Study of the ^{198}Hg(d,d') Inelastic Scattering Reaction

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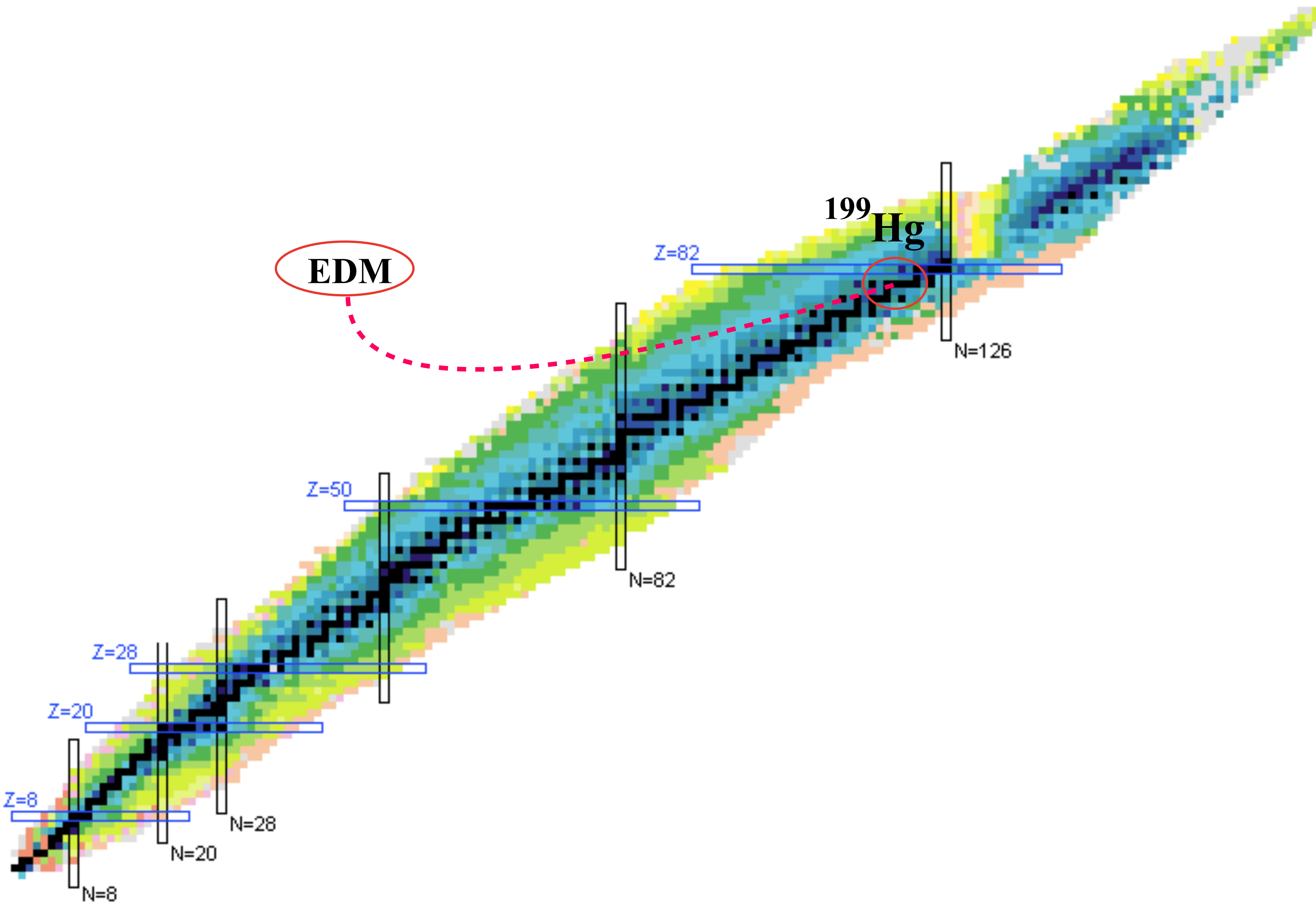
MOTIVATION



