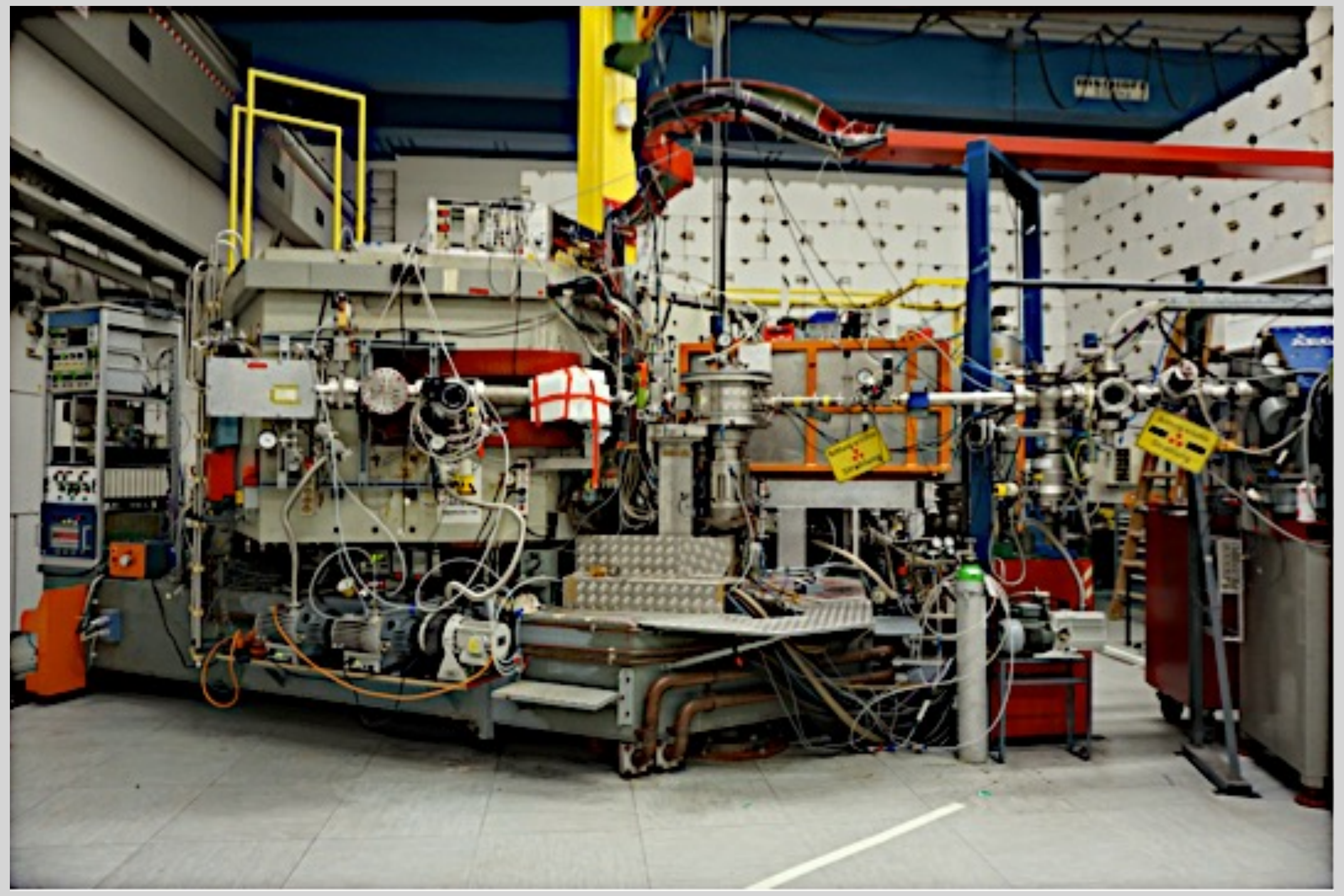
Ithemba LABS: Beta Decay



June 2018

Cape Town, South Africa

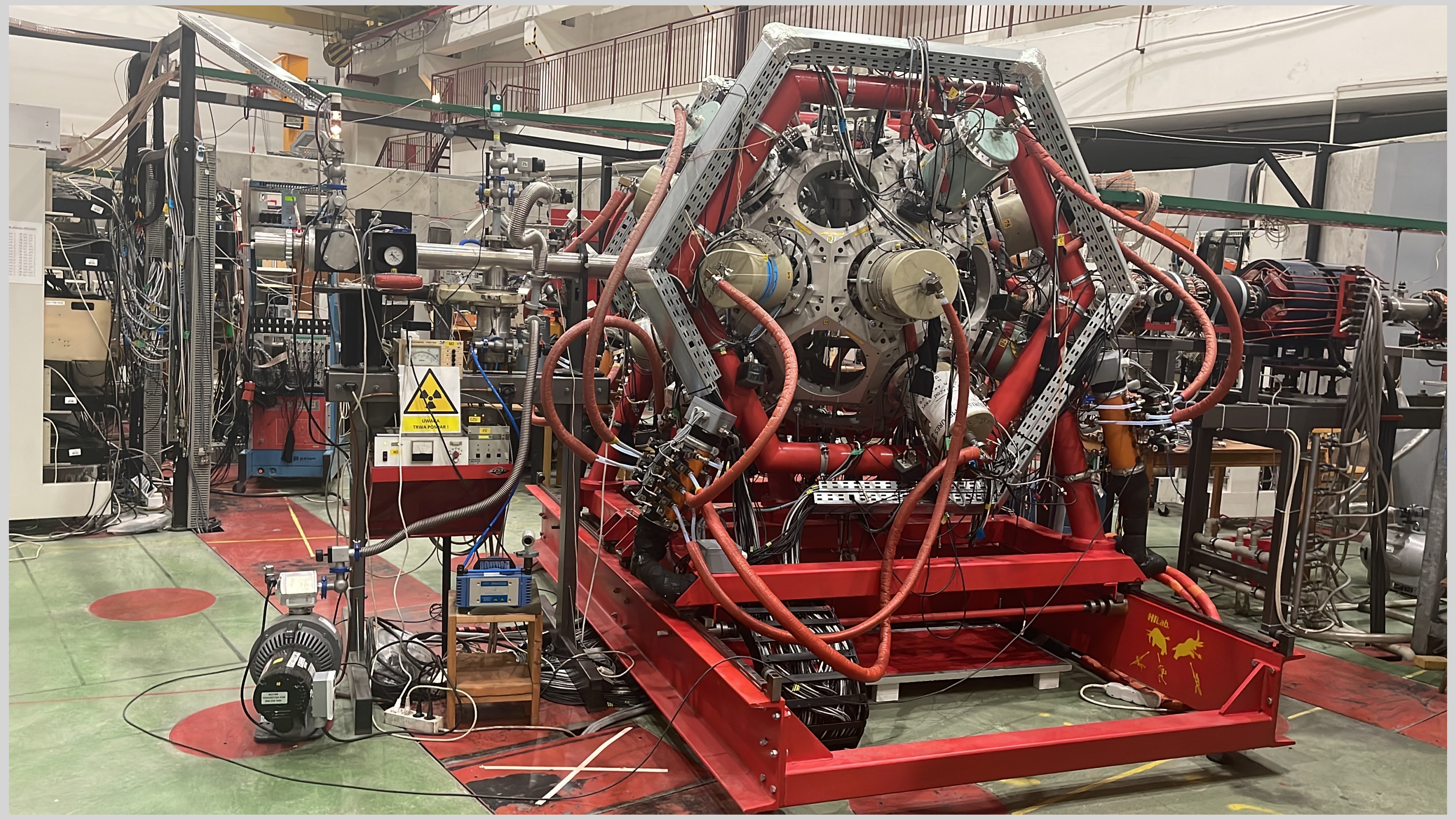
MLL Q3D Magnetic Spectrograph : Transfer Reaction



August 2019

Garching, Germany

HIL: Coulomb Excitation



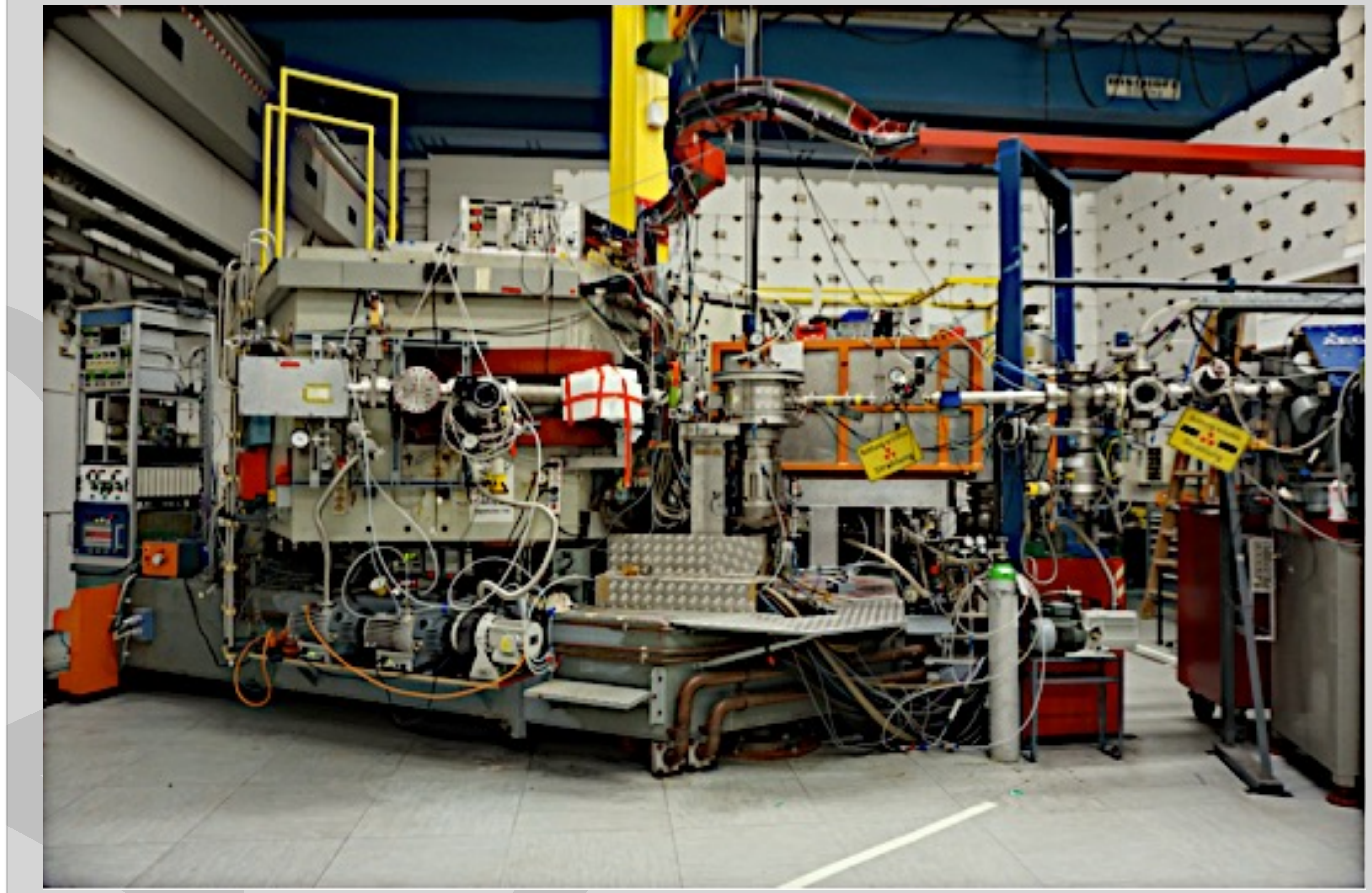
March 2022

Warsaw, Poland

Experiment: ^{102}Ru(p,t)^{100}Ru

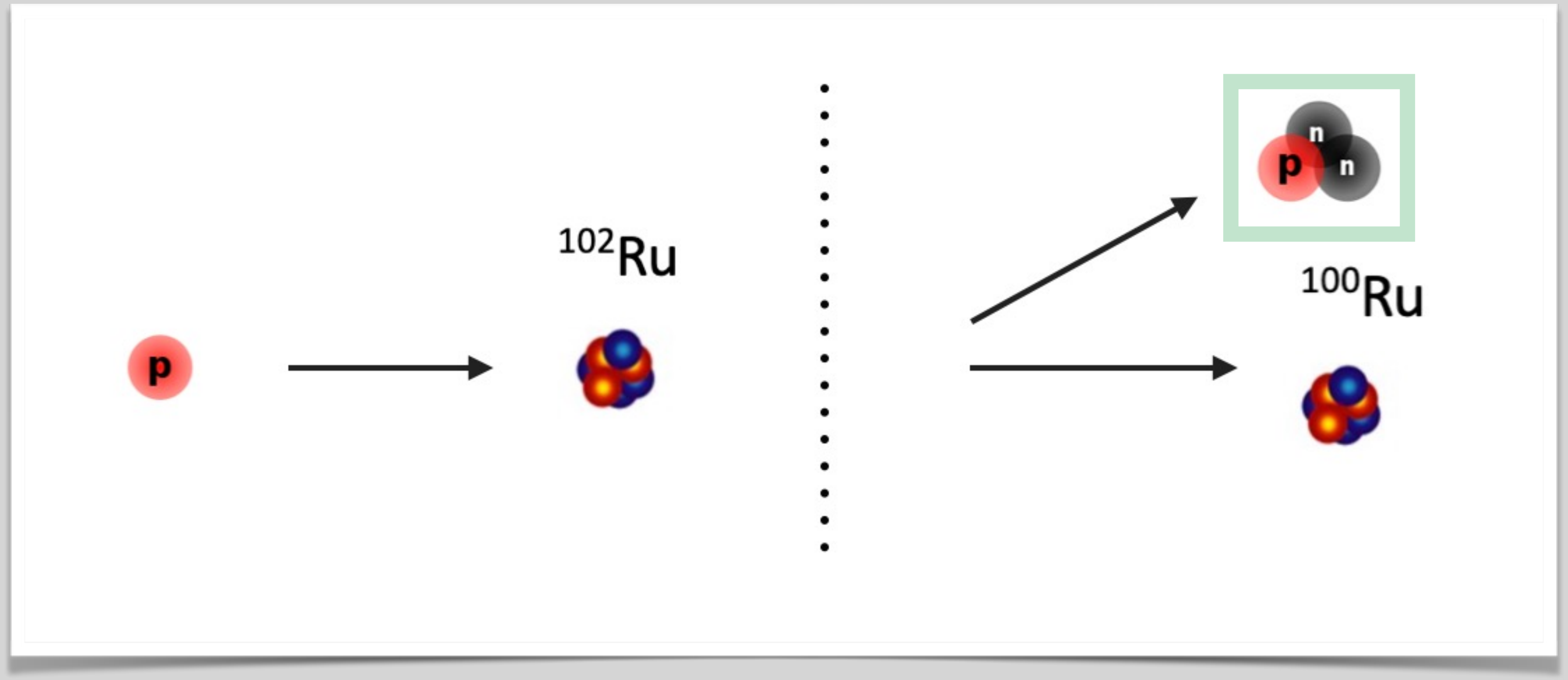
^{102}Ru(p,t)^{100}Ru : Study of ^{100}Ru via a two-neutron transfer reaction experiment performed using the Q3D magnetic spectrograph at the Maier-Leibnitz Laboratory, in Garching, Germany

