Collinear laser spectroscopy at COLLAPS and analysis of $^{155\text{-}175}$Tm

STFC summer school 2024

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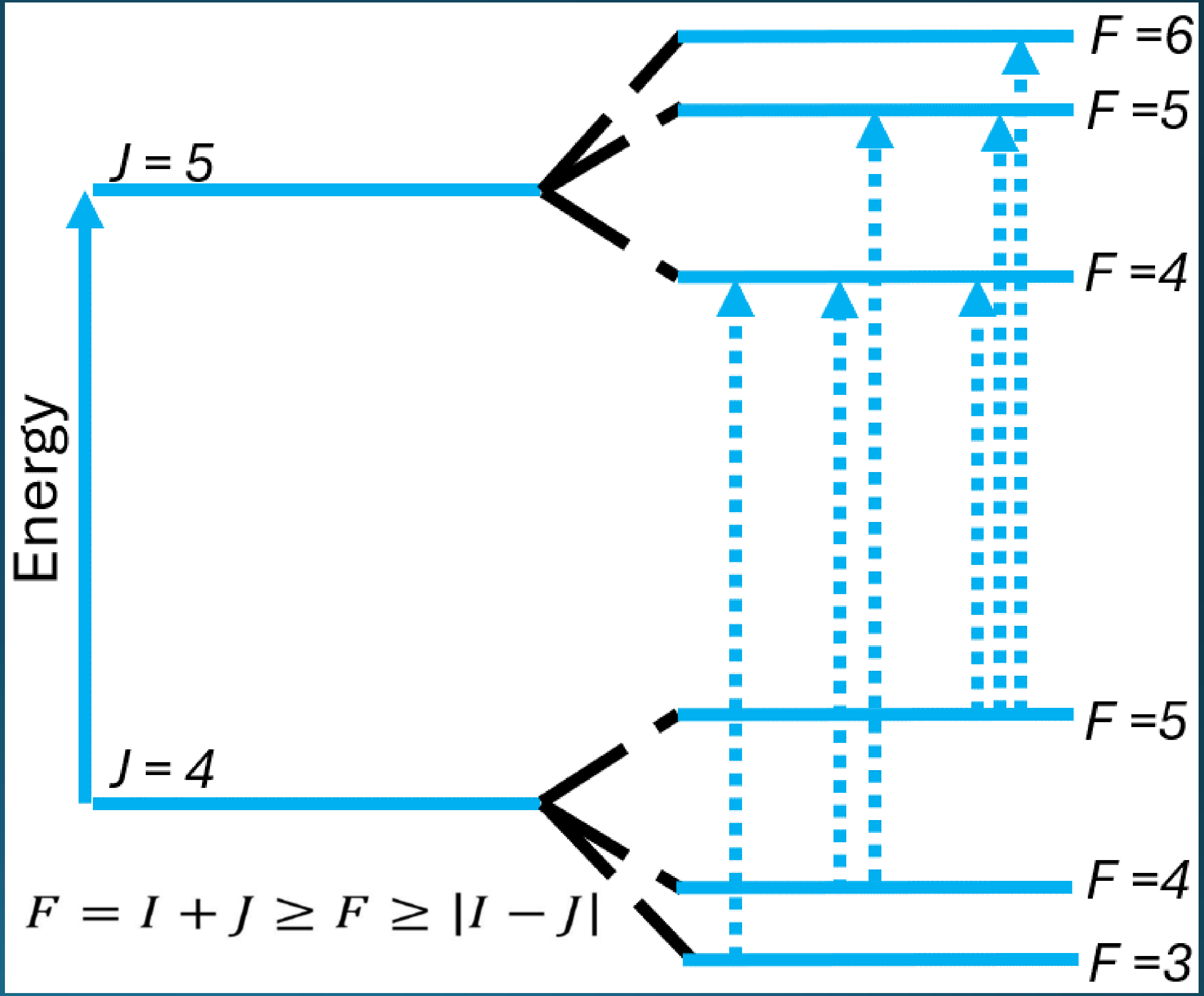
Laser spectroscopy

Laser spectroscopy gives a window into the Hyperfine structure.

Hyperfine structure arises in the atomic spectra from the fine structure of a nucleus due to interactions between electrons and the nucleus.

With enough resolution, a single electronic transition can be seen to split into various transitions between different levels.



$F = I + J \geq F \geq |I - J|$

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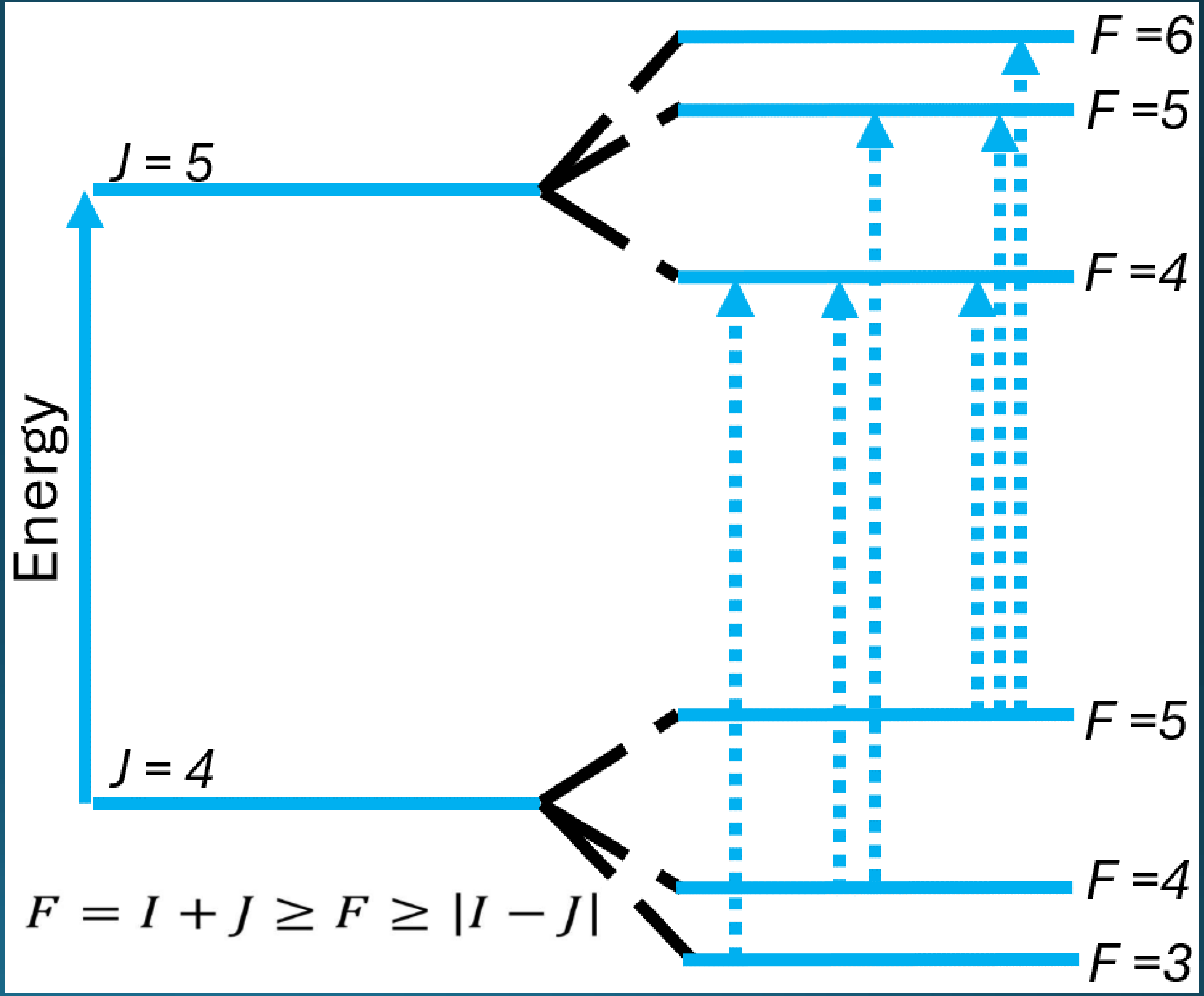
This splitting is given by:

$$\frac{\Delta E}{h} = \frac{K}{2}A + \frac{3K(K+1)-4I(I+1)J(J+1)}{8I(2I-1)J(2J-1)}B$$

A and *B* are the main parameters of note, as they relate to the nuclear properties:

$$A = \frac{\mu_I B_e(0)}{I\,J}\ , B = eQ_s\left\langle\frac{\partial^2 V_e}{\partial z^2}\right\rangle$$



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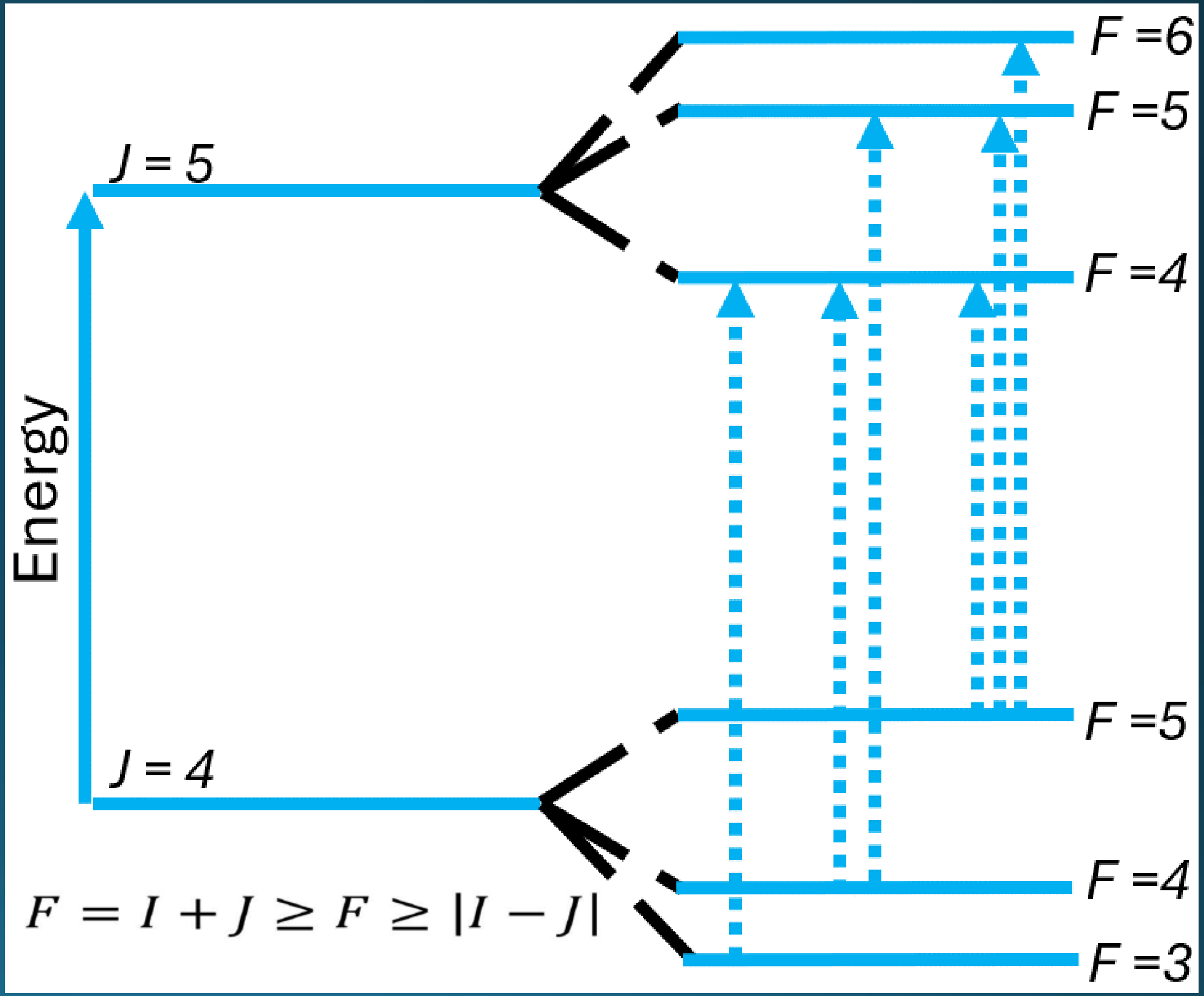