From NNDC

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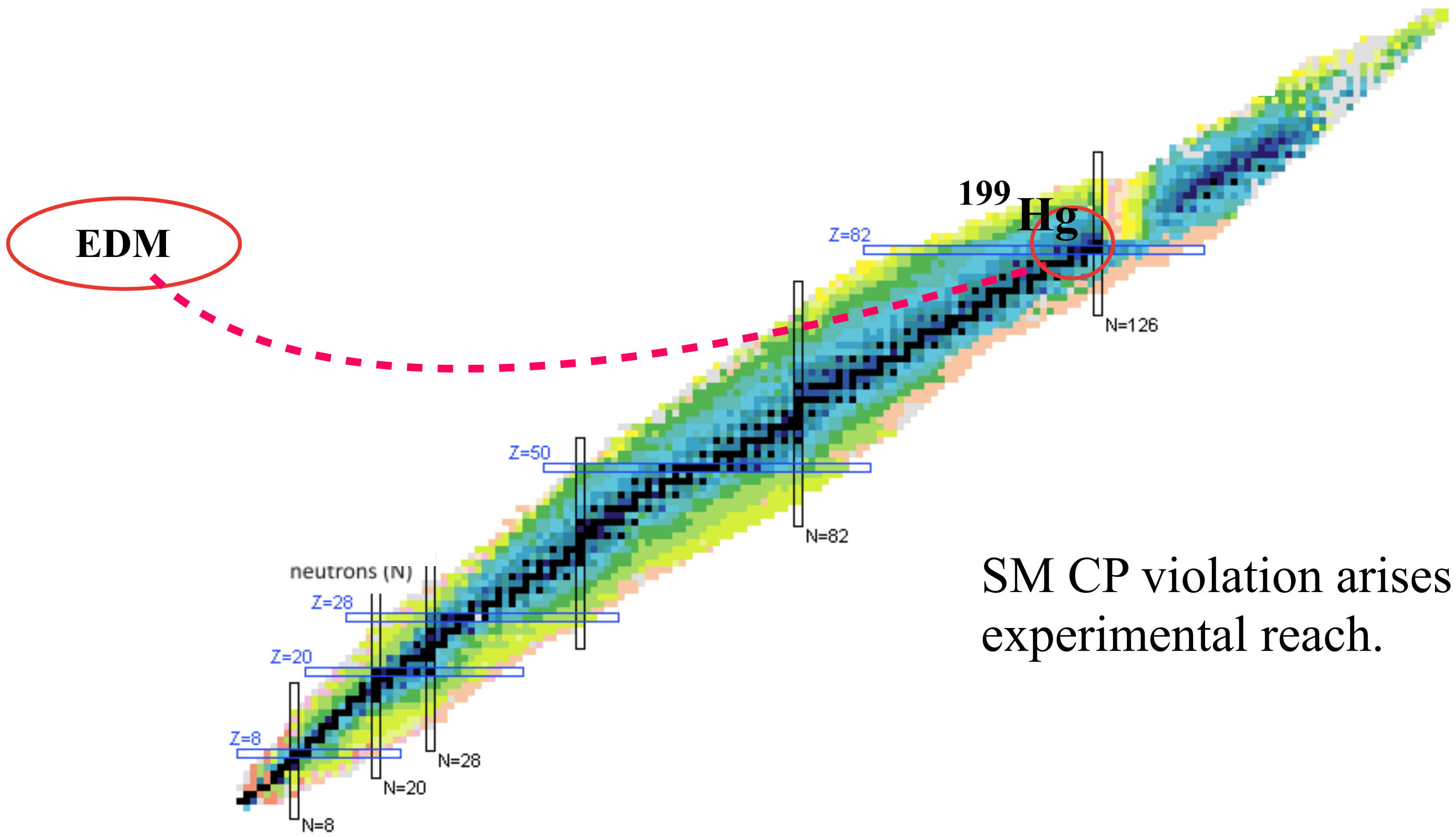
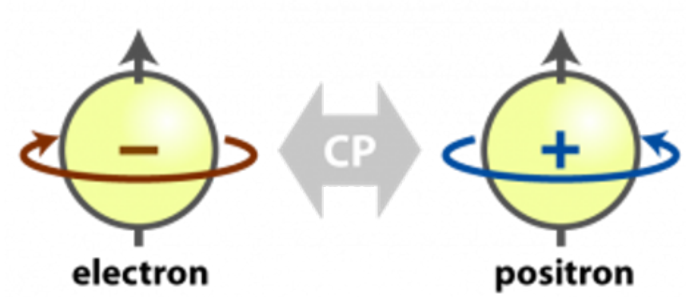
MOTIVATION