Q3D Magnetic Spectrograph :
Transfer Reaction



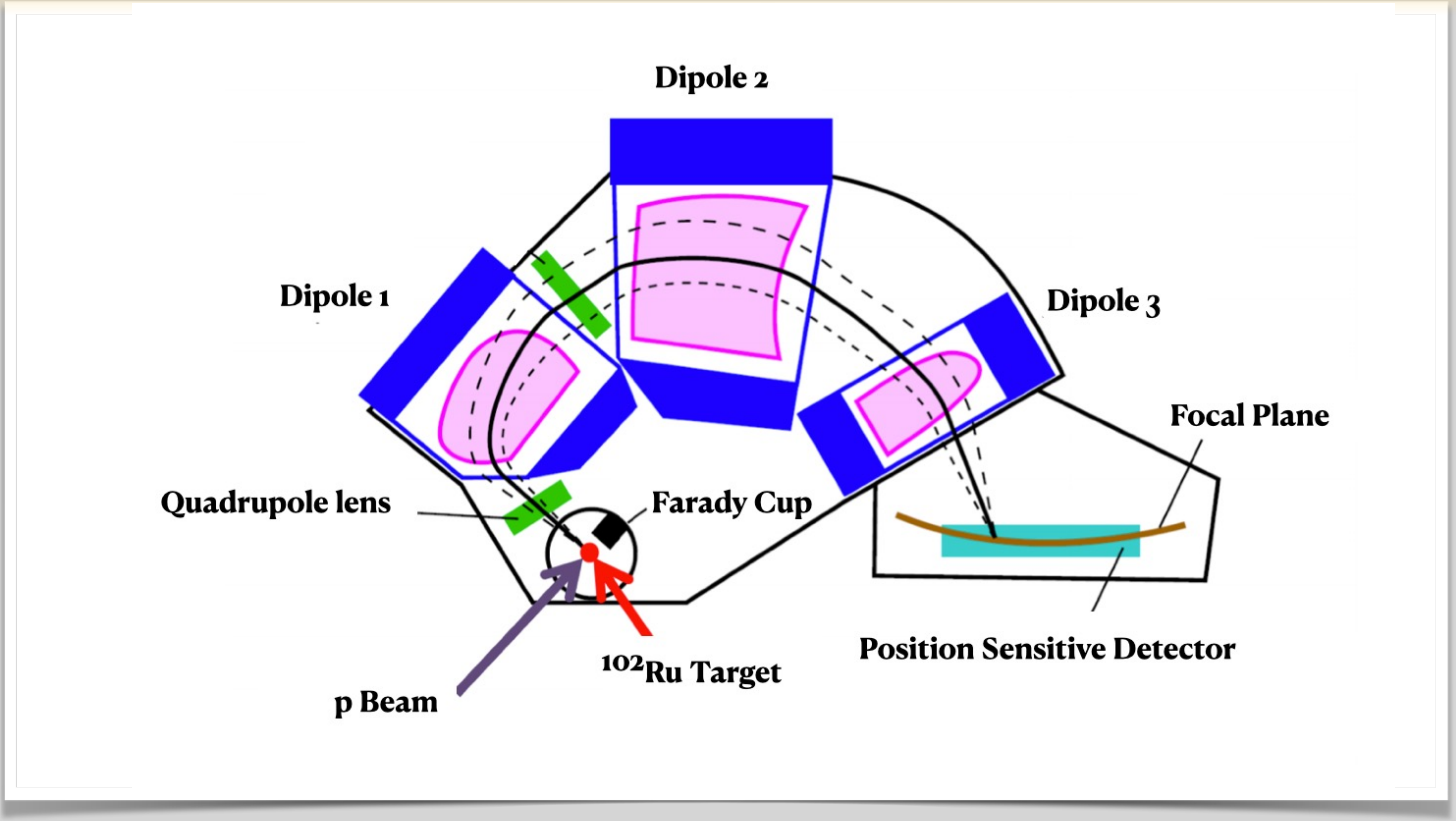
Garching, Germany

- ***Experimental Procedure** employed a target of ^{102}Ru and bombard it with protons that effectively "pick-up" two neutrons from this target, resulting in the production of ^{100}Ru.*



- *By removing a pair of particles from the system, one can study the neutron-pair properties of the states we observe in the reaction, leading to a better understanding of the structure of ^{100}Ru.*

Quadrapole-3-Dipole Magnetic Spectrograph (Q3D)



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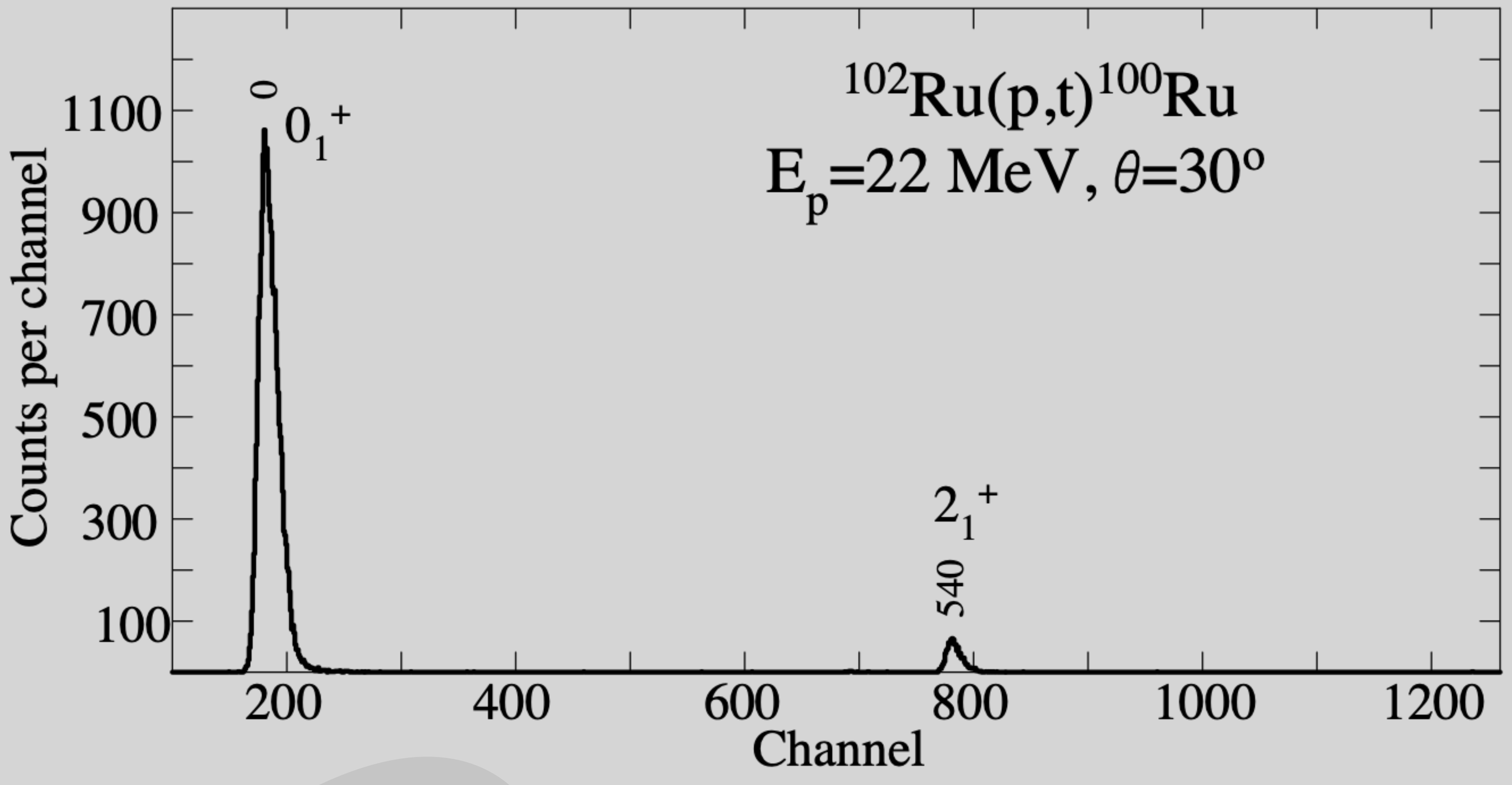
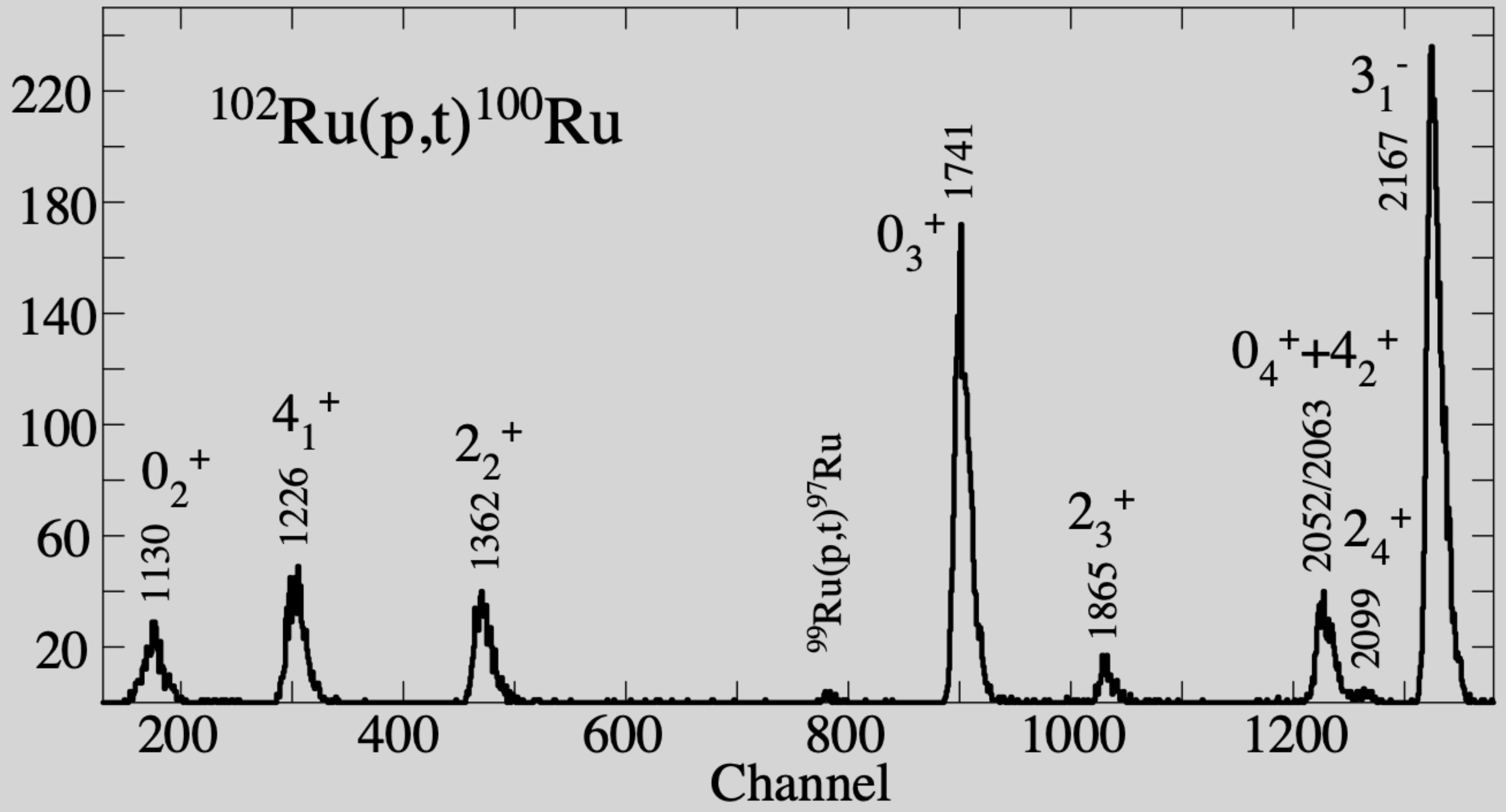
Spectra

Due to the finite acceptance of the focal plane (i.e. length of the detector), data are collected in finite "bites" differentiated with different magnetic field settings