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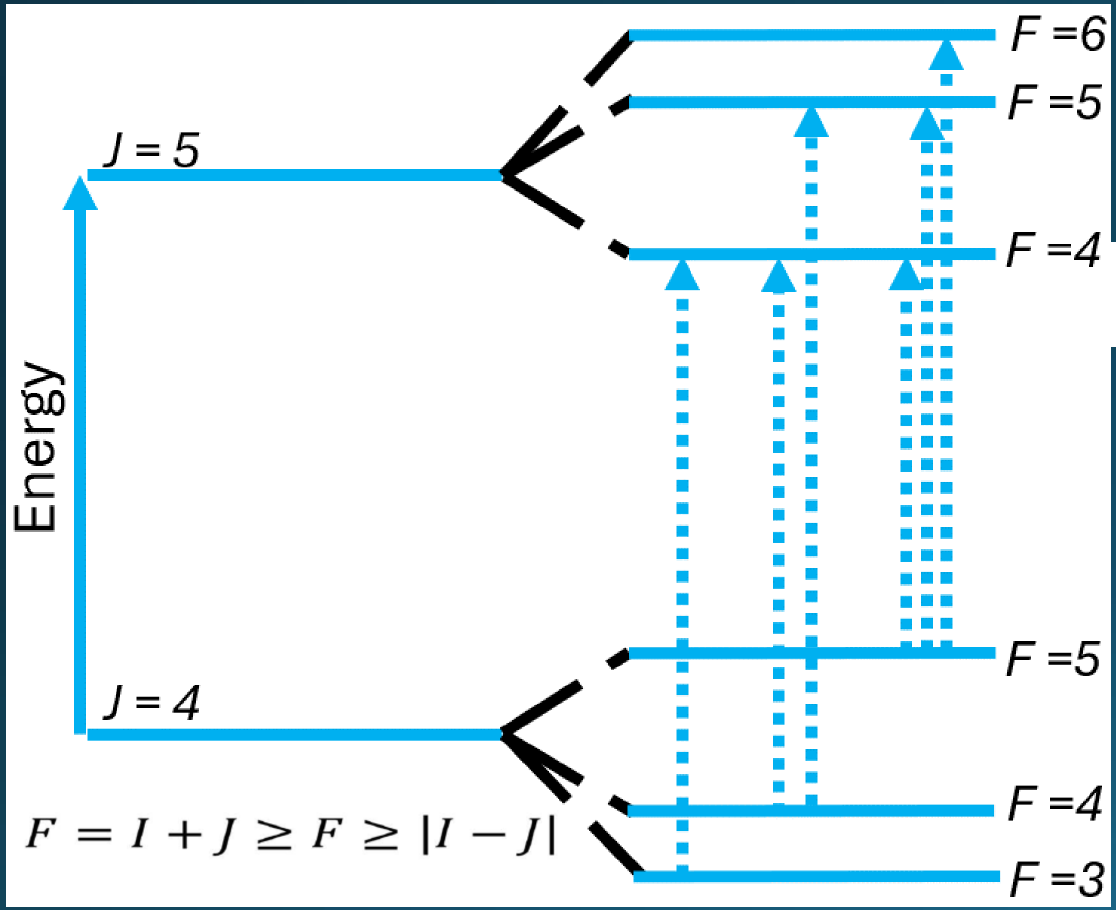


$F = I + J \geq F \geq |I - J|$

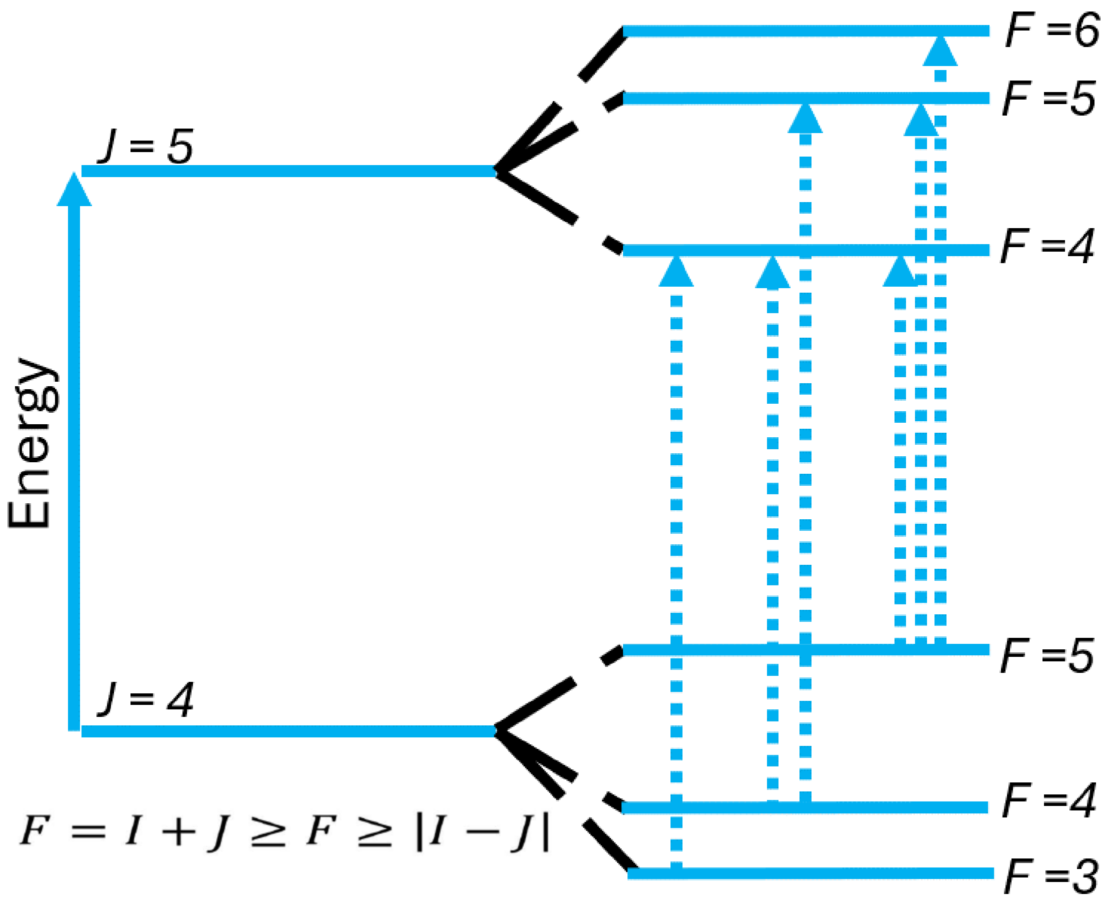
For each one of those transitions. A hyperfine peak can be detected.

The hyperfine peak will have a frequency:

$$\gamma = \nu + \alpha_u A_u + \beta_u B_u - \alpha_l A_l - \beta_l B_l$$

The structure will have a centroid, ν

Laser spectroscopy



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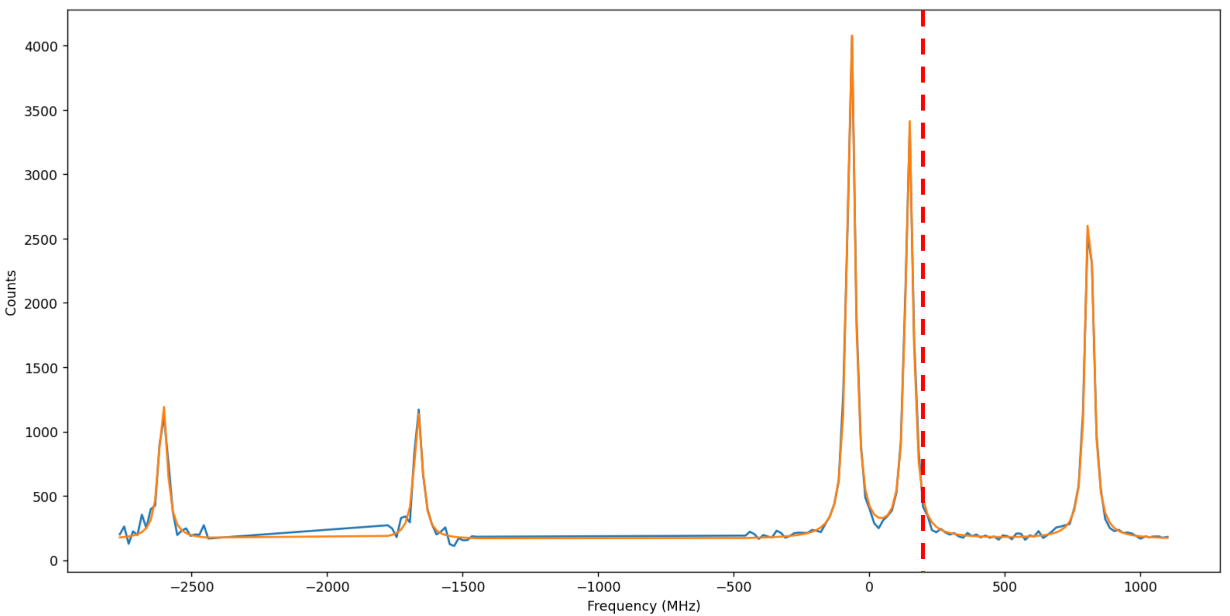

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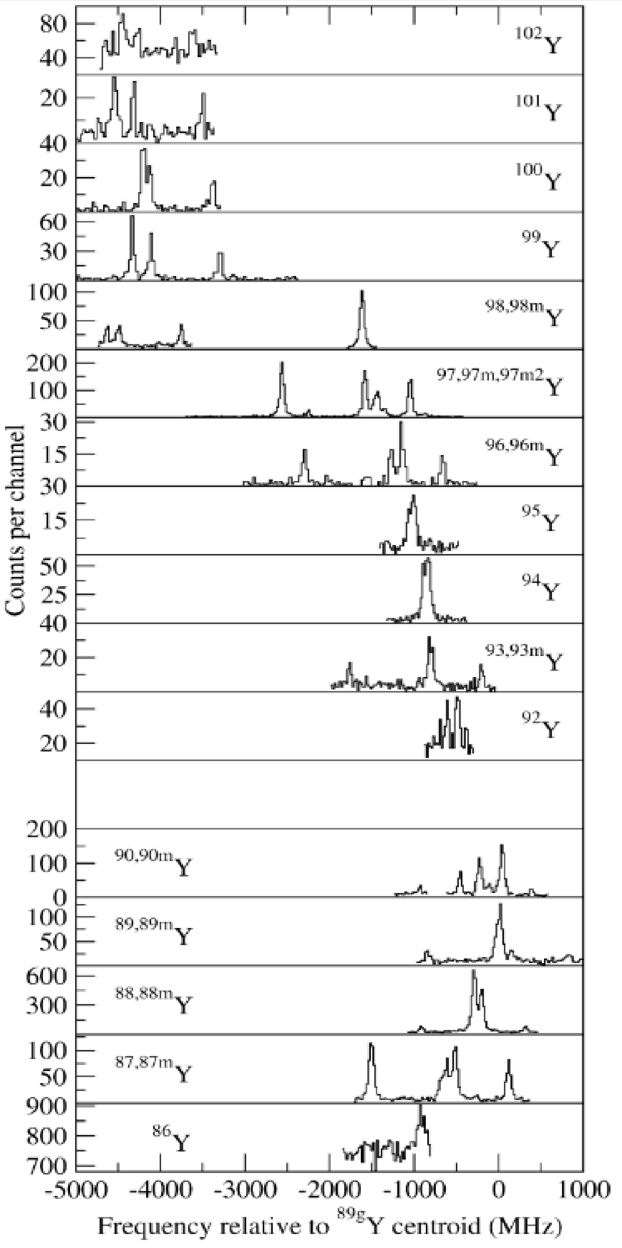

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This centroid is seen to change from isotope to isotope, and is known as the isotope shift.

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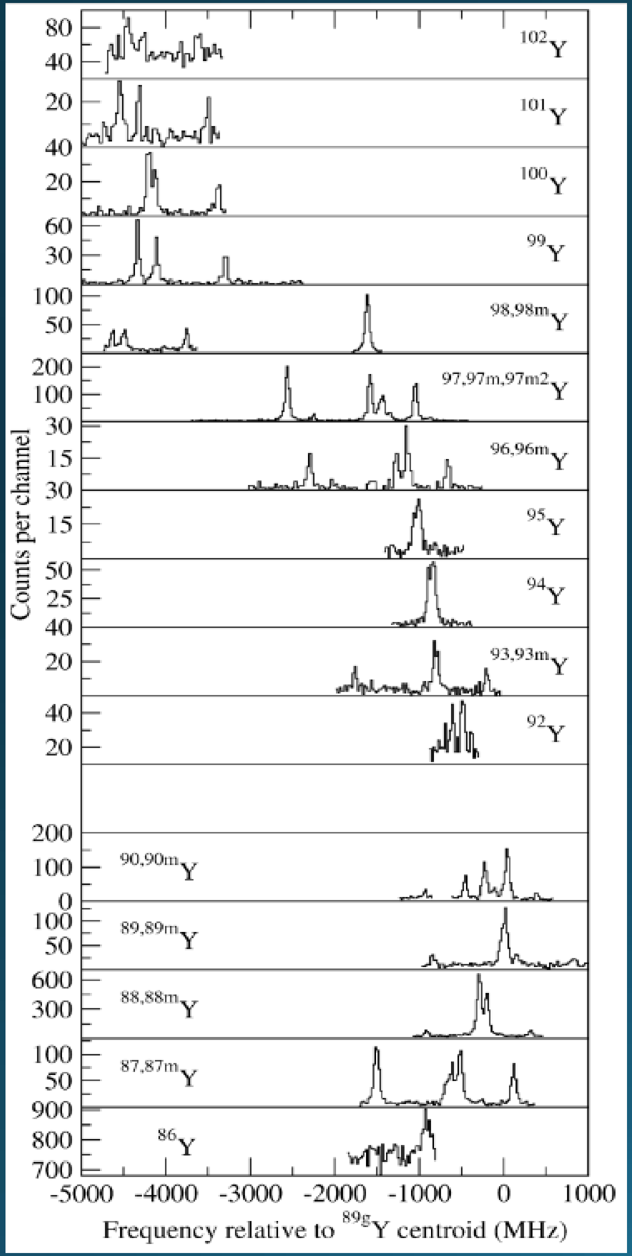

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From this, we can deduce The change in mean square charge radius between 2 isotopes $(A\ and\ A')$:

$$\nu_{A'} - \nu_A = \delta\nu^{AA'} = M\frac{A'-A}{AA'} + F\delta\langle r^2\rangle^{AA'}$$