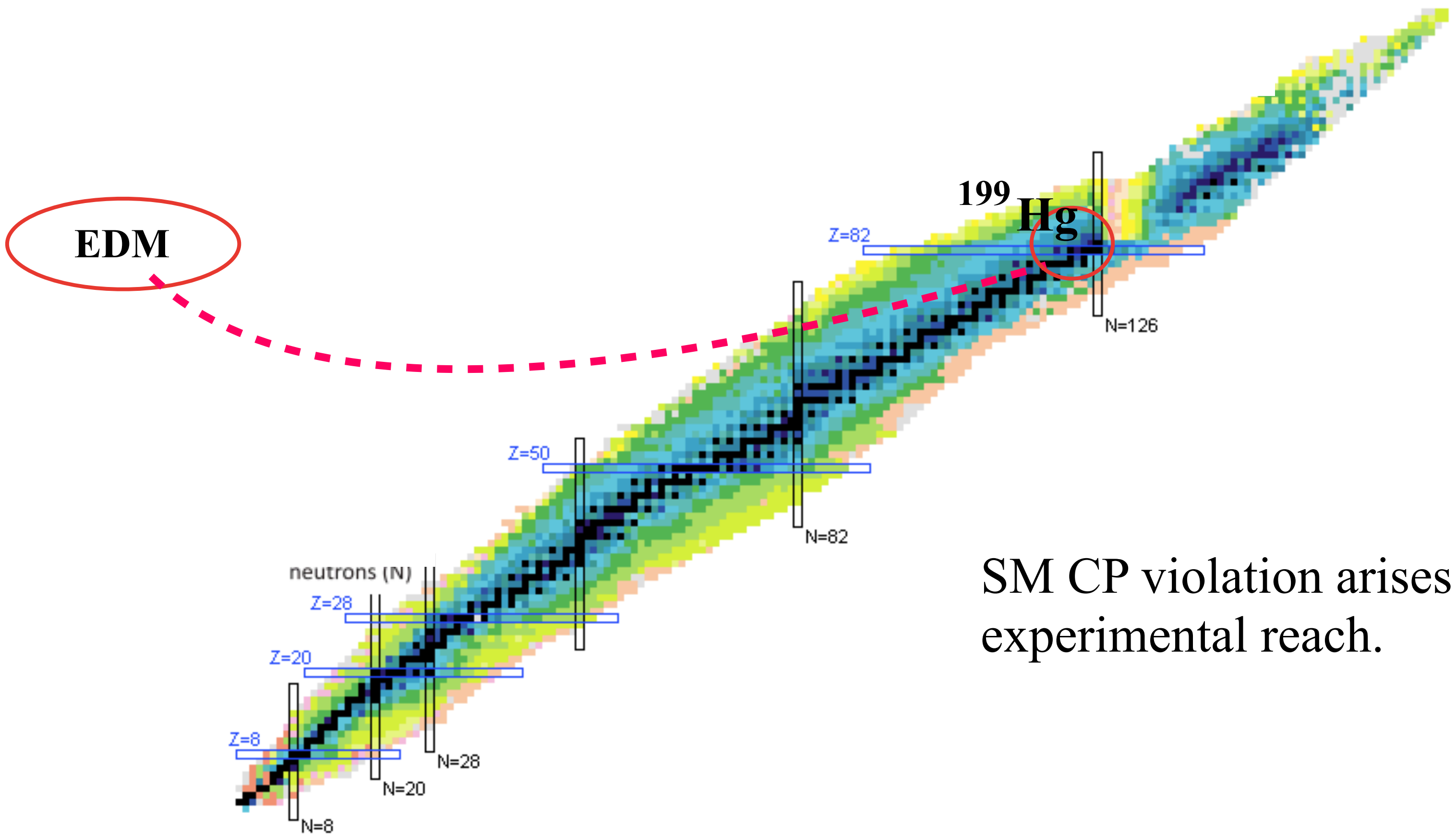
From NNDC

SM CP violation arises from a complex phase in CKM << Current experimental reach.

BSM → larger EDM → SIGNAL OF CP Violation



MOTIVATION

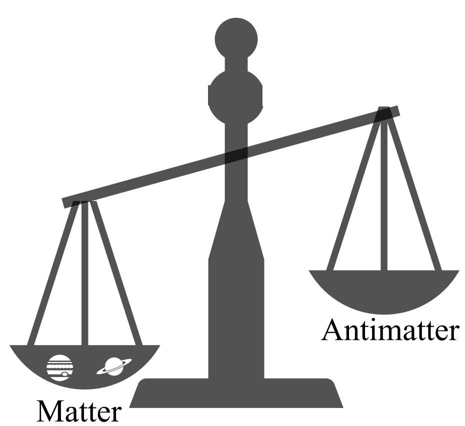


SM CP violation arises from a complex phase in CKM << Current experimental reach.