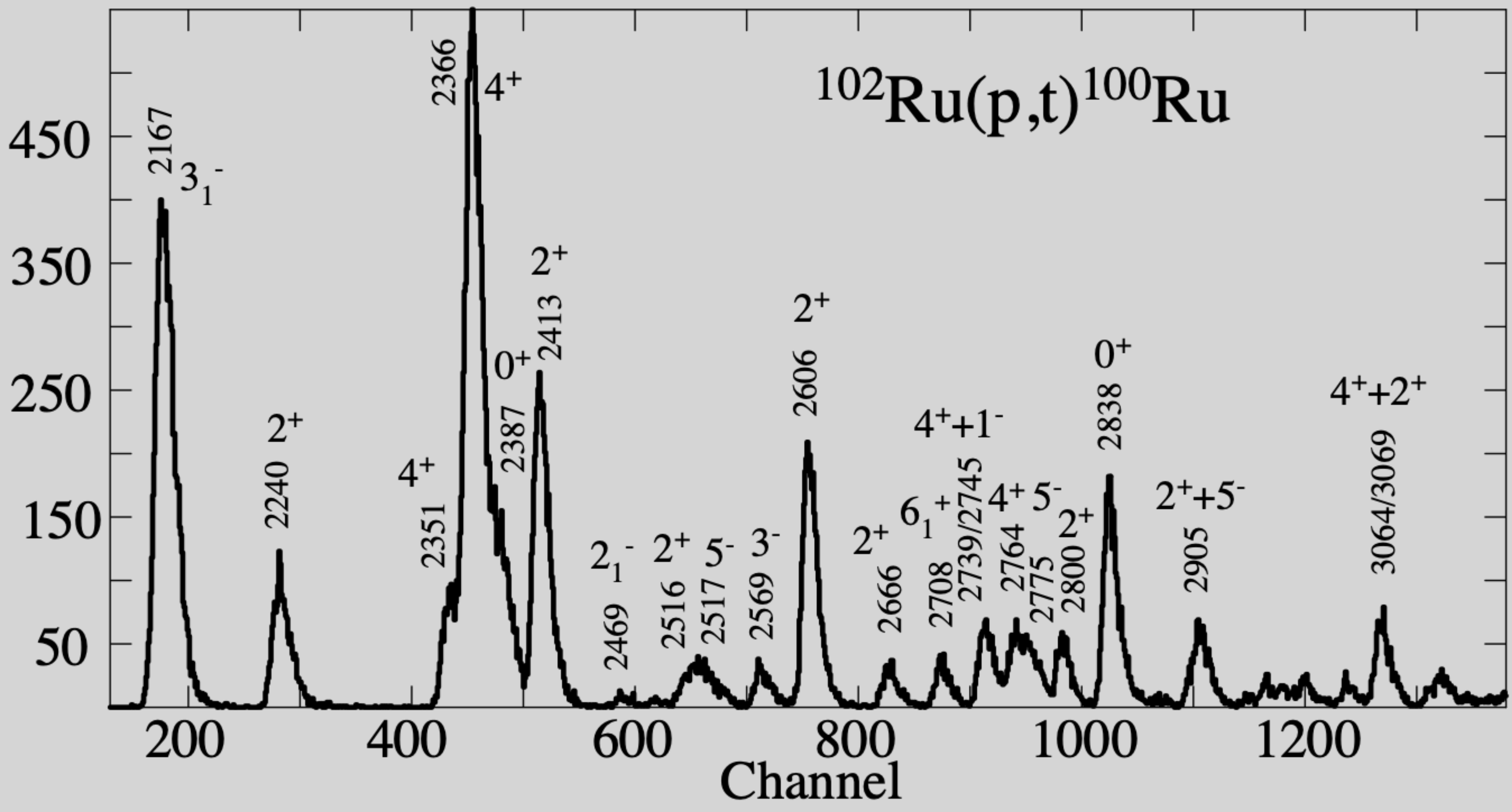
^{100}Ru 450 keV Excitation Energy Spectrum



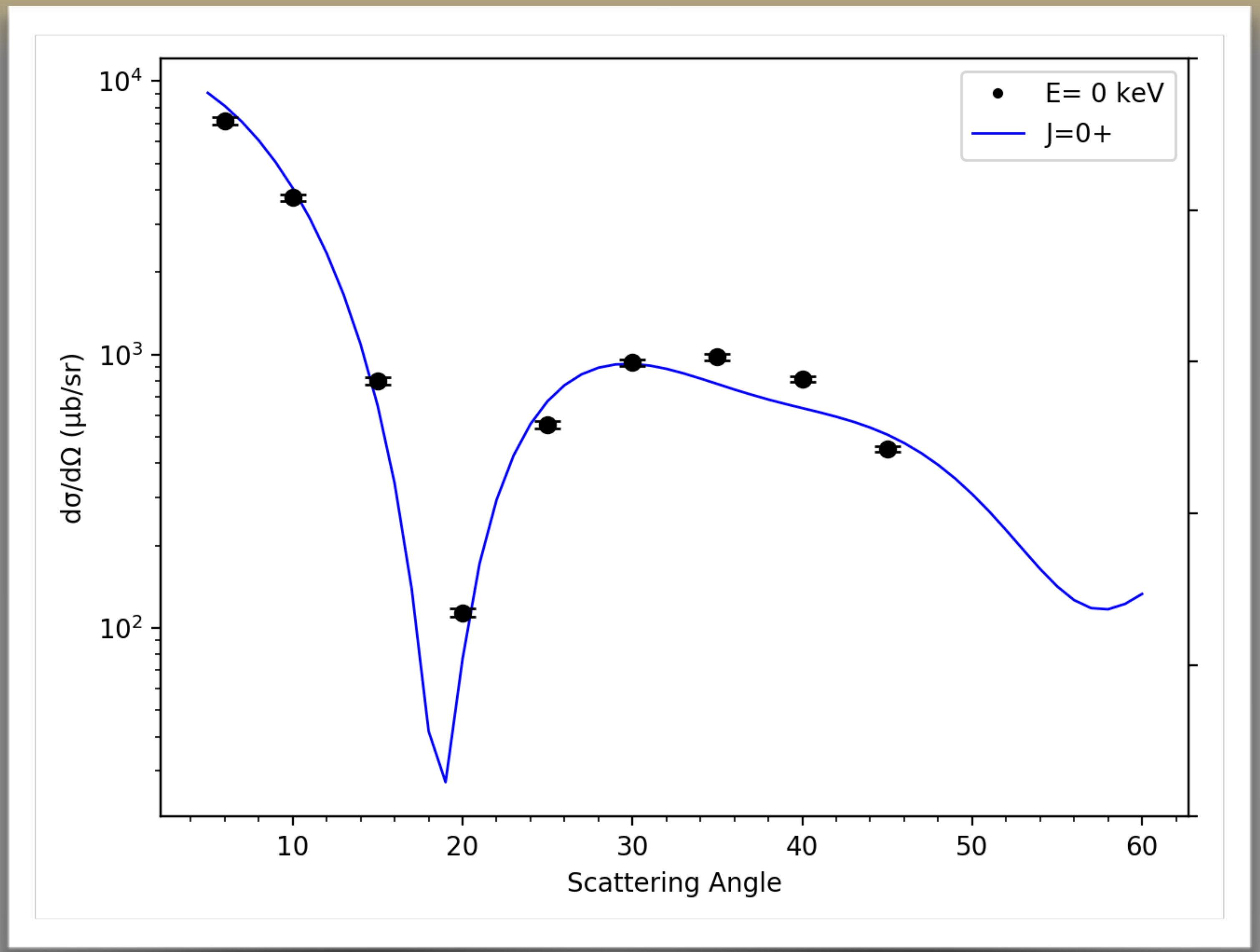
^{100}Ru 1550 keV Excitation Energy Spectrum

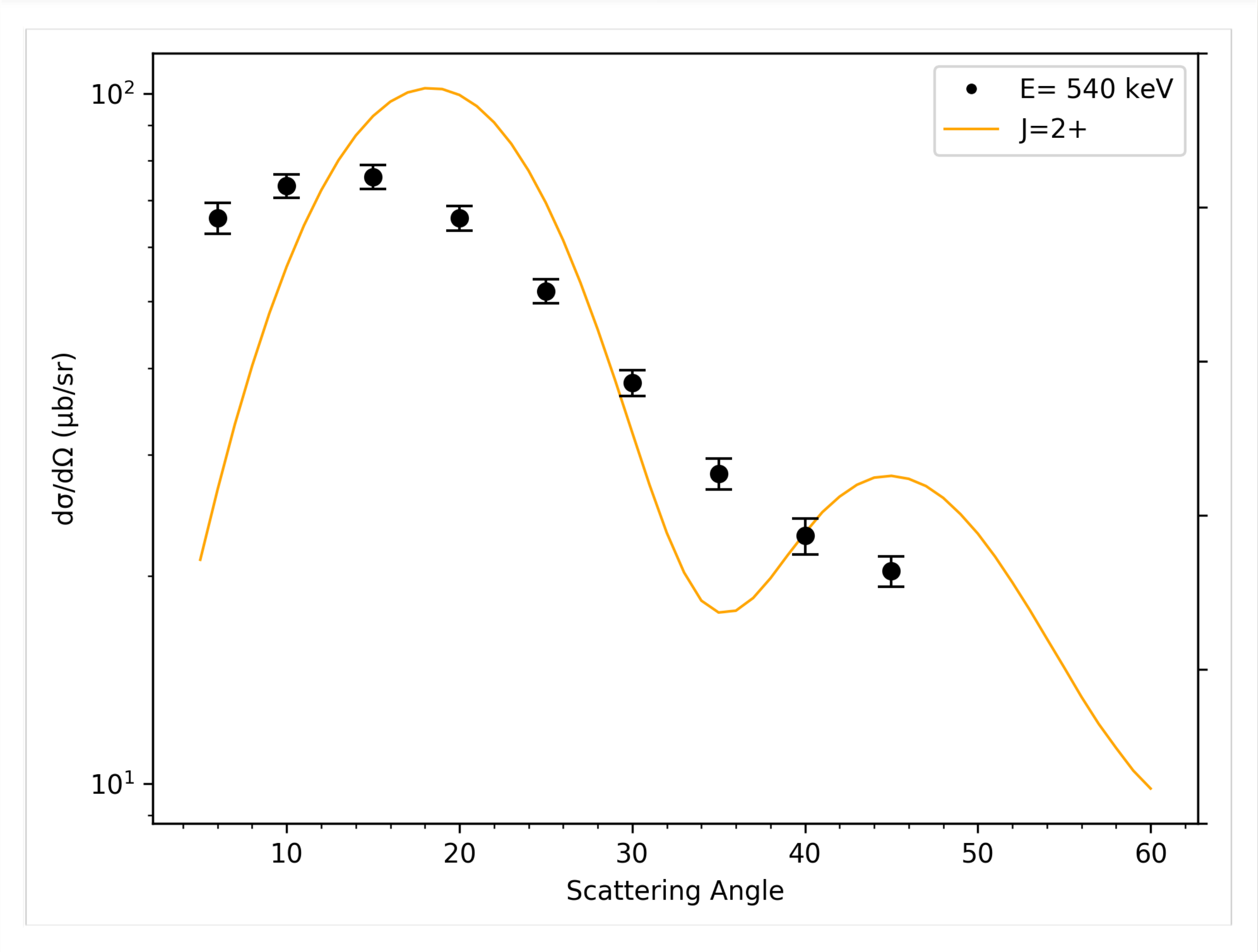


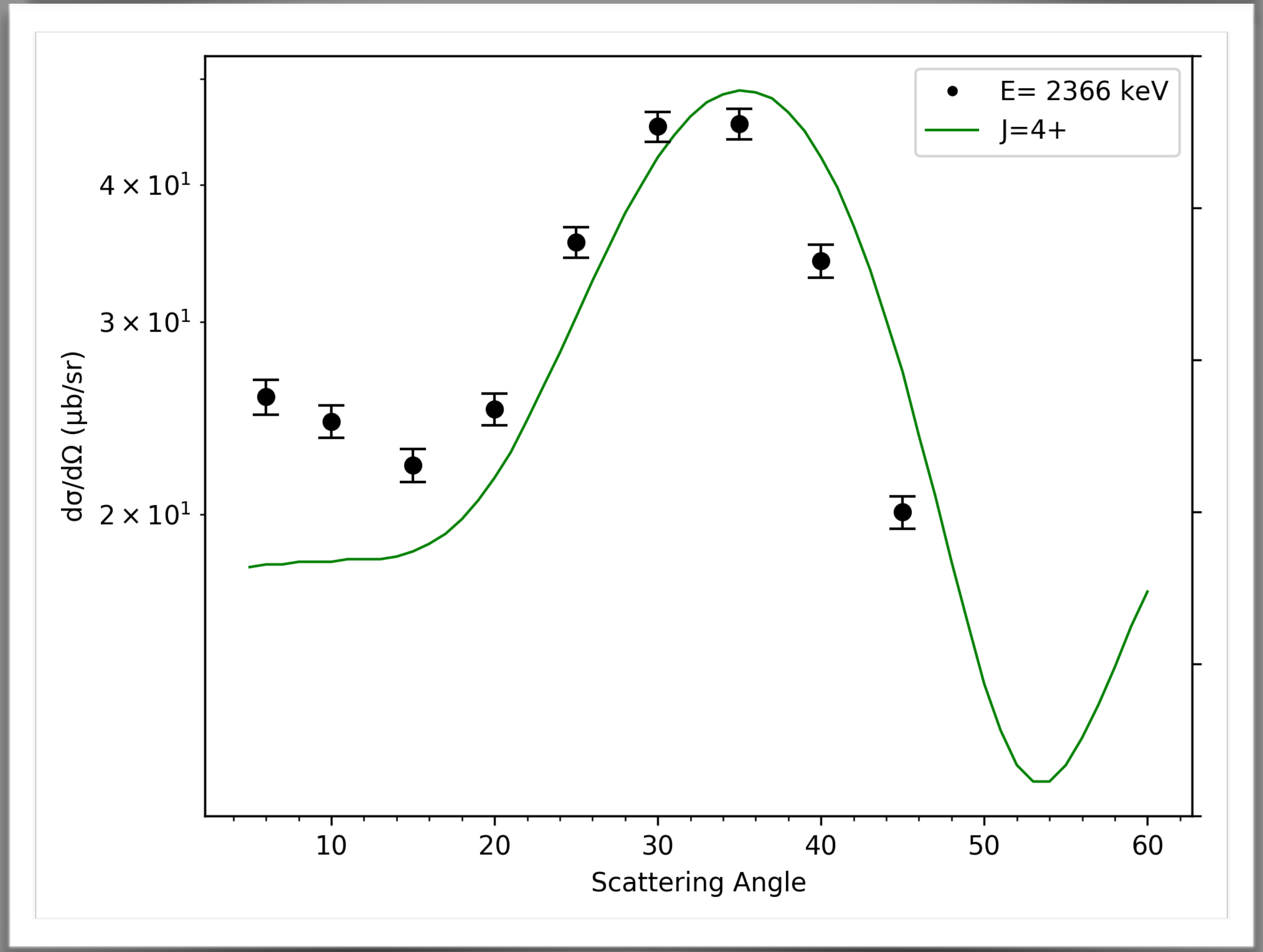
^{100}Ru 2550 keV Excitation Energy Spectrum