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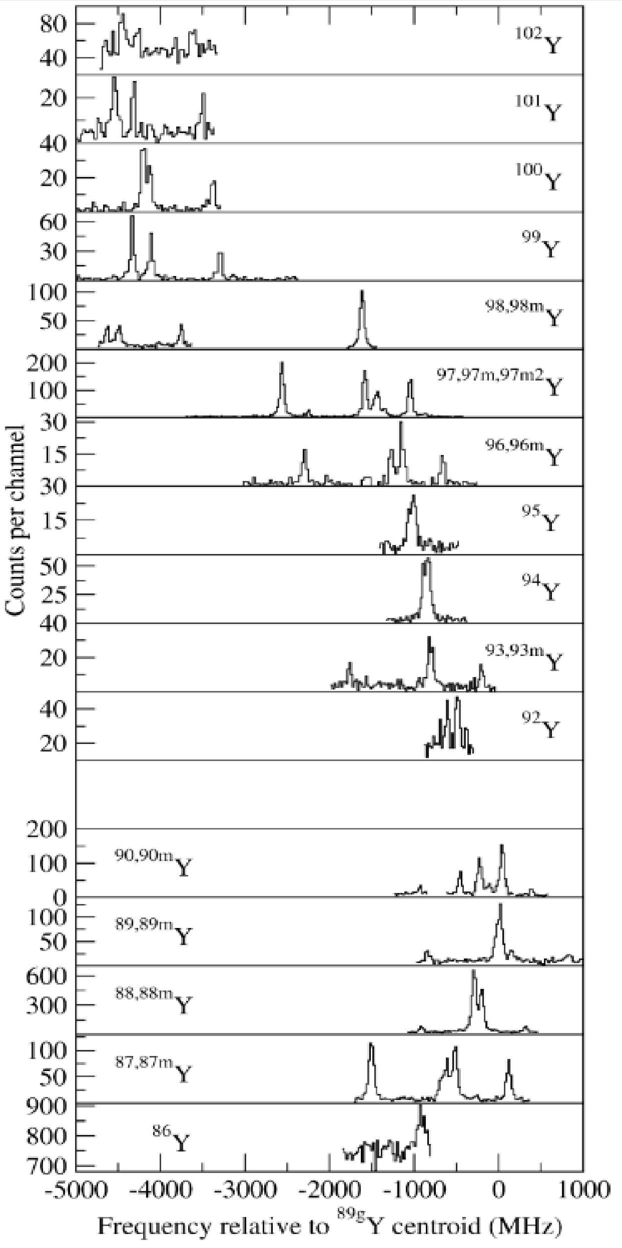

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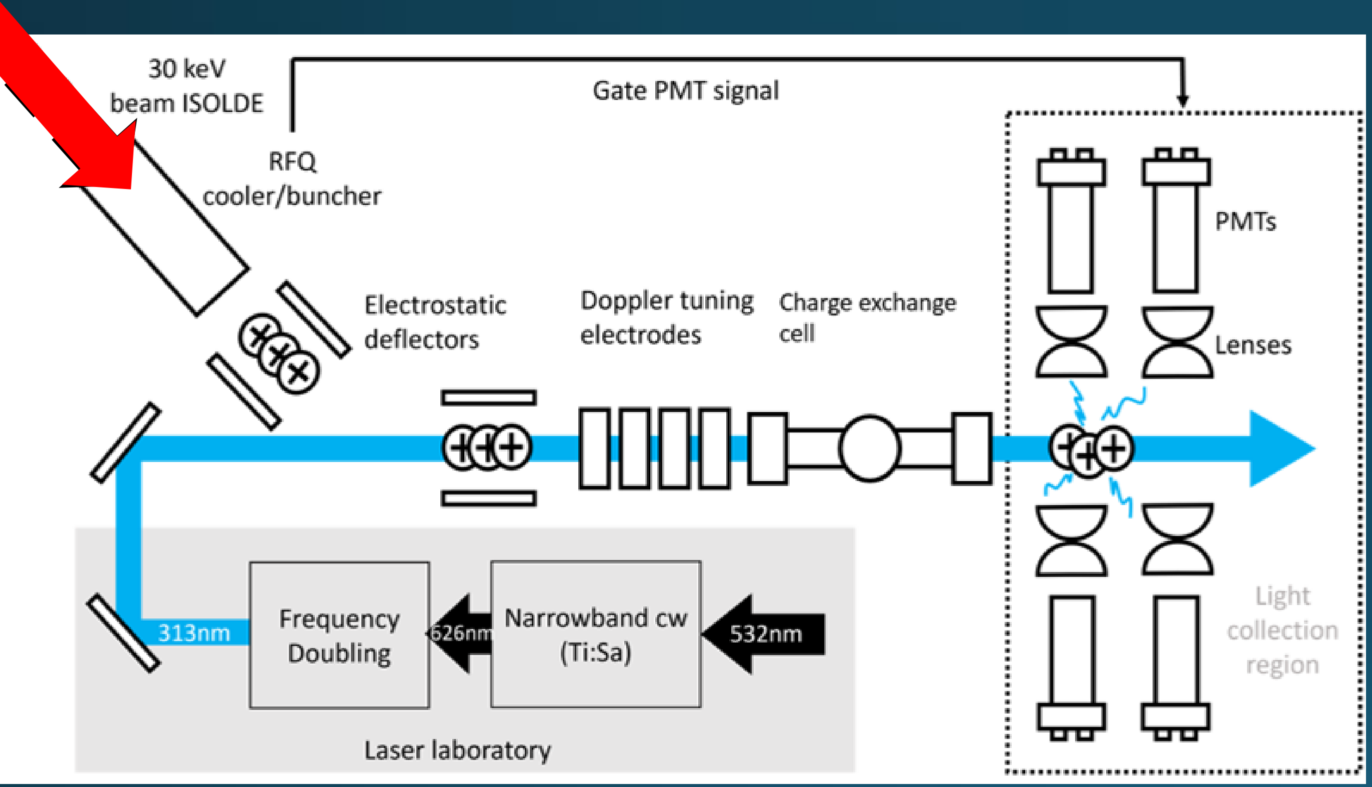
This property gives insight into the size and deformation of the nucleus

COLLAPS



Radioactive ion beam from ISOLDE arrives into the cooler/buncher.

Cooler buncher converts the continuous beam into pulsed bunches.

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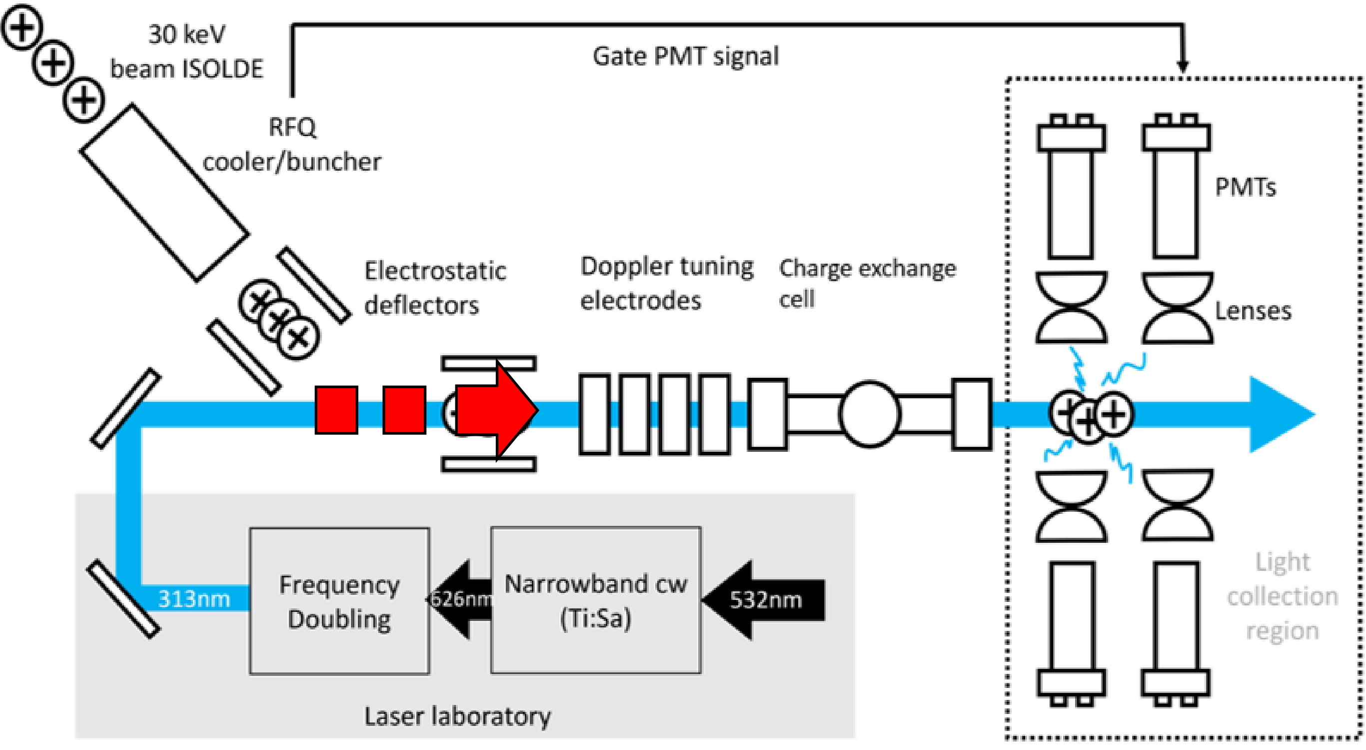


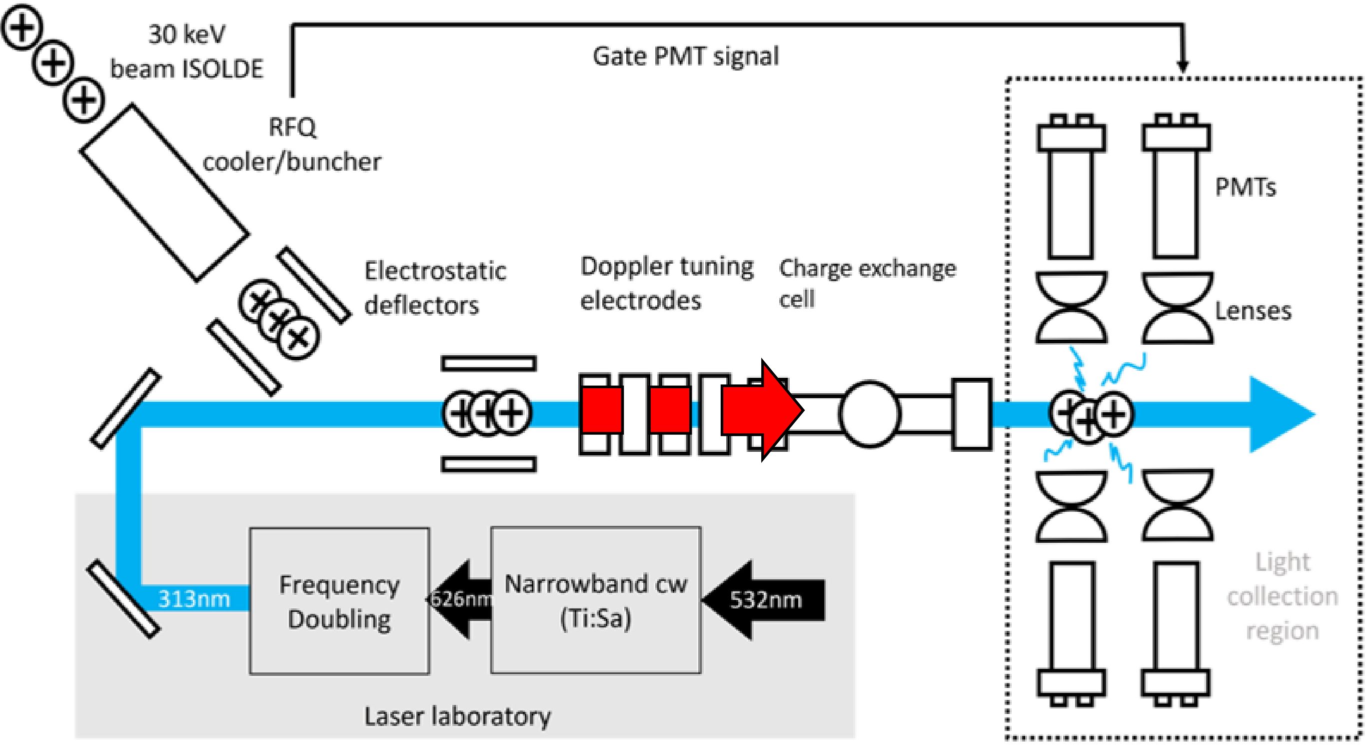
Radioactive ion beam from ISOLDE arrives into the cooler/buncher.

Cooler buncher converts the continuous beam into pulsed bunches.

Beam accumulates in the buncher through the use of a potential.

Pulses are then accelerated and released from the buncher.