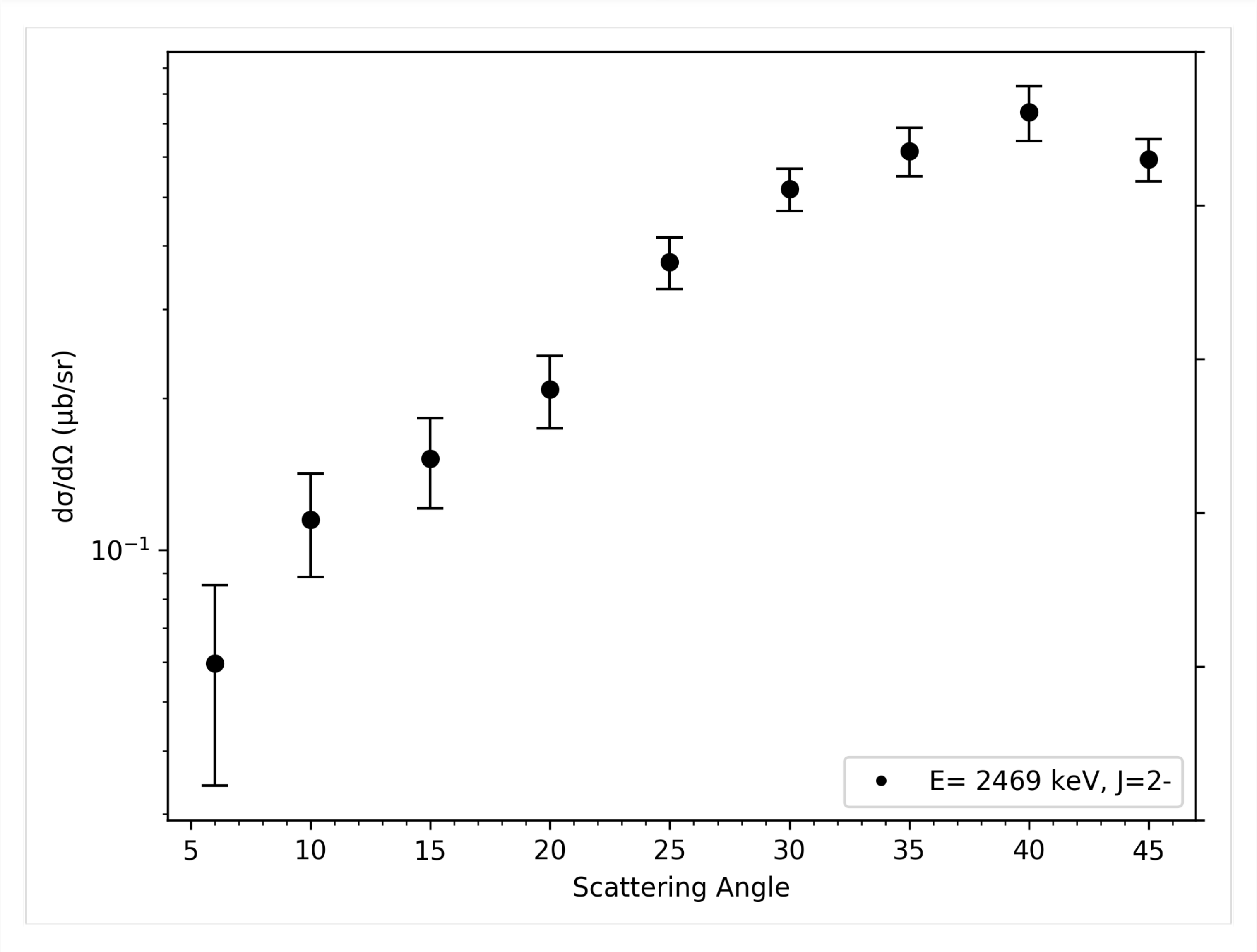


Angular Distributions Compared with FRESCO Calculation









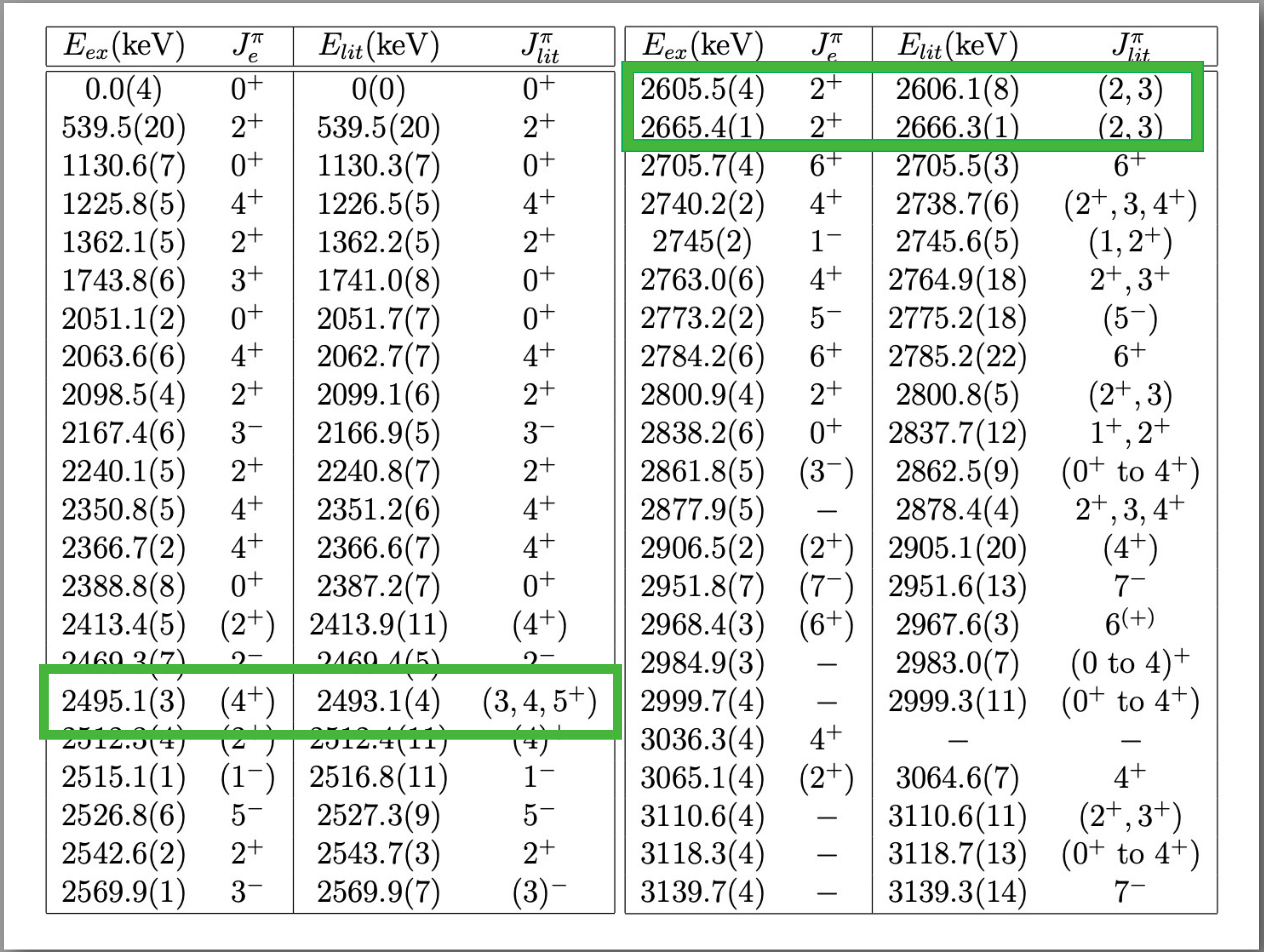
- Calculations were performed by assuming a direct di-neutron transfer of particles in the $j_i = g_{7/2}$ orbit; shapes are nearly independent of j_i

- The calculations are *not* expected to accurately reproduce the shape, but rather to act as a guide.

Spin Assignments

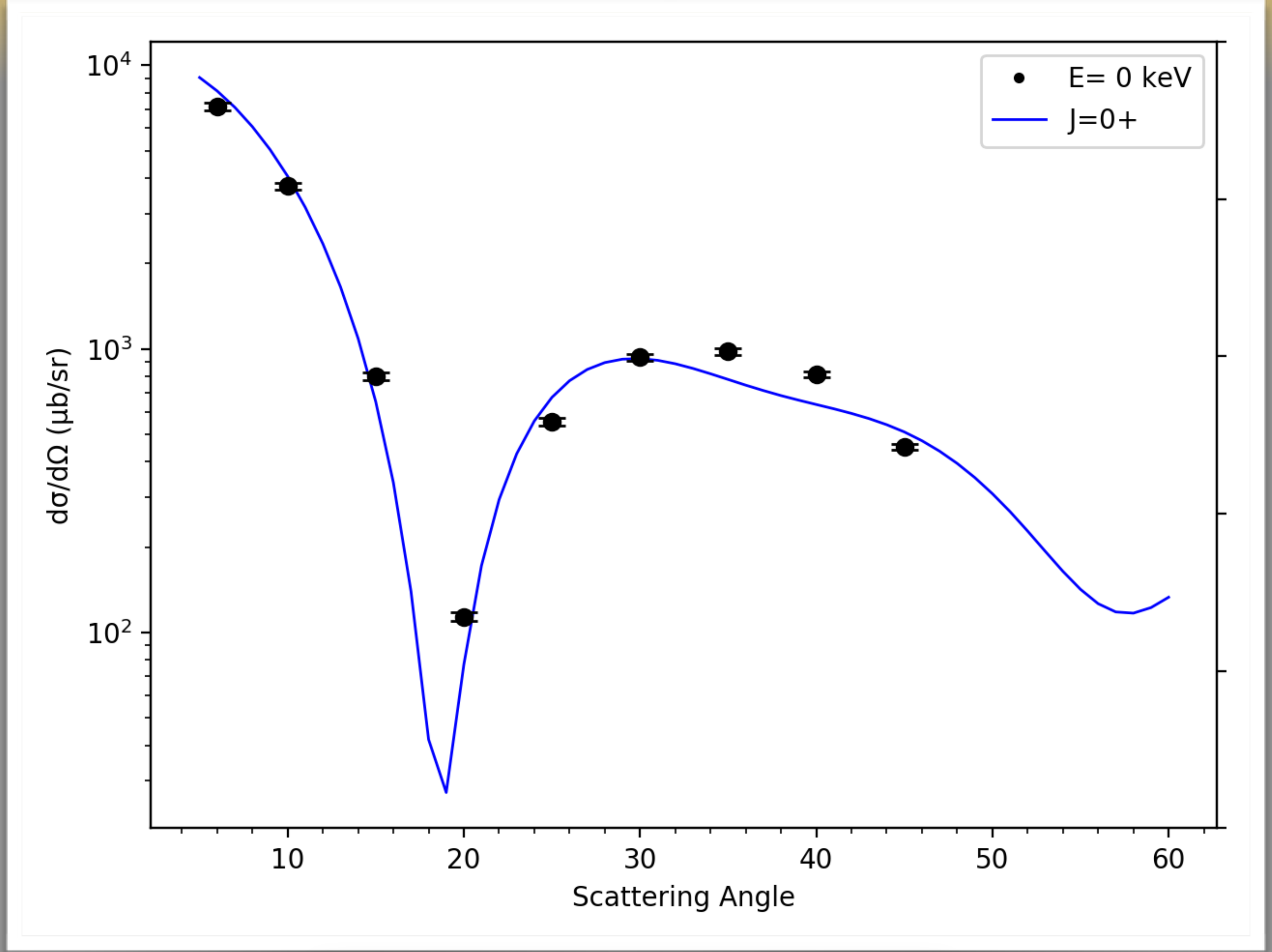
Energy and Angular Momentum Assignments for observed energy levels in the first and second momentum bite of collected ^{102}Ru(p,t) data at a beam energy of 22MeV.