COLLAPS



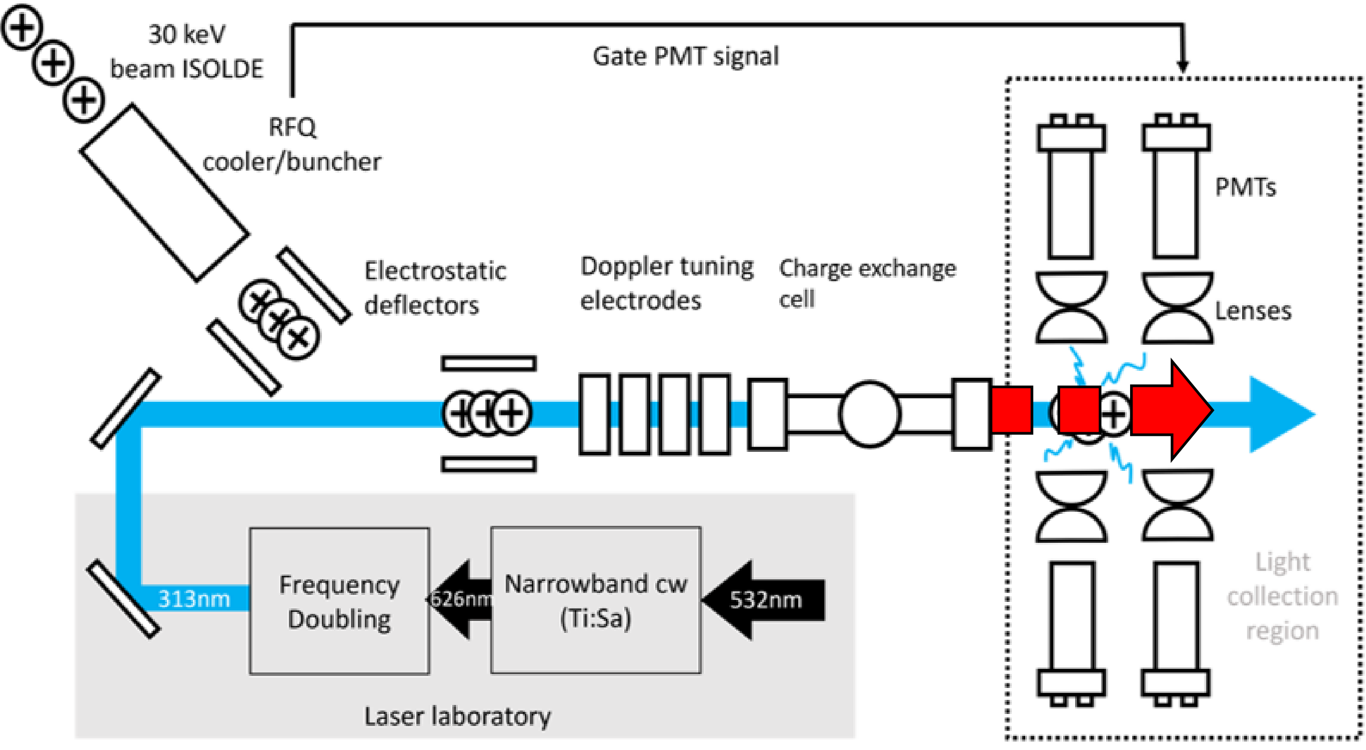
Pulses are then accelerated and released from the buncher.

Ion pulses are deflected into the path of the laser.

The speed of the ions is adjusted by the tuning electrodes.

This allows the frequency to be scanned using the Doppler shift

COLLAPS



This allows the frequency to be scanned using the Doppler shift

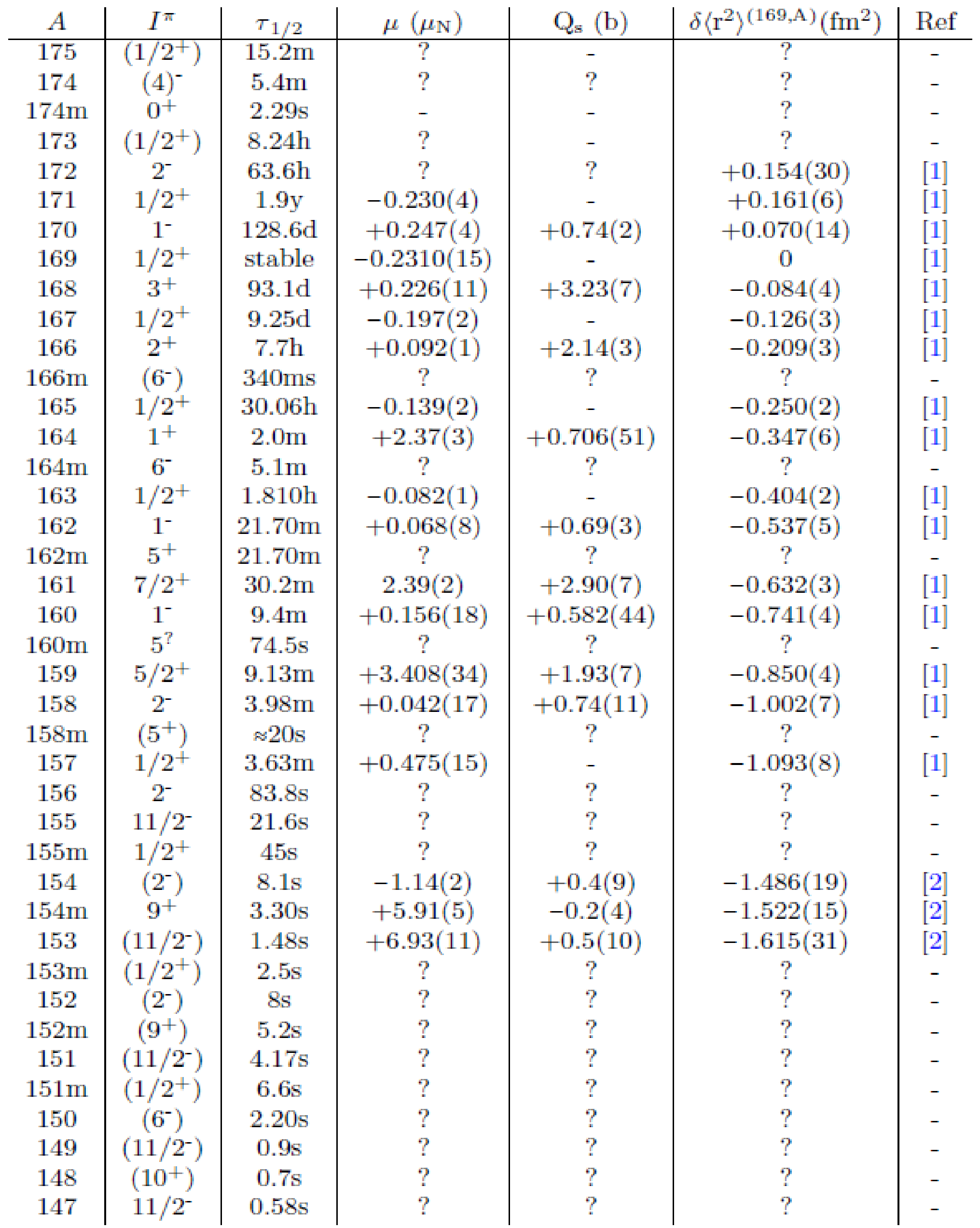
Ions travel through the CEC and arrive at the light collection region

Photons which are re-emitted after resonant excitation can then be detected.

Pulsed beams allow for substantial background suppression.

From this, a hyperfine spectrum of counts against frequency can be obtained.

Previous work



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174	$(4)^-$	5.4m	?	?	?	-
174m	0^+	2.29s	-	-	?	-
173	$(1/2^+)$	8.24h	?	-	?	-
172	2^-	63.6h	?	?	+0.154(30)	[1]
171	$1/2^+$	1.9y	−0.230(4)	-	+0.161(6)	[1]
170	1^-	128.6d	+0.247(4)	+0.74(2)	+0.070(14)	[1]
169	$1/2^+$	stable	−0.2310(15)	-	0	[1]
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165	$1/2^+$	30.06h	−0.139(2)	-	−0.250(2)	[1]
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162m	5^+	21.70m	?	?	?	-
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155m	$1/2^+$	45s	?	?	?	-
154	(2^-)	8.1s	−1.14(2)	+0.4(9)	−1.486(19)	[2]
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149	$(11/2^-)$	0.9s	?	?	?	-
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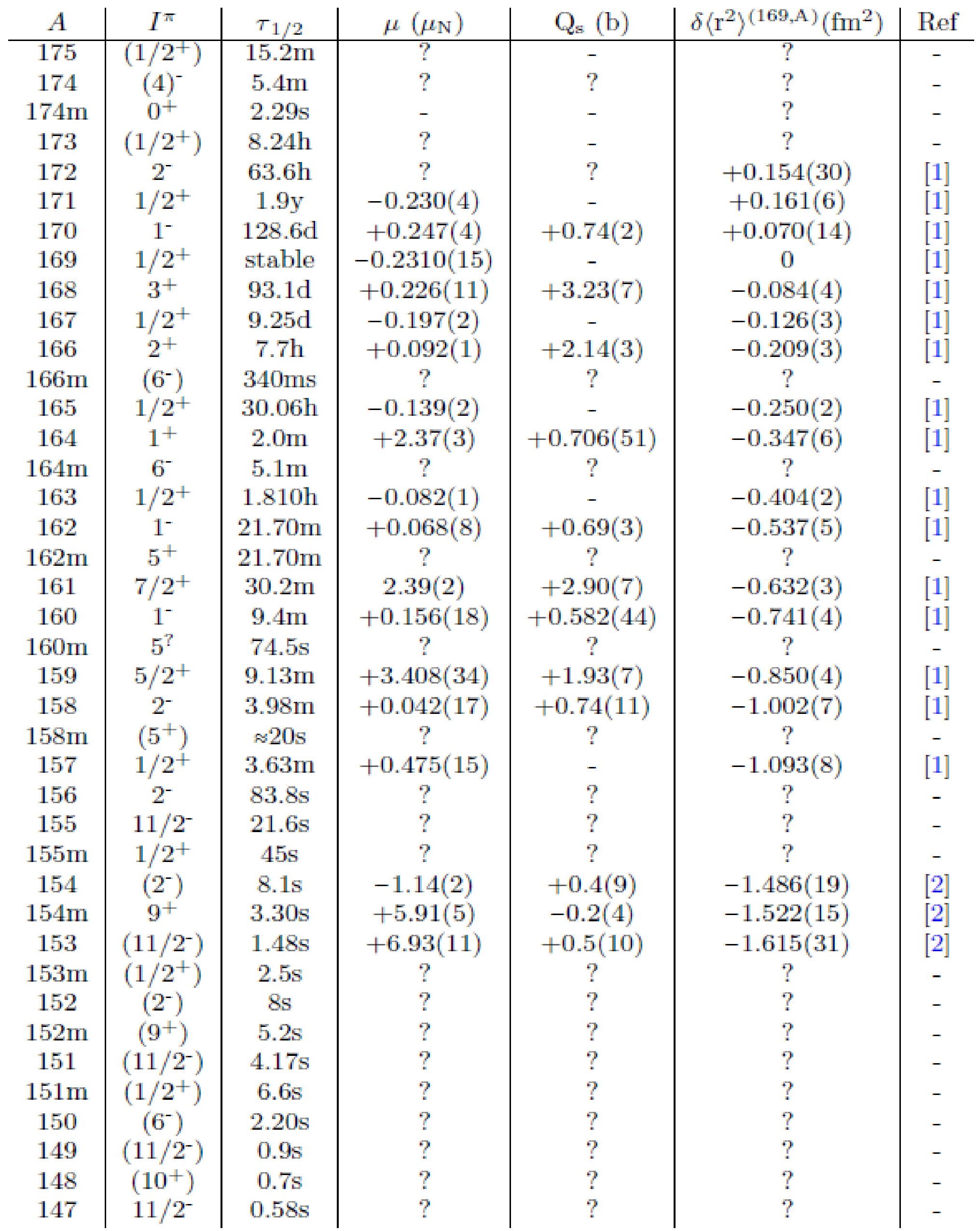
147	$11/2^-$	0.58s	?	?	?	-

Previous laser spectroscopy performed on isotopes ^{153}Tm - ^{172}Tm in the work by G. D. Alkhazov *et al* [1] and A. E. Barzakh et al [2] .

Previous and current work



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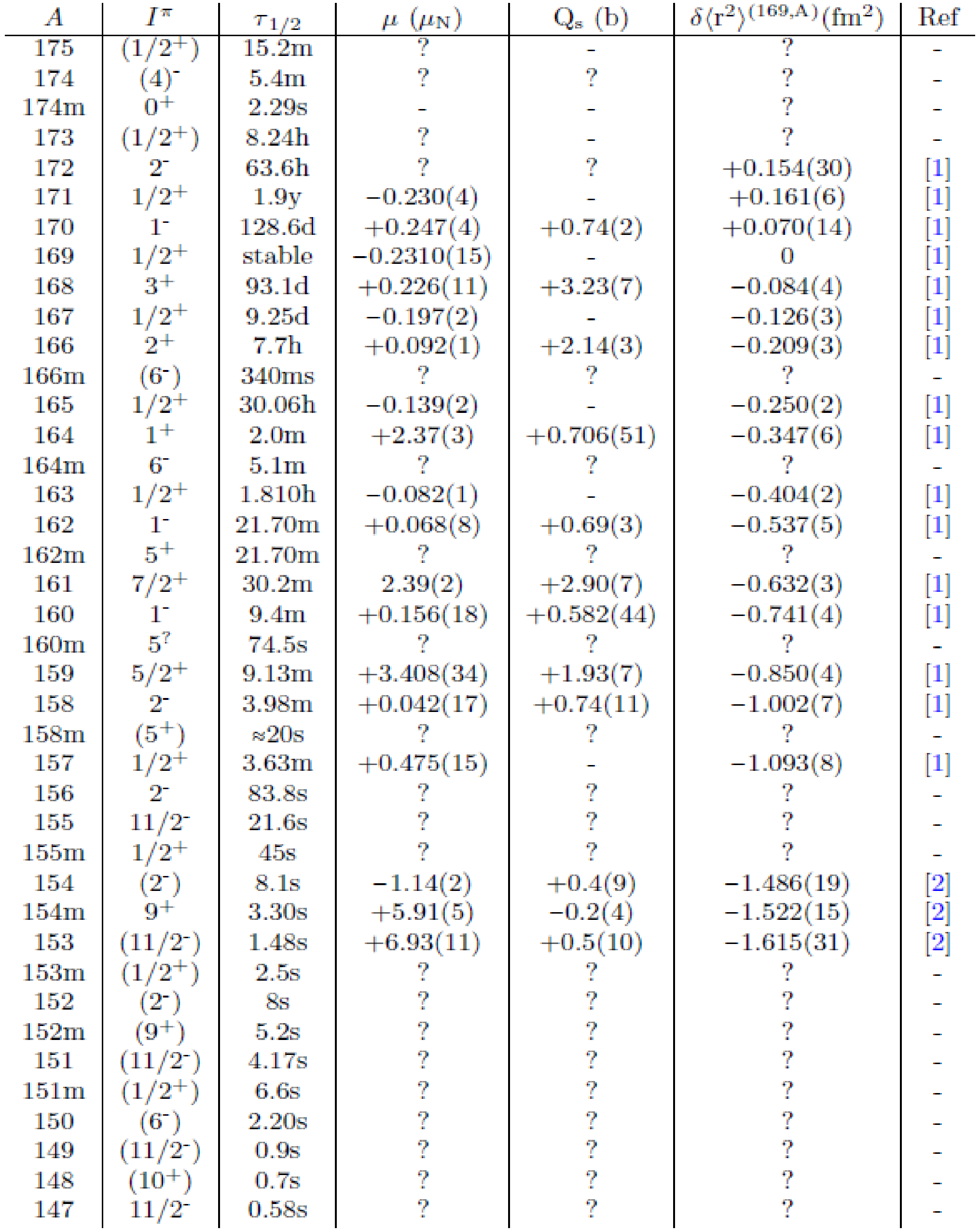
The eventual goal is to reach the heavily neutron deficient side of thulium to reach ^{147}Tm. This is because ^{147}Tm is a proton emitter with a 15% proton emission branch.

In august, 3 days of beam time were allocated to primarily test the yields of neutron deficient thulium and to find a suitable spectroscopic transition with sensitivity to the nuclear properties

New data



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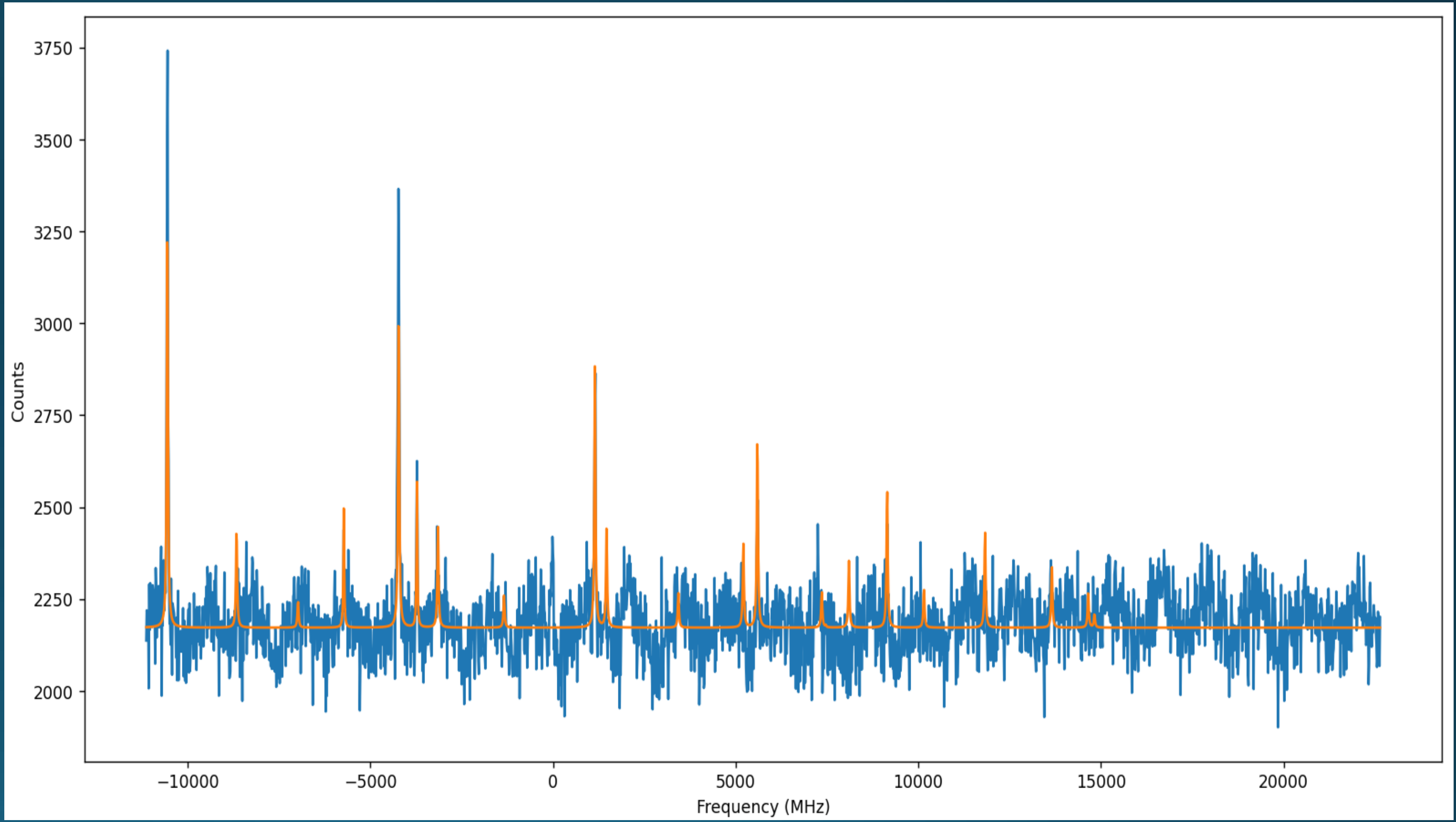
The transition of the ionic 313nm J=4 → J=5 line from the ground state was tested and was very promising.

During these 3 days, despite various issues, lots of isotopes were measured with ^{155}Tm, ^{156}Tm, ^{172}Tm, ^{173}Tm, ^{174}Tm, ^{175}Tm being measured, via laser spectroscopy, for the first time. Several isomeric states were measured for the first time as well.

Issues in ^{155}Tm

^{155}Tm was the limit of the study, a poor signal to noise ratio was caused by isobaric contamination in the beam.

Despite this, there are clearly enough peaks visible to be able to fit and analyse the data.



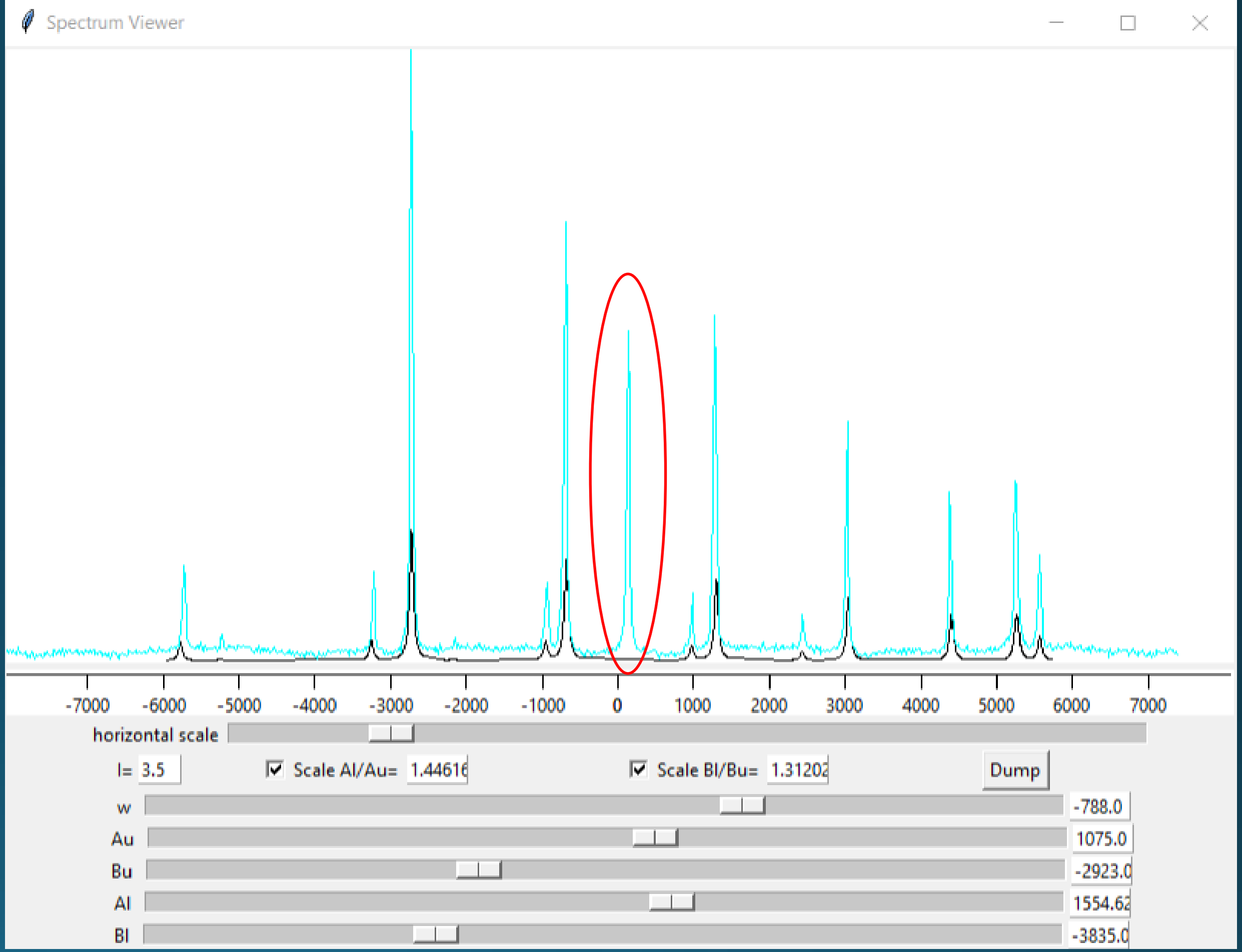
Isomer in ^{161}Tm

^{161}Tm was more complex due to a single peak that could not be accounted for by the ground state alone.

There is no listed isomeric state on Nudat3 or the IAEA nuclear moments.

As it is an odd-even nucleus, an isomeric state spin cannot be an integer, and so a spin of ½ is the lowest possible spin state for this peak.

Having only the one peak, however, suggests that the isomeric peaks have collapsed into this single peak.



I= 3.5

☑ Scale Al/Au= 1.44616

☑ Scale Bl/Bu= 1.31202

w -788.0

Au 1075.0

Bu -2923.0

Al 1554.62

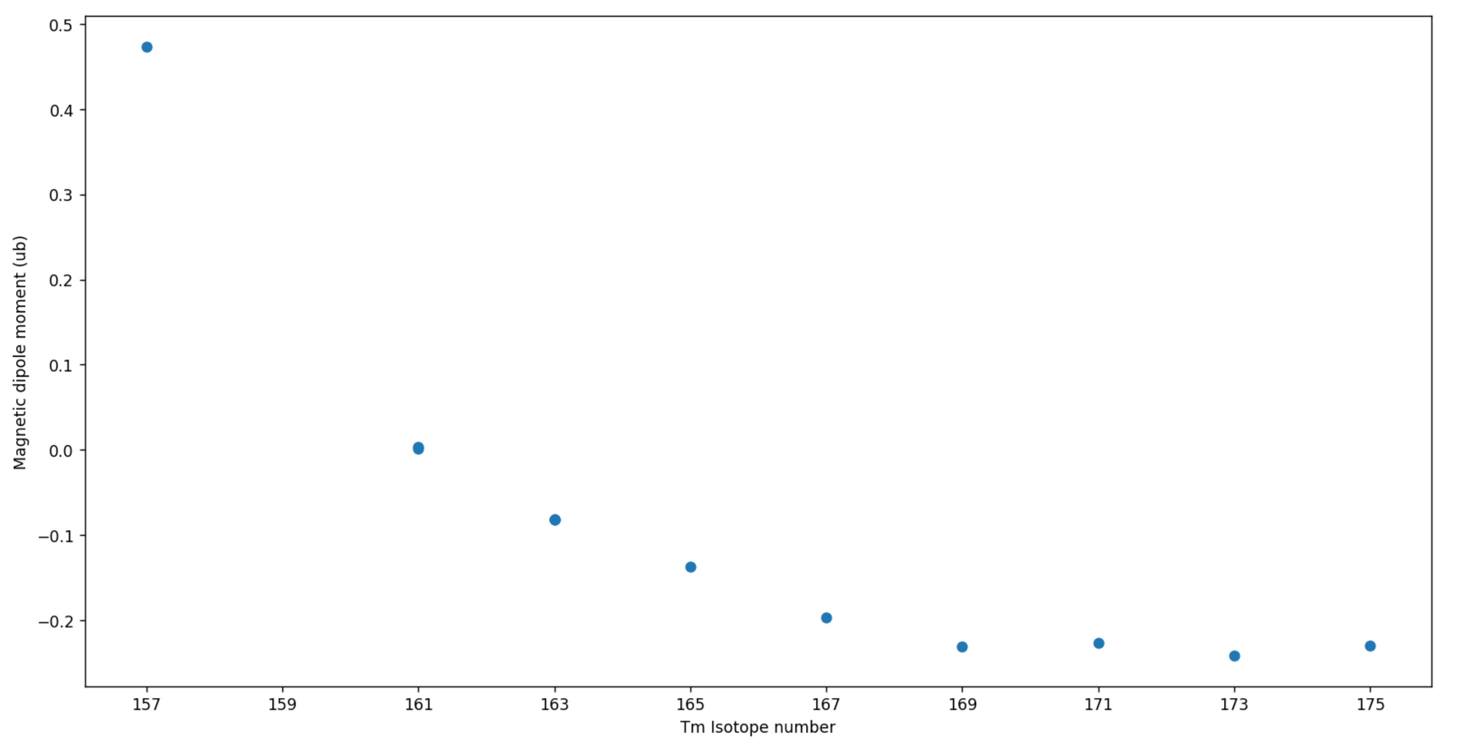
Bl -3835.0

Initial estimate of the ground state ^{161}Tm (black) against converted data from run 63 (blue). The single unaccounted peak has been circled in red

Isomer in ^{161}Tm

Having only the one peak, however, suggests that the isomeric peaks have collapsed into this single peak.