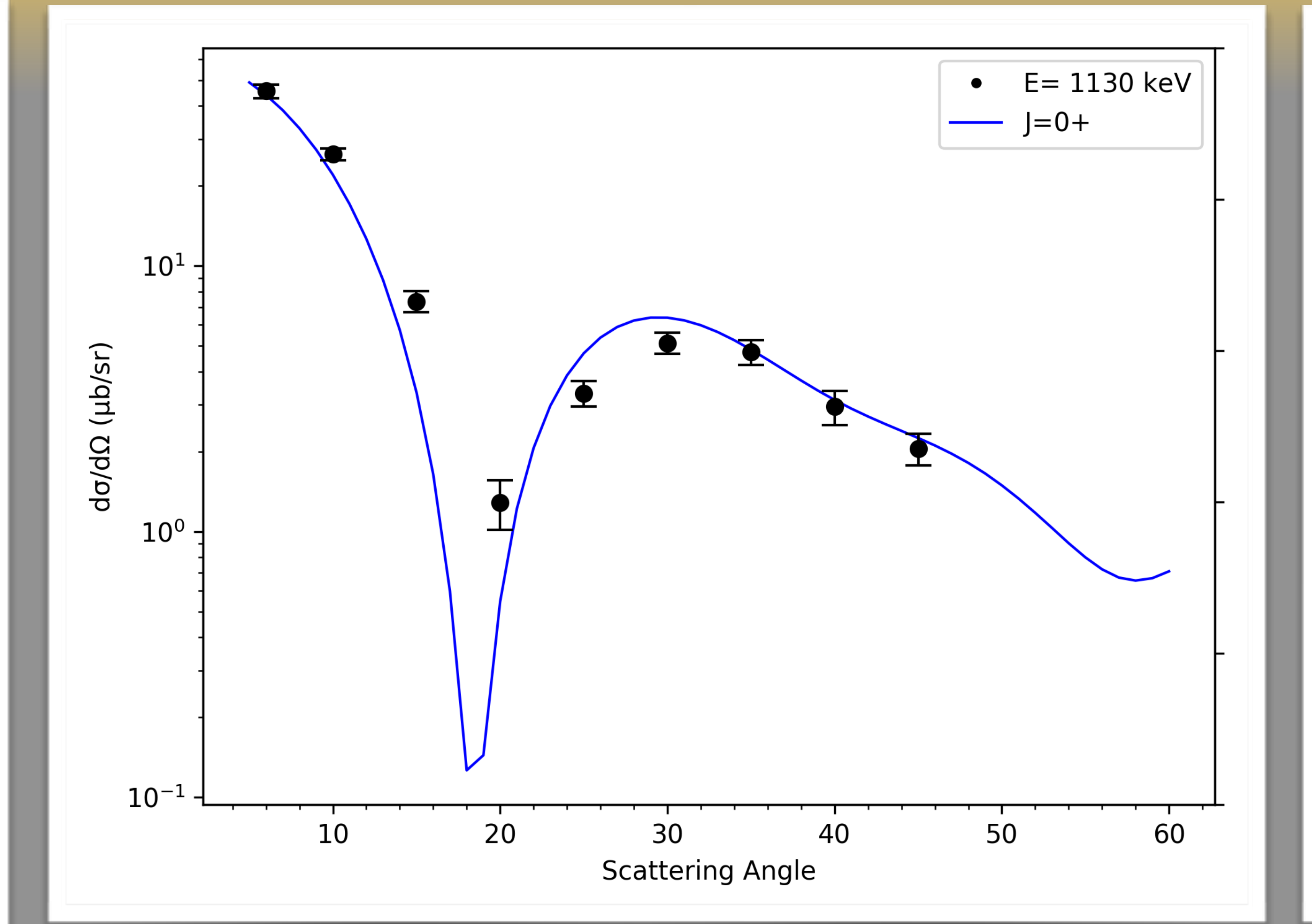
The literature values for energy and parities are from the Nuclear Data Sheets found on NNDC

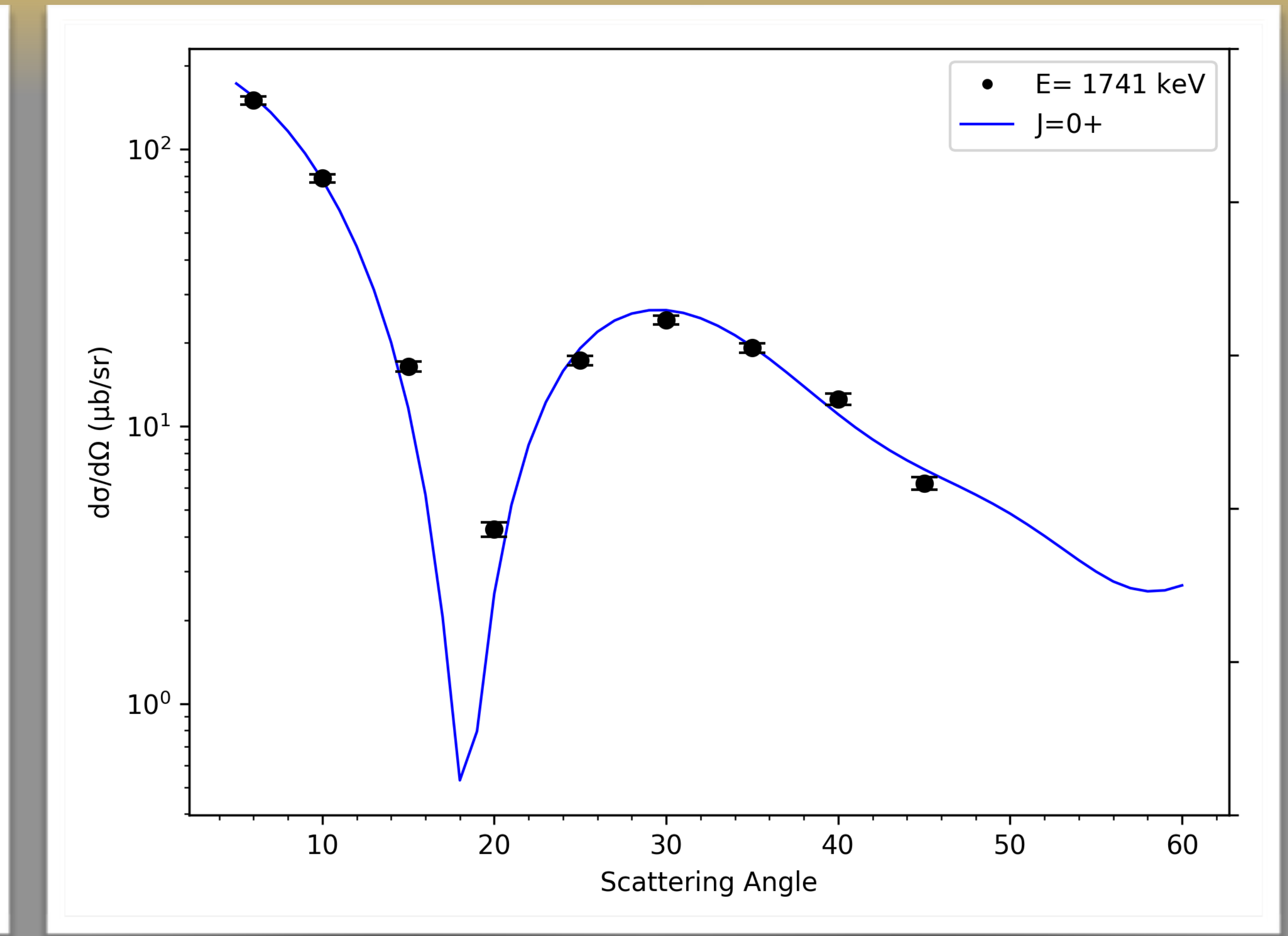


E_{ex}(keV)	J^{π}_{e}	E_{lit}(keV)	J^{π}_{lit}
0.0(4)	0^+	0(0)	0^+
539.5(20)	2^+	539.5(20)	2^+
1130.6(7)	0^+	1130.3(7)	0^+
1225.8(5)	4^+	1226.5(5)	4^+
1362.1(5)	2^+	1362.2(5)	2^+
1743.8(6)	3^+	1741.0(8)	0^+
2051.1(2)	0^+	2051.7(7)	0^+
2063.6(6)	4^+	2062.7(7)	4^+
2098.5(4)	2^+	2099.1(6)	2^+
2167.4(6)	3^-	2166.9(5)	3^-
2240.1(5)	2^+	2240.8(7)	2^+
2350.8(5)	4^+	2351.2(6)	4^+
2366.7(2)	4^+	2366.6(7)	4^+
2388.8(8)	0^+	2387.2(7)	0^+
2413.4(5)	(2^+)	2413.9(11)	(4^+)
2469.3(7)	2^-	2469.4(5)	2^-
2495.1(3)	(4^+)	2493.1(4)	$(3, 4, 5^+)$
2512.3(4)	(2^+)	2512.4(11)	$(4)^+$
2515.1(1)	(1^-)	2516.8(11)	1^-
2526.8(6)	5^-	2527.3(9)	5^-
2542.6(2)	2^+	2543.7(3)	2^+
2569.9(1)	3^-	2569.9(7)	$(3)^-$
2605.5(4)	2^+	2606.1(8)	$(2, 3)$
2665.4(1)	2^+	2666.3(1)	$(2, 3)$
2705.7(4)	6^+	2705.5(3)	6^+
2740.2(2)	4^+	2738.7(6)	$(2^+, 3, 4^+)$
2745(2)	1^-	2745.6(5)	$(1, 2^+)$
2763.0(6)	4^+	2764.9(18)	$2^+, 3^+$
2773.2(2)	5^-	2775.2(18)	(5^-)
2784.2(6)	6^+	2785.2(22)	6^+
2800.9(4)	2^+	2800.8(5)	$(2^+, 3)$
2838.2(6)	0^+	2837.7(12)	$1^+, 2^+$
2861.8(5)	(3^-)	2862.5(9)	$(0^+$ to $4^+)$
2877.9(5)	–	2878.4(4)	$2^+, 3, 4^+$
2906.5(2)	(2^+)	2905.1(20)	(4^+)
2951.8(7)	(7^-)	2951.6(13)	7^-
2968.4(3)	(6^+)	2967.6(3)	$6^{(+)}$
2984.9(3)	–	2983.0(7)	$(0$ to $4)^+$
2999.7(4)	–	2999.3(11)	$(0^+$ to $4^+)$
3036.3(4)	4^+	–	–
3065.1(4)	(2^+)	3064.6(7)	4^+
3110.6(4)	–	3110.6(11)	$(2^+, 3^+)$
3118.3(4)	–	3118.7(13)	$(0^+$ to $4^+)$
3139.7(4)	–	3139.3(14)	7^-

Population of Excited 0+ States

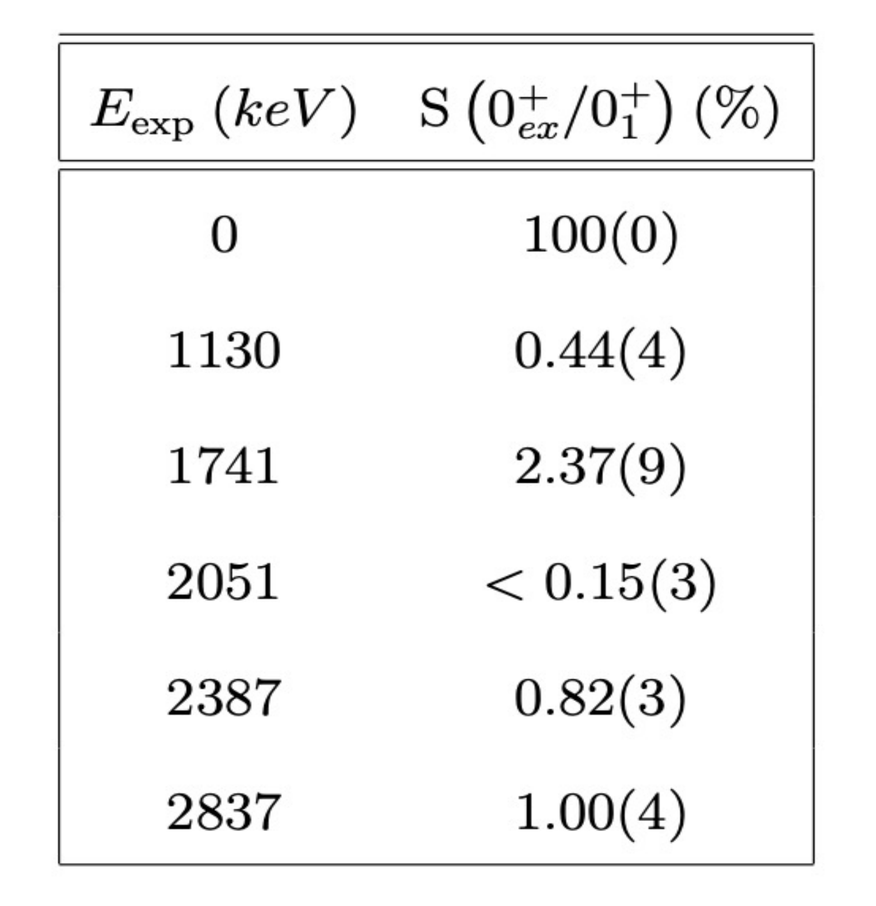






$$\text{Ratio } \frac{0_2^+}{0_1^+} = 0.44\%$$

$$\text{Ratio } \frac{0_3^+}{0_1^+} = 2.37\%$$



E_{exp} (keV)	S $(0^+_{ex}/0^+_1)$ (%)
0	100(0)
1130	0.44(4)
1741	2.37(9)
2051	$<$ 0.15(3)
2387	0.82(3)
2837	1.00(4)

Small enhancement for the population of 0_3^+ but not unusually strong!

No evidence against a normal BCS distribution for the neutrons

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Summary

- Motivation: To study the structure of ^{100}Ru via di-neutron transfer using Q3D Magnetic Spectrograph to perform ^{102}Ru(p,t)^{100}Ru.
- Unique assignments of the excited spin states and their parities (natural spin states)
- Two-neutron transfer reactions probe the pairing correlations between nuclear wave functions; if the relative 0+→ 0+ transition strengths to excited states are greatly enhanced (i.e. greater than a few percent), it indicates disruption of normal BCS pairing distribution
- Nothing has been observed out of the expected range of relative strengths to excited 0+ states
- Total of forty-four energy levels were observed and angular momenta for thirty-eight of these states were assigned. Several previously unconfirmed spins were confirmed, and a new (previously unobserved) level at 3036 keV was assigned

Thank you!