This suggestion is supported as it would follow the trend seen here, placing the magnetic dipole moment at 0, which would collapse the isomeric spin ½ peaks into a single peak



Isomer in ^{161}Tm

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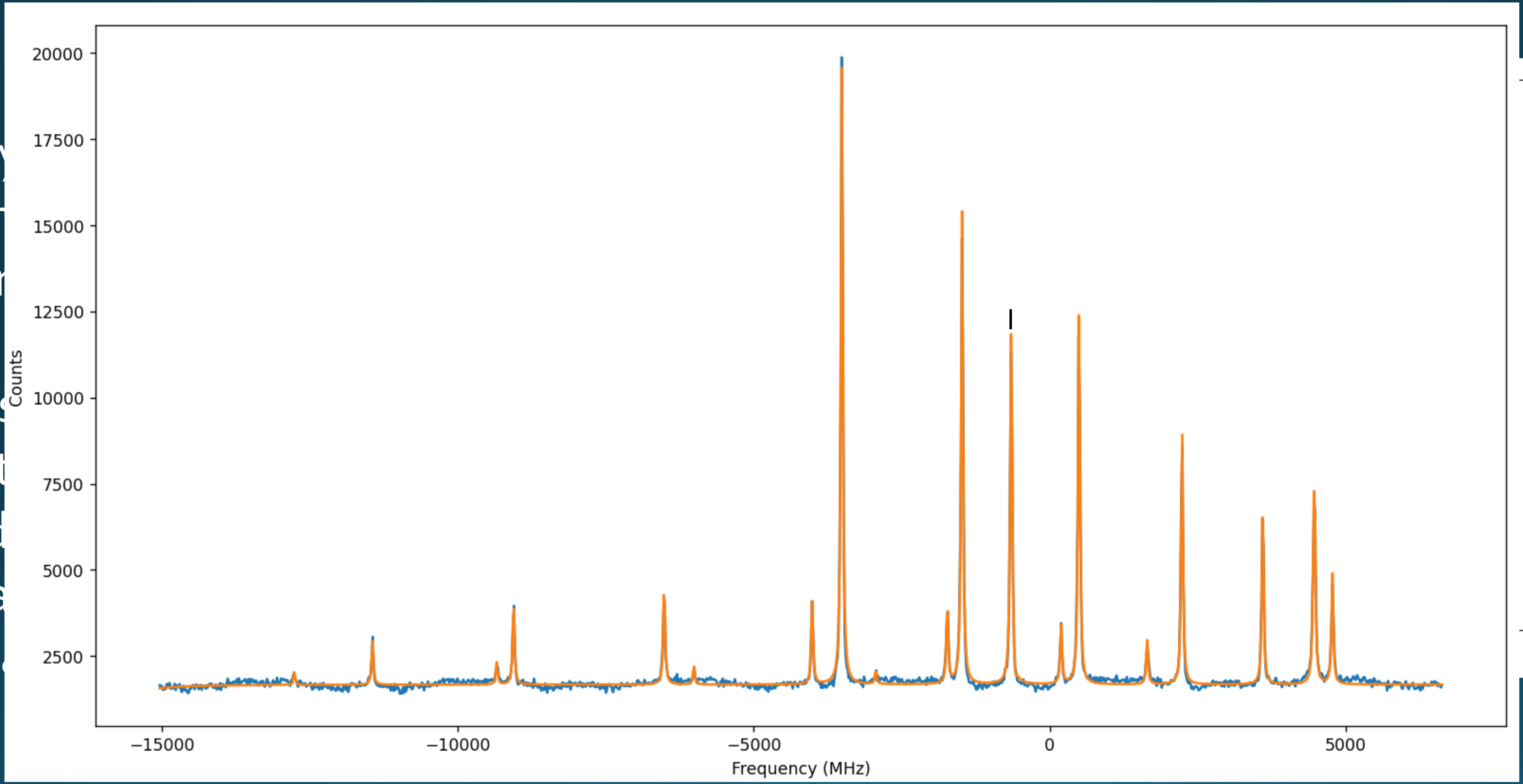
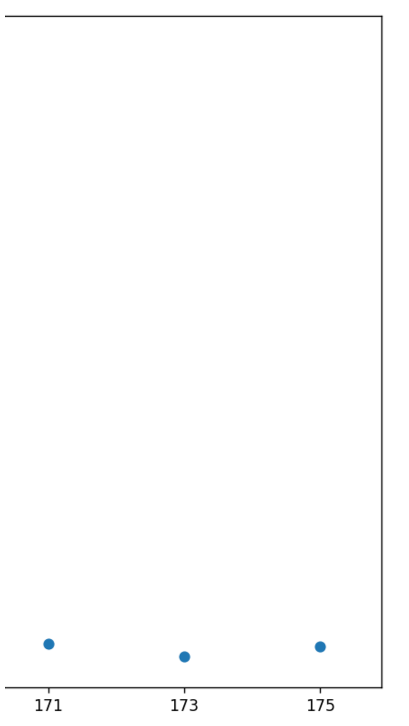
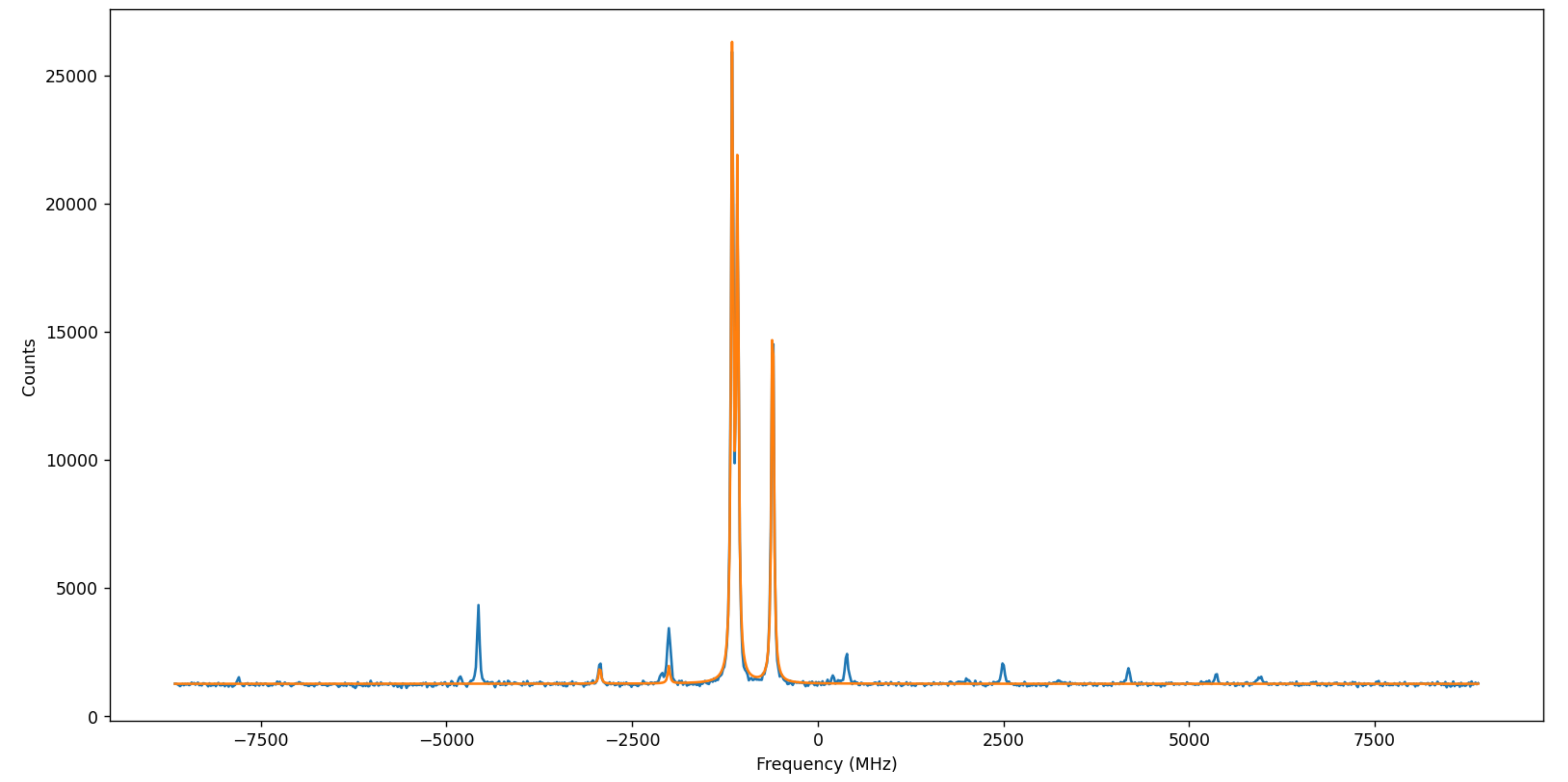




Isomer spin in ^{160}Tm

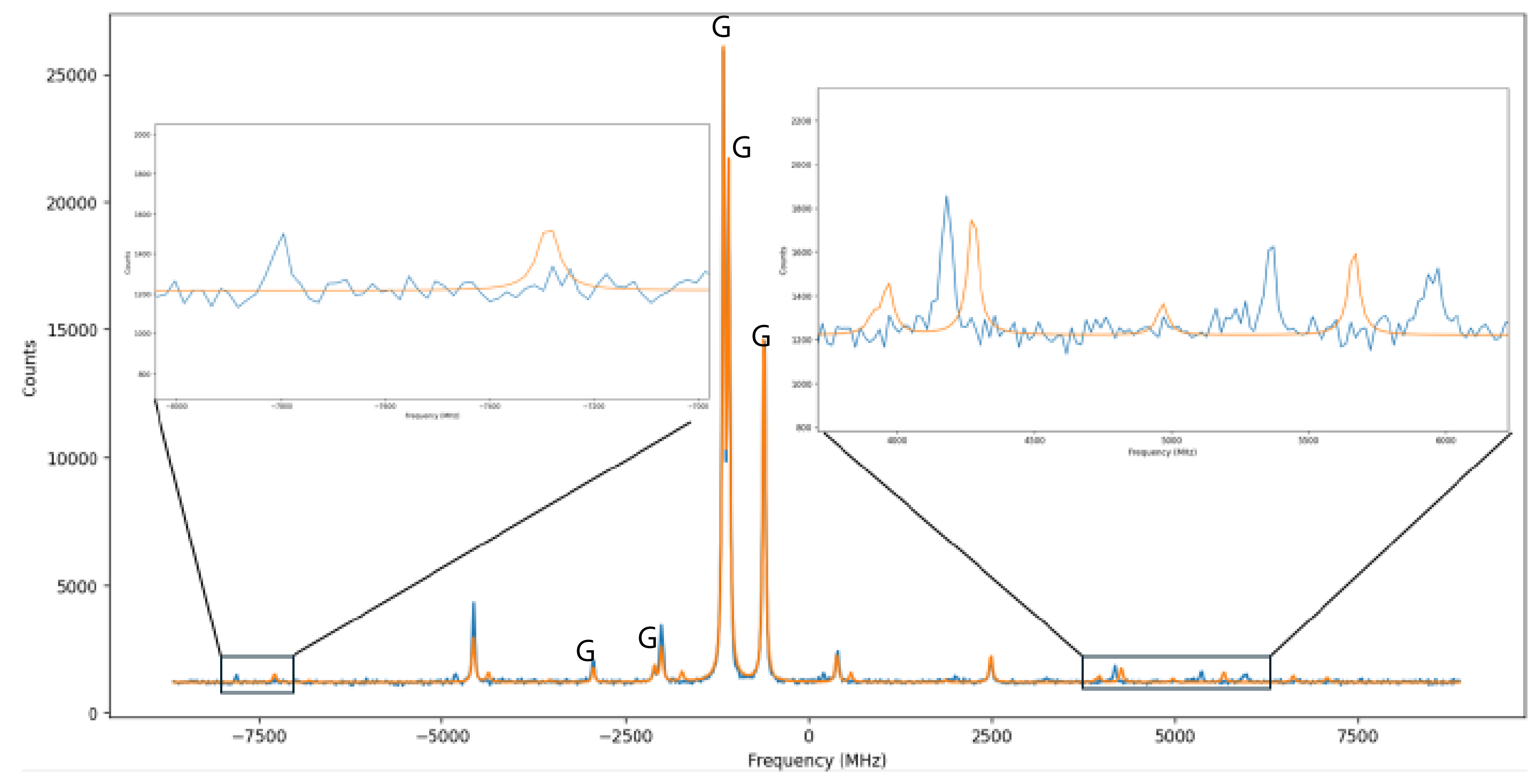


Fit of ground state peaks (orange) against data (blue) for ^{160}Tm.