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MLL
Maier-Leibnitz-Laboratorium
für Kern-, Teilchen- & Beschleunigerphysik

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Quadrapole-3-Dipole Magnetic Spectrograph (Q3D)

Momentum Bites

Proton Beam Energy

22 MeV

$\xrightarrow{+}$

Q-Value Reaction

Q = -7.53995

$\xrightarrow{x}$

Energy Range Accepted by Focal Plane Detector

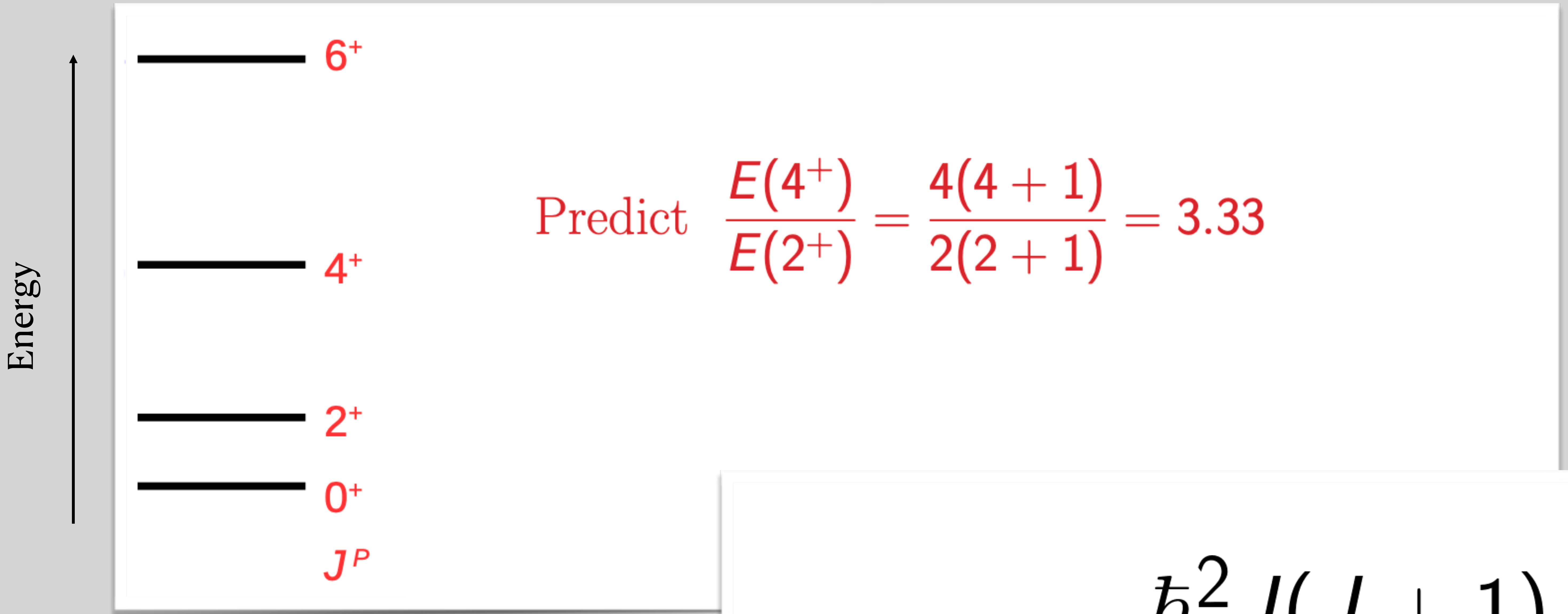
8%

Focal plane covered a momentum range of ~ 1.15 MeV per momentum bite

Four momentum bites of data were collected to cover and excitation energy range of ~4 MeV

Collective Model: Rotations

Energies of rotational excitations are not predicted, but ratios are!



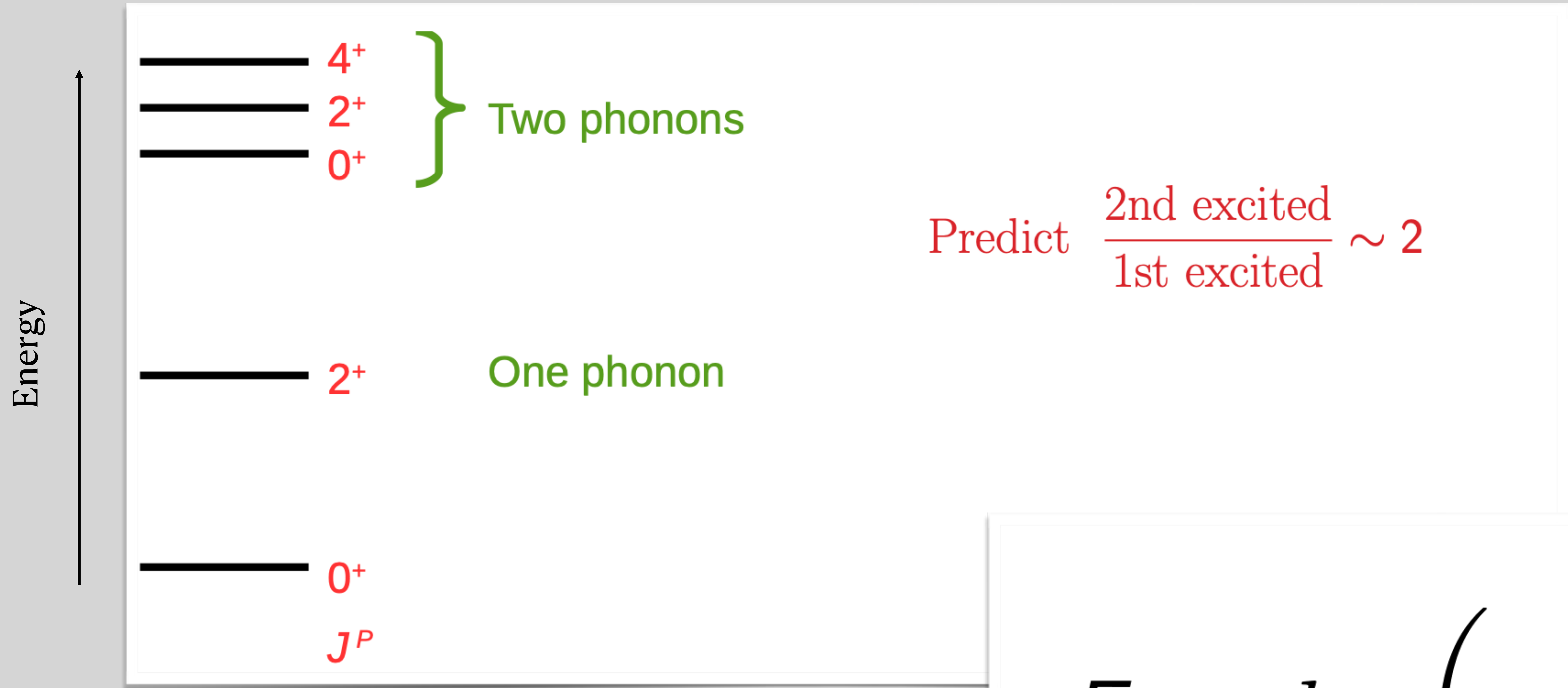
Predict $\frac{E(4^+)}{E(2^+)} = \frac{4(4+1)}{2(2+1)} = 3.33$

$$E_{rot}(J) = \frac{\hbar^2 J(J+1)}{2I}$$

$$\frac{E\left(4_1^+\right)}{E\left(2_1^+\right)}$$

Collective Model: Vibrations

Energy spacing example of vibrational excitations:

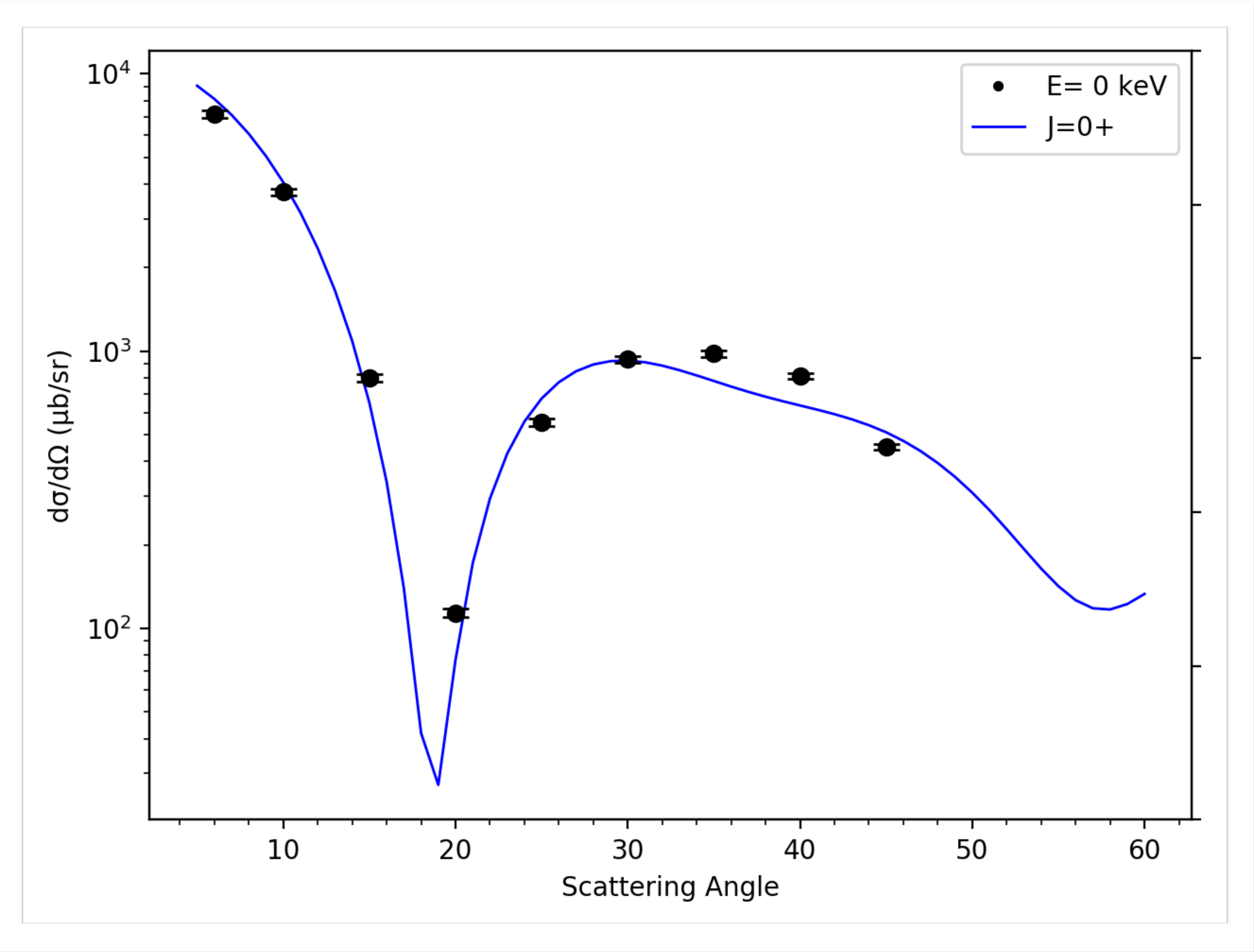


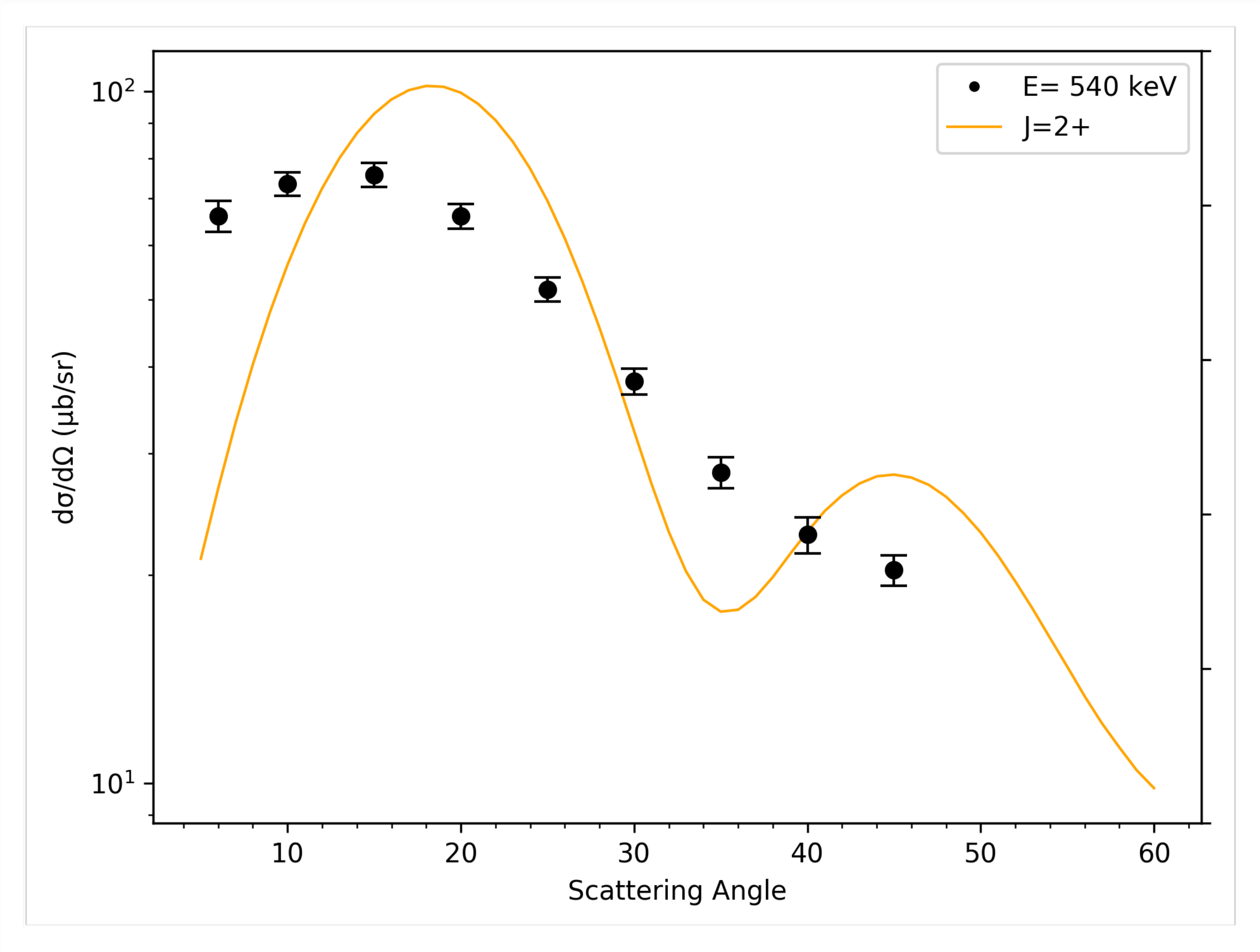
$$\text{Predict}\ \frac{\text{2nd excited}}{\text{1st excited}} \sim 2$$