The ground state of ^{160}Tm was simple to fit, as all peaks could be accounted for.

However, the Isomeric state was significantly harder to find an initial estimate for

Isomer spin in ^{160}Tm



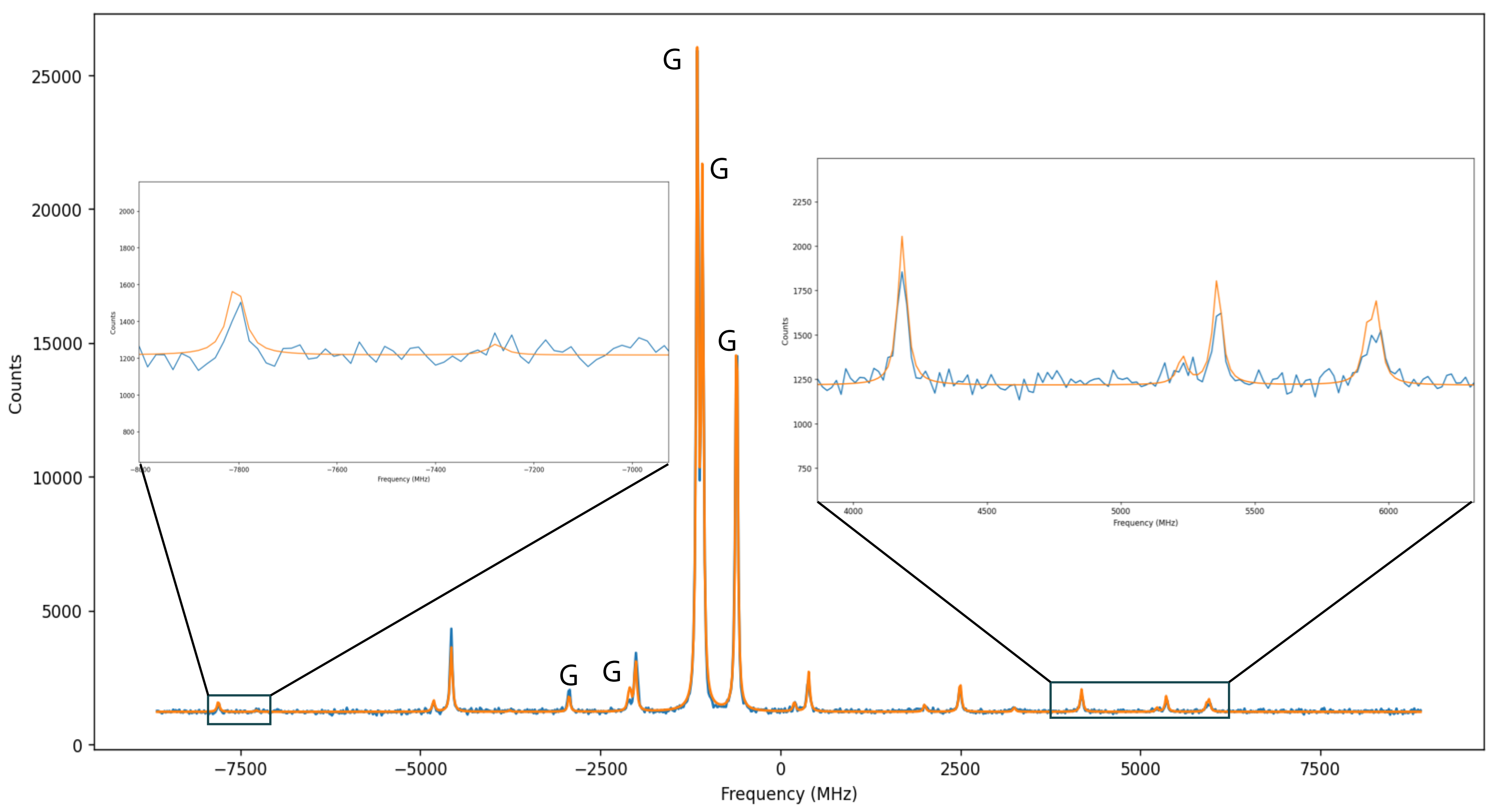
Fit of ground and isomeric state peaks (orange) against data (blue) with an isomeric spin assignment of 5

Even with a good estimate, multiple discrepancies can be found.

This led to some questions regarding the spin assignment of the isomeric state of ^{160}Tm

As such, different spins were investigated to see if other spins would produce a better fit

Isomer spin in ^{160}Tm

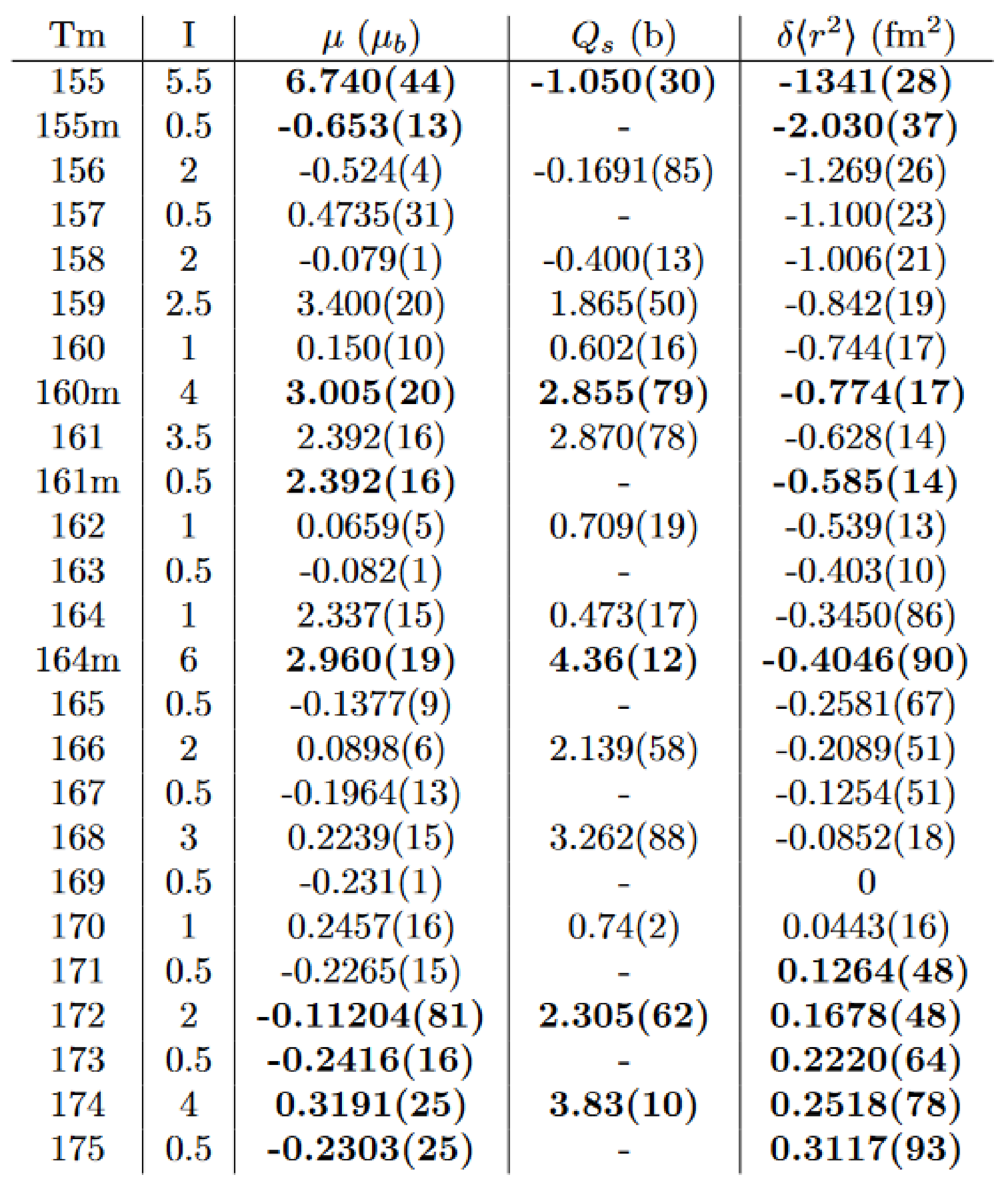


Fit of ground and isomeric state peaks (orange) against data (blue) with an isomeric spin assignment of 4

As such, different spins were investigated to see if other spins would produce a better fit

An isomeric state with a spin of 4 can be seen to be much more agreeable.

Results



Tm	I	μ (μ_b)	Q_s (b)	$\delta\langle r^2\rangle$ (fm^2)
155	5.5	**6.740(44)**	**-1.050(30)**	**-1341(28)**
155m	0.5	**-0.653(13)**	-	**-2.030(37)**
156	2	-0.524(4)	-0.1691(85)	-1.269(26)
157	0.5	0.4735(31)	-	-1.100(23)
158	2	-0.079(1)	-0.400(13)	-1.006(21)
159	2.5	3.400(20)	1.865(50)	-0.842(19)
160	1	0.150(10)	0.602(16)	-0.744(17)
160m	4	**3.005(20)**	**2.855(79)**	**-0.774(17)**
161	3.5	2.392(16)	2.870(78)	-0.628(14)
161m	0.5	**2.392(16)**	-	**-0.585(14)**
162	1	0.0659(5)	0.709(19)	-0.539(13)
163	0.5	-0.082(1)	-	-0.403(10)
164	1	2.337(15)	0.473(17)	-0.3450(86)
164m	6	**2.960(19)**	**4.36(12)**	**-0.4046(90)**
165	0.5	-0.1377(9)	-	-0.2581(67)
166	2	0.0898(6)	2.139(58)	-0.2089(51)
167	0.5	-0.1964(13)	-	-0.1254(51)
168	3	0.2239(15)	3.262(88)	-0.0852(18)
169	0.5	-0.231(1)	-	0
170	1	0.2457(16)	0.74(2)	0.0443(16)
171	0.5	-0.2265(15)	-	**0.1264(48)**
172	2	**-0.11204(81)**	**2.305(62)**	**0.1678(48)**
173	0.5	**-0.2416(16)**	-	**0.2220(64)**
174	4	**0.3191(25)**	**3.83(10)**	**0.2518(78)**
175	0.5	**-0.2303(25)**	-	**0.3117(93)**

New nuclear moments for various isotopes and isomers across the thulium chain (bold).

Very strong evidence for a spin reassignment, as no other spin value can reproduce the frequency pattern of all the peaks simultaneously.

Very strong evidence for new isomeric state(s) as well.

Still a long way to go to get to ^{147}Tm.

Thank you!