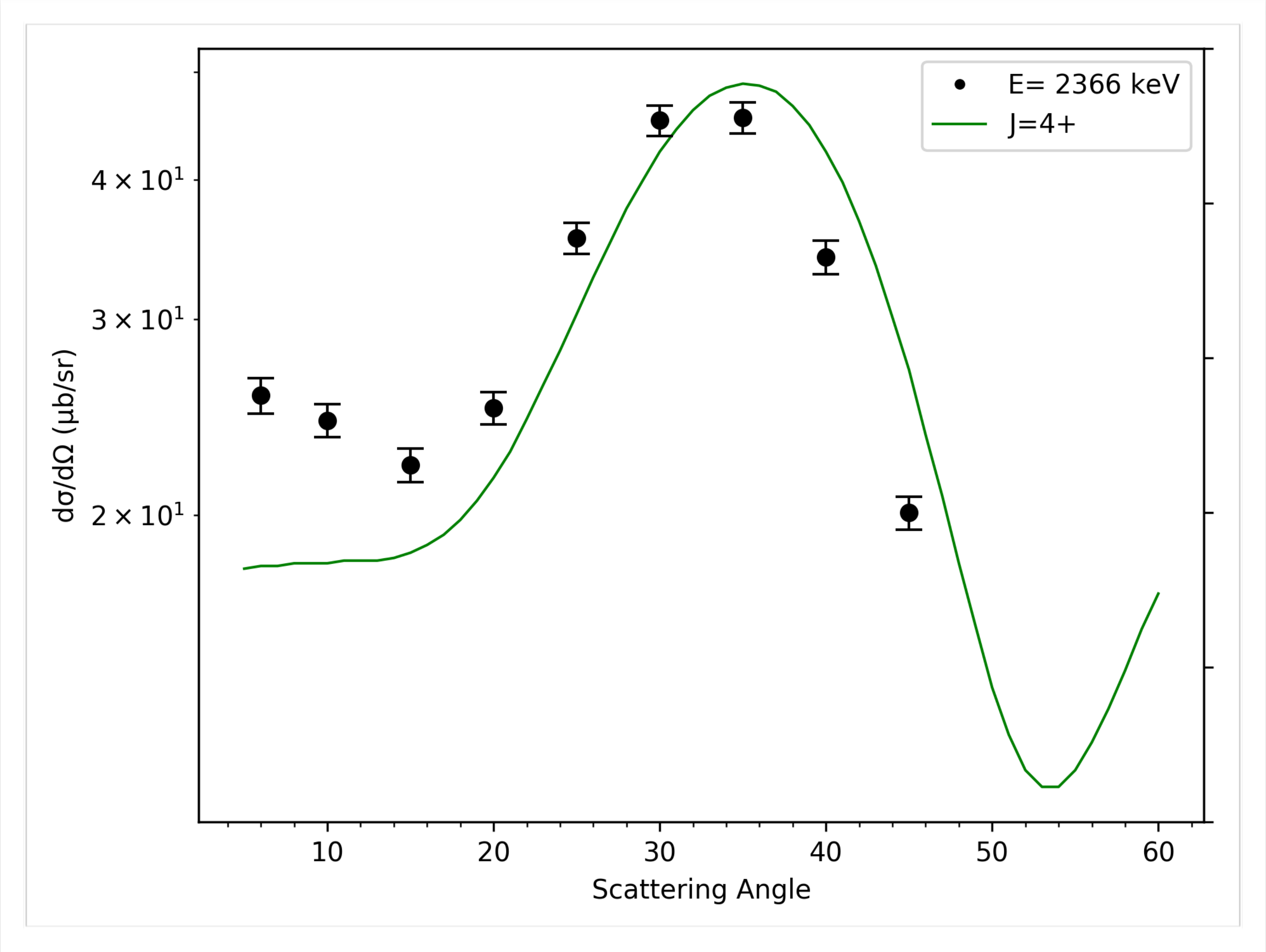
$$\frac{E\left(4_1^+\right)}{E\left(2_1^+\right)}$$

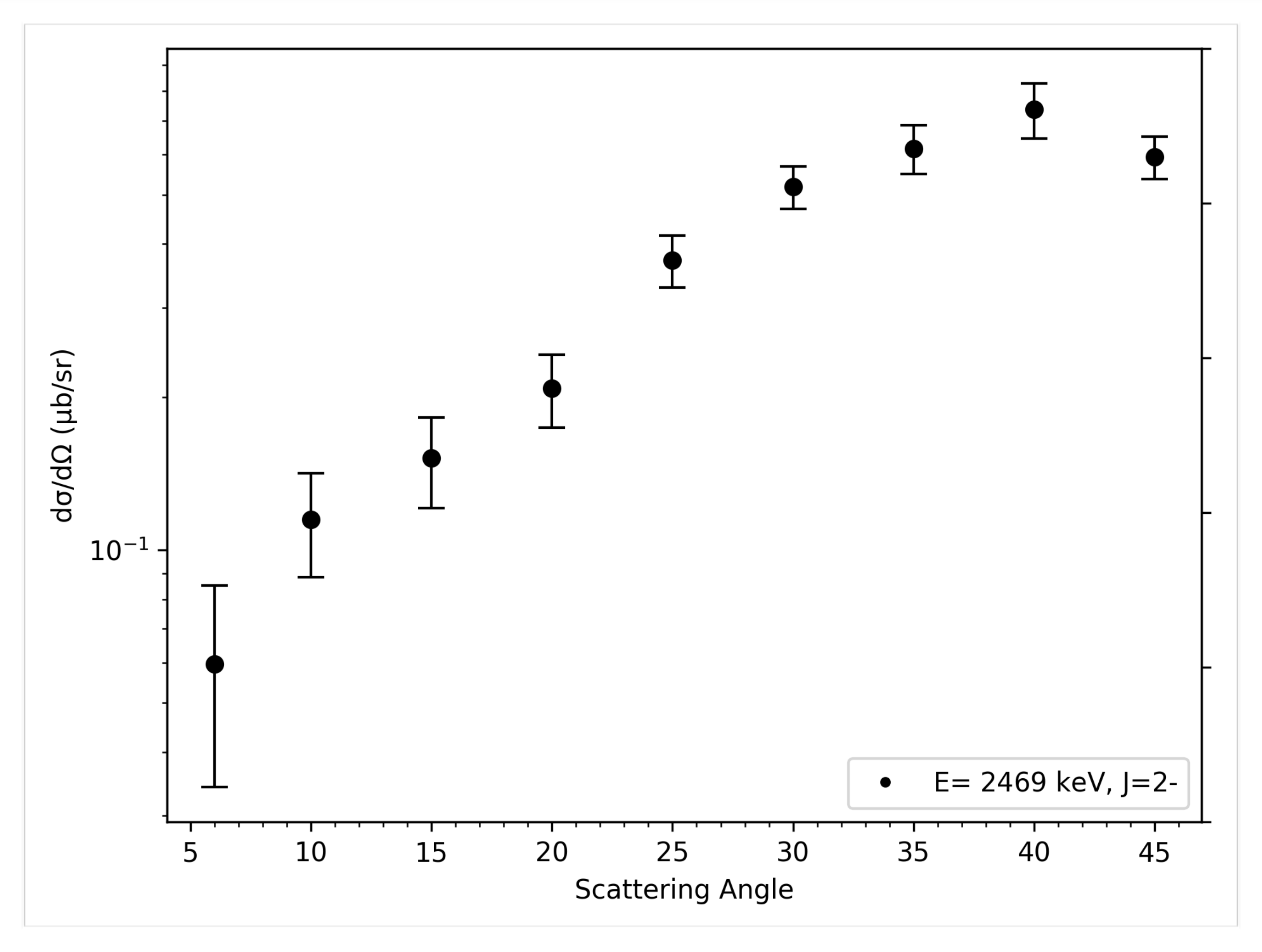
$$E_n = \hbar\omega\left(n + \frac{1}{2}\right)$$

Angular Distributions Compared with FRESCO Calculation







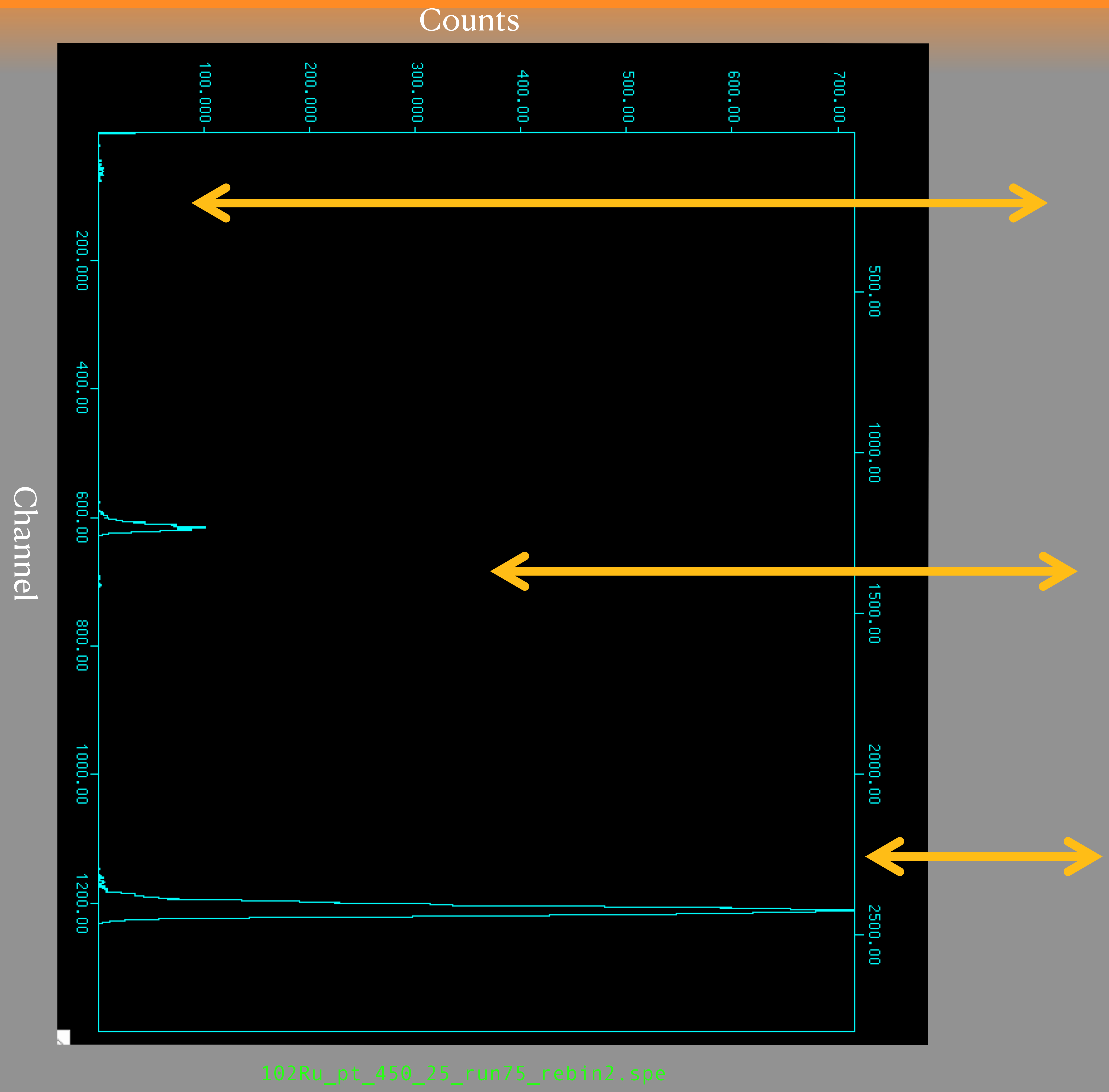


- Calculations were performed by assuming a direct di-neutron transfer of particles in the $j_i=g_{7/2}$ orbit; shapes are nearly independent of j_i

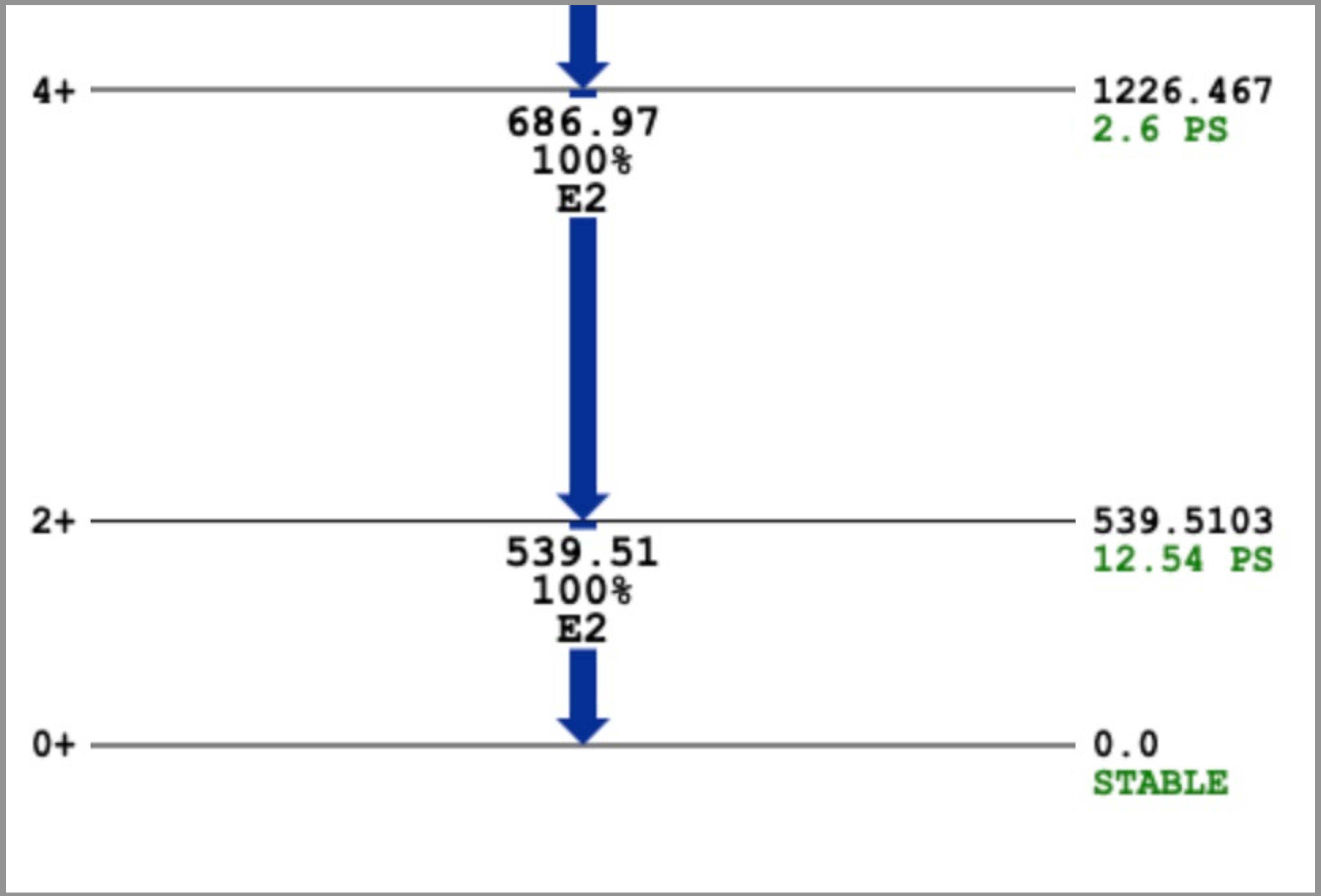
- The calculations are *not* expected to accurately reproduce the shape, but rather to act as a guide.

Optical Model Parameters:
- Proton: RL Varner et al., physics report, 201 pg 57 (pub 1991)
- Triton: FD Becchetti and GW Greenless, PhysRev 182 pg 1190 (pub 1969)

Spectral Analysis



100Ru



https://www.nndc.bnl.gov/nudat3/levelscheme/?nucleus=100Ru

Project Motivation

Significance of Studying ^{100}Ru: Double beta decay of ^{100}Mo to excited states of ^{100}Ru. Potential importance due to the possibility of using ^{100}Mo for studies of the neutrino-less double-beta-decay process, that would shed light on the fundamental nature of neutrinos.

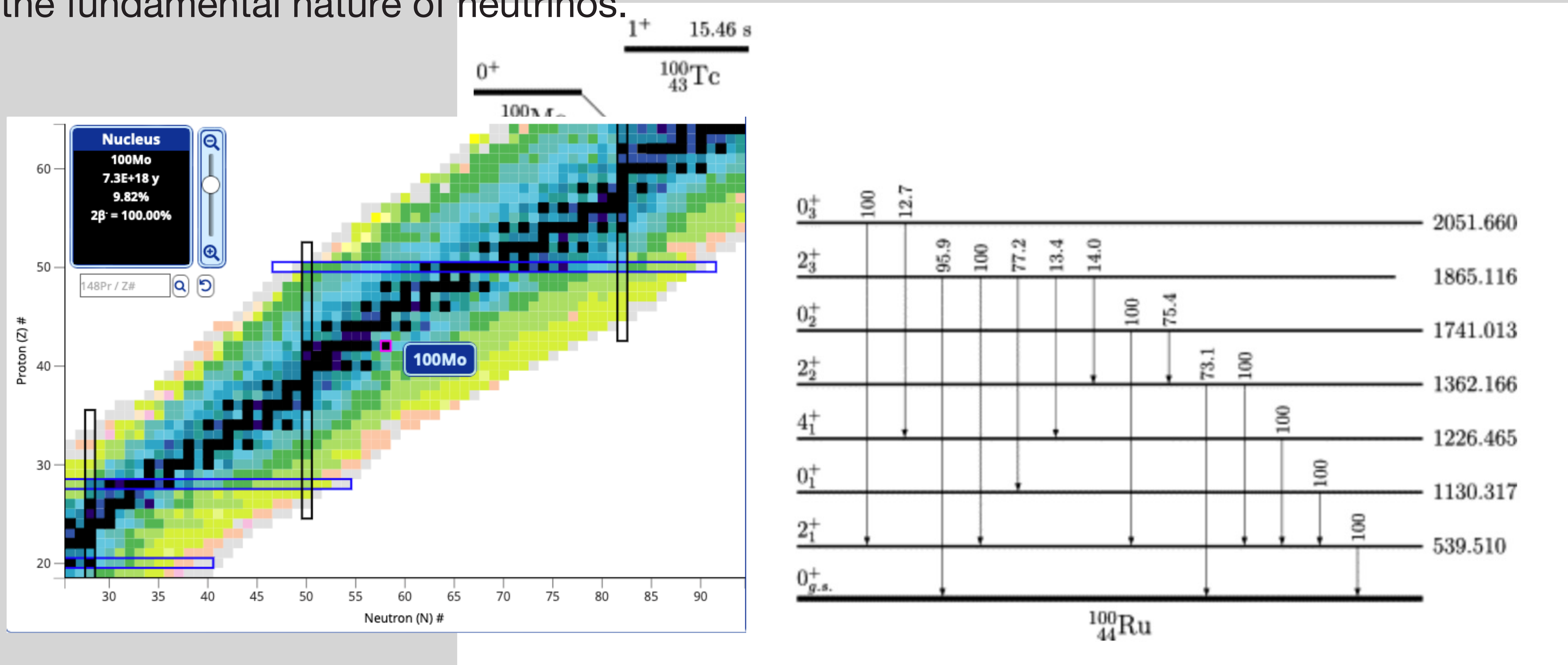
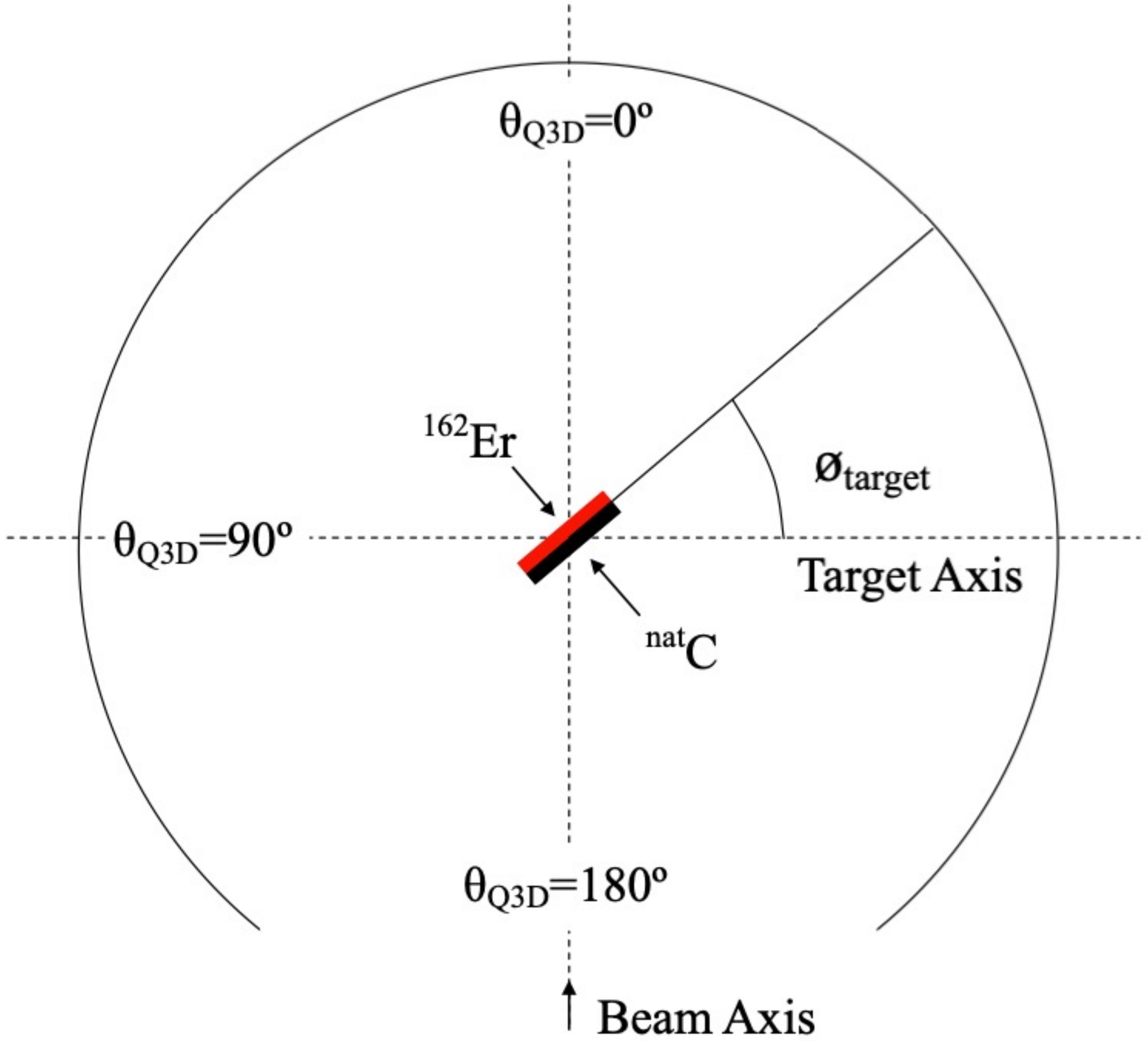


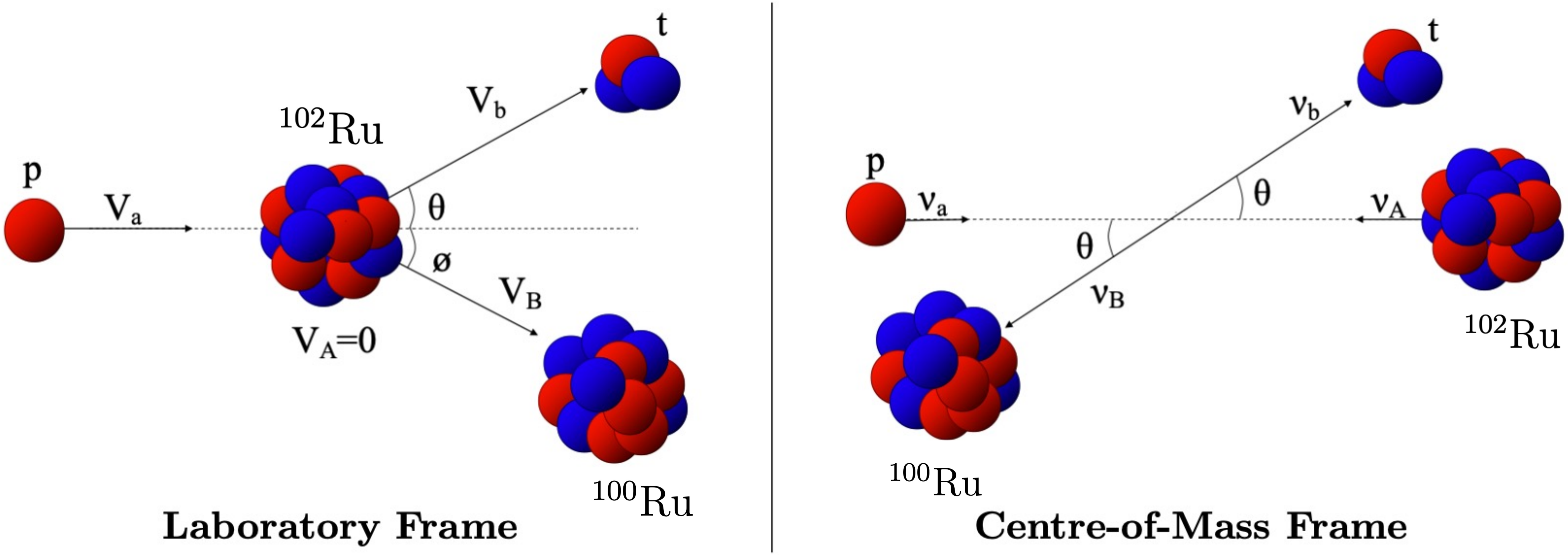
Figure: Investigation of double beta decay of ^{100}Mo to excited states of ^{100}Ru

May 2014, p.25-36, Nuclear Physics, Section A

Quadrapole-3-Dipole Magnetic Spectrograph (Q3D)



Target position with respect to the Q3D and beam axis. For transfer reactions, the target is positioned such that the carbon backing faces the beam so that the straggling effect of the beam through the target is minimized. For elastic scattering beyond 90°, the target is often inverted such that scattering from the carbon backing is minimized.



Laboratory Frame

Centre-of-Mass Frame