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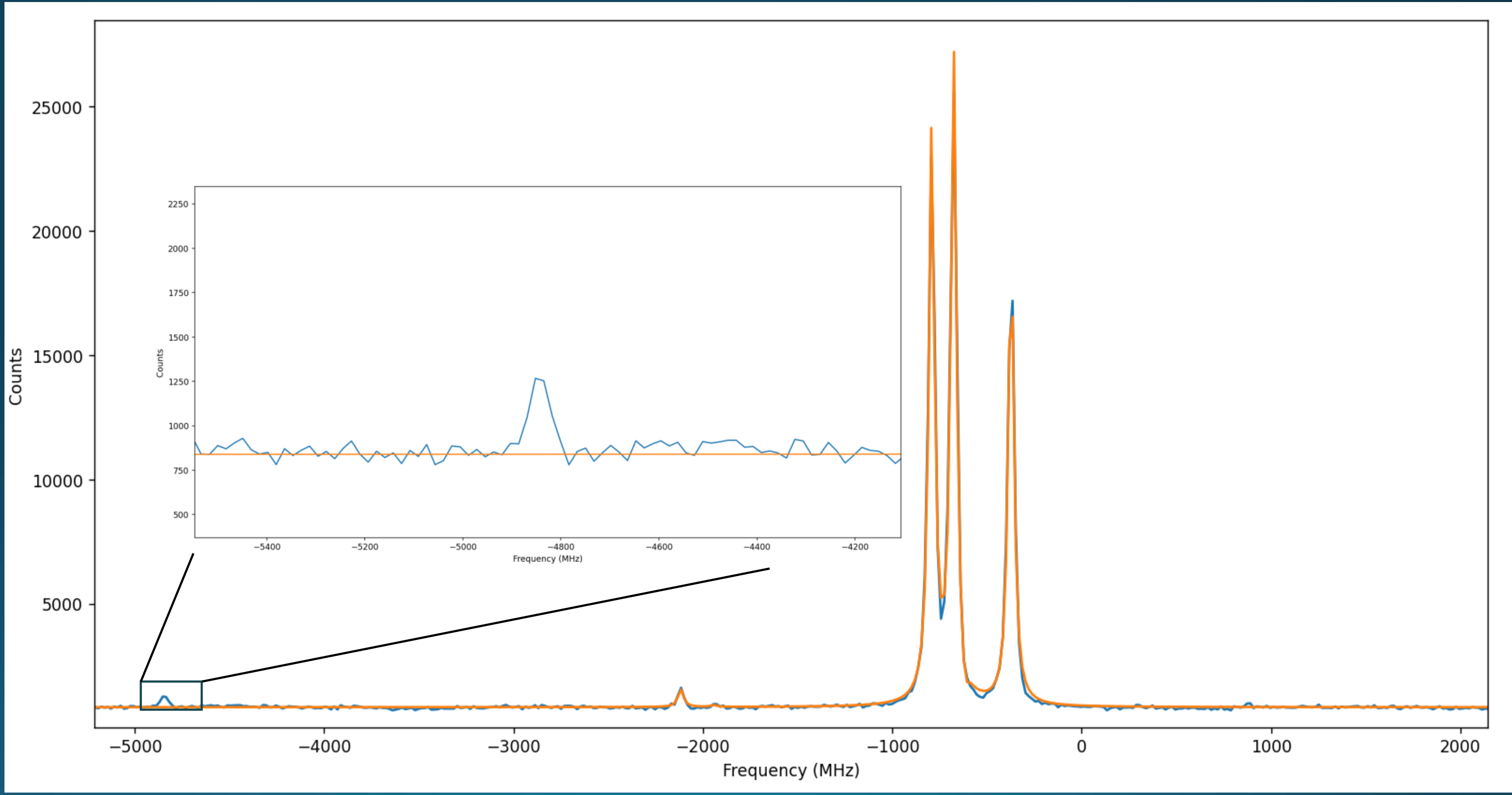
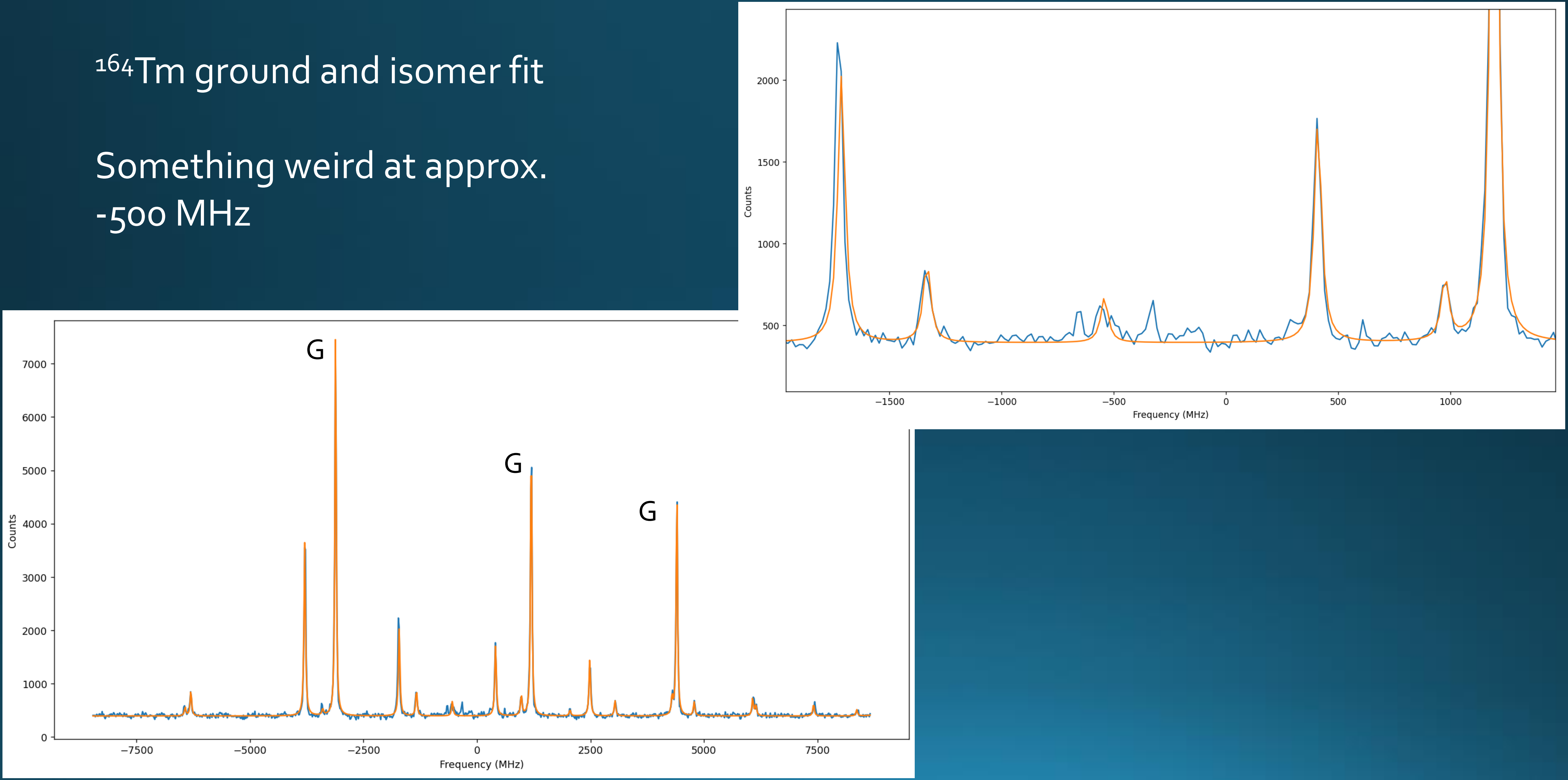
^{162}Tm ground state fit

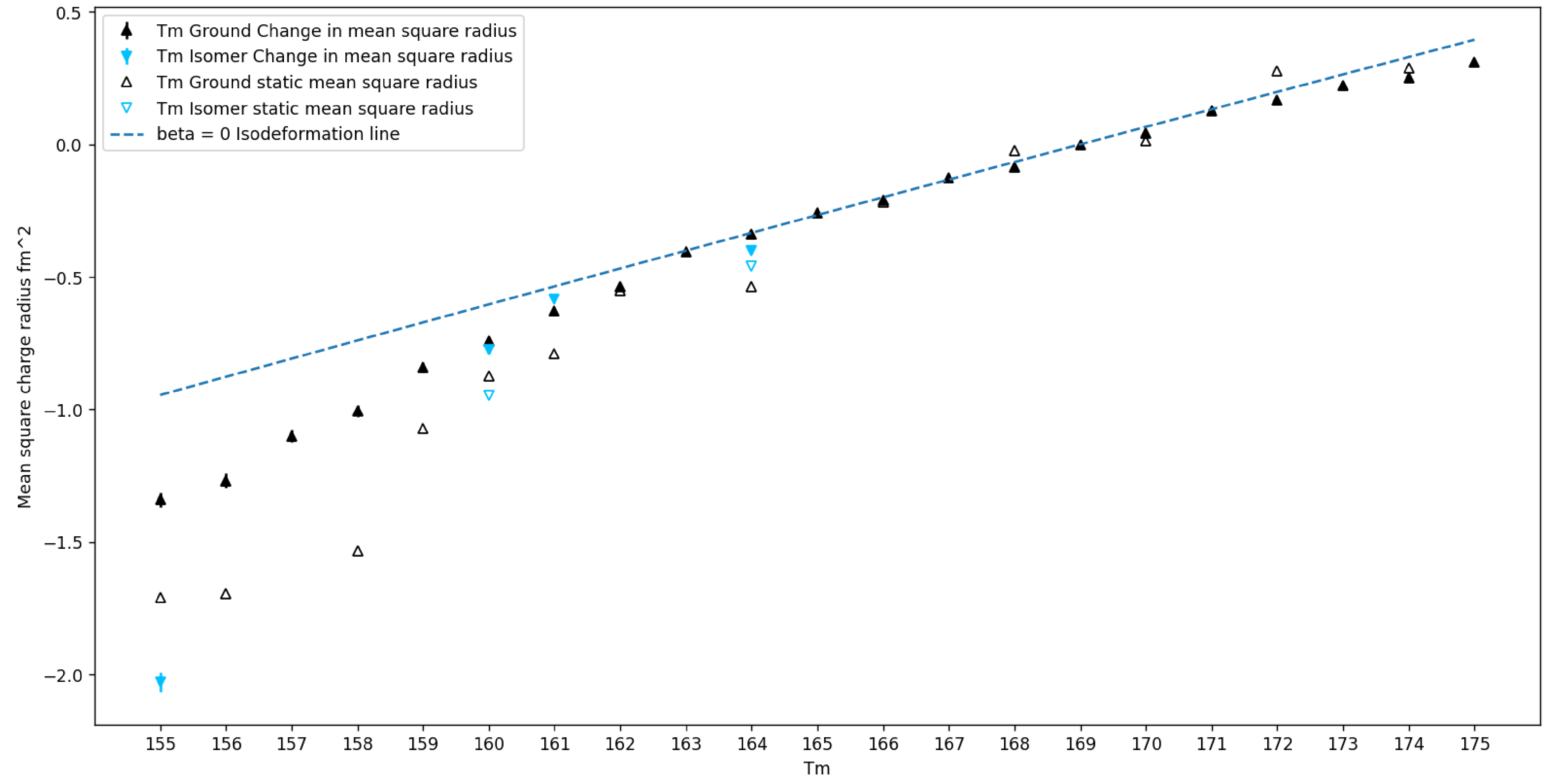
Small peaks above background at -5000 and 1000 MHz

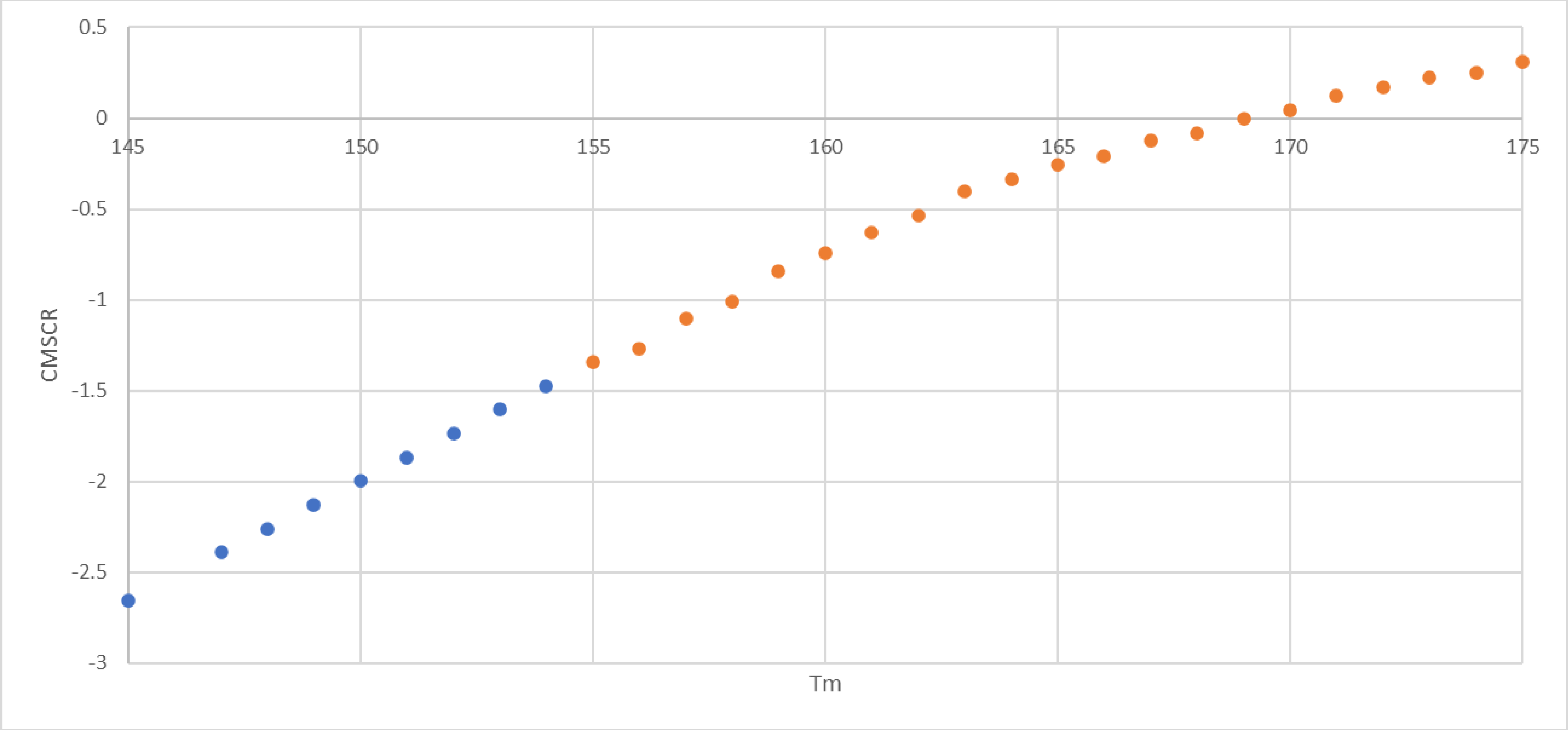


^{164}Tm ground and isomer fit

Something weird at approx. -500 MHz




Tm Ground Change in mean square radius
Tm Isomer Change in mean square radius
Tm Ground static mean square radius
Tm Isomer static mean square radius
beta = 0 Isodeformation line
Mean square charge radius fm^2
0.5
0.0
−0.5
−1.0
−1.5
−2.0
155
156
157
158
159
160
161
162
163
164
165
166
167
168
169
170
171
172
173
174
175
Tm


0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
CMSCR
145
150
155
160
165
170
175
Tm

^{155}Tm raw data

Background increase at high line voltage in PMT 1