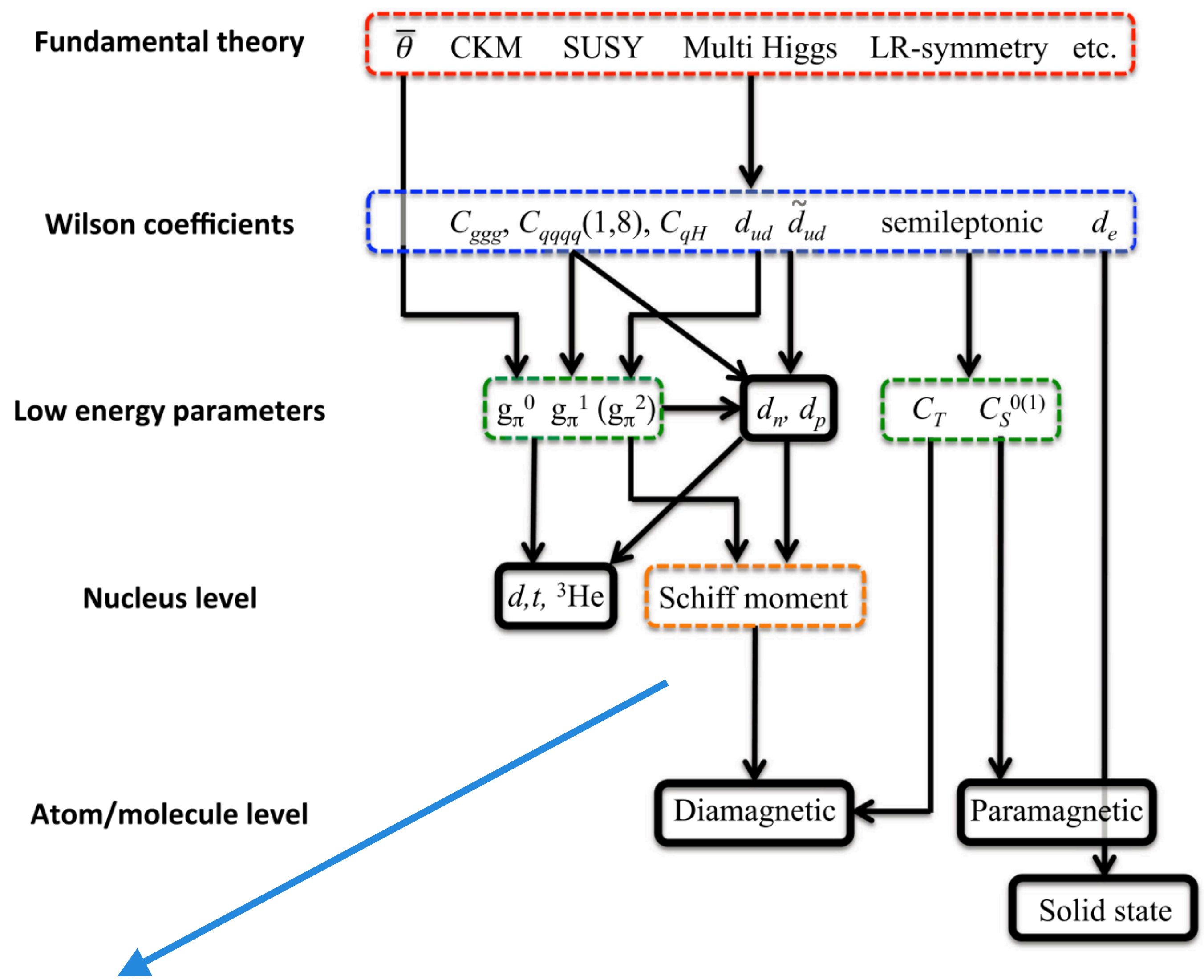
BSM → larger EDM

↓

SIGNAL OF CP Violation



SCHIFF MOMENT



Lowest-order observable EDM for a neutral atom in its ground state

$$\mathbf{S} = \frac{1}{10}\left(\int e\rho(\mathbf{r})r^2\mathbf{r}d^3\mathbf{r} - \frac{5}{3}\mathbf{d}\frac{1}{Z}\int\rho(\mathbf{r})r^2d^3\mathbf{r}\right), \qquad \mathbf{d} = \frac{1}{10}\left(\int e\mathbf{r}\rho(\mathbf{r})d^3\mathbf{r}\right.$$

[4]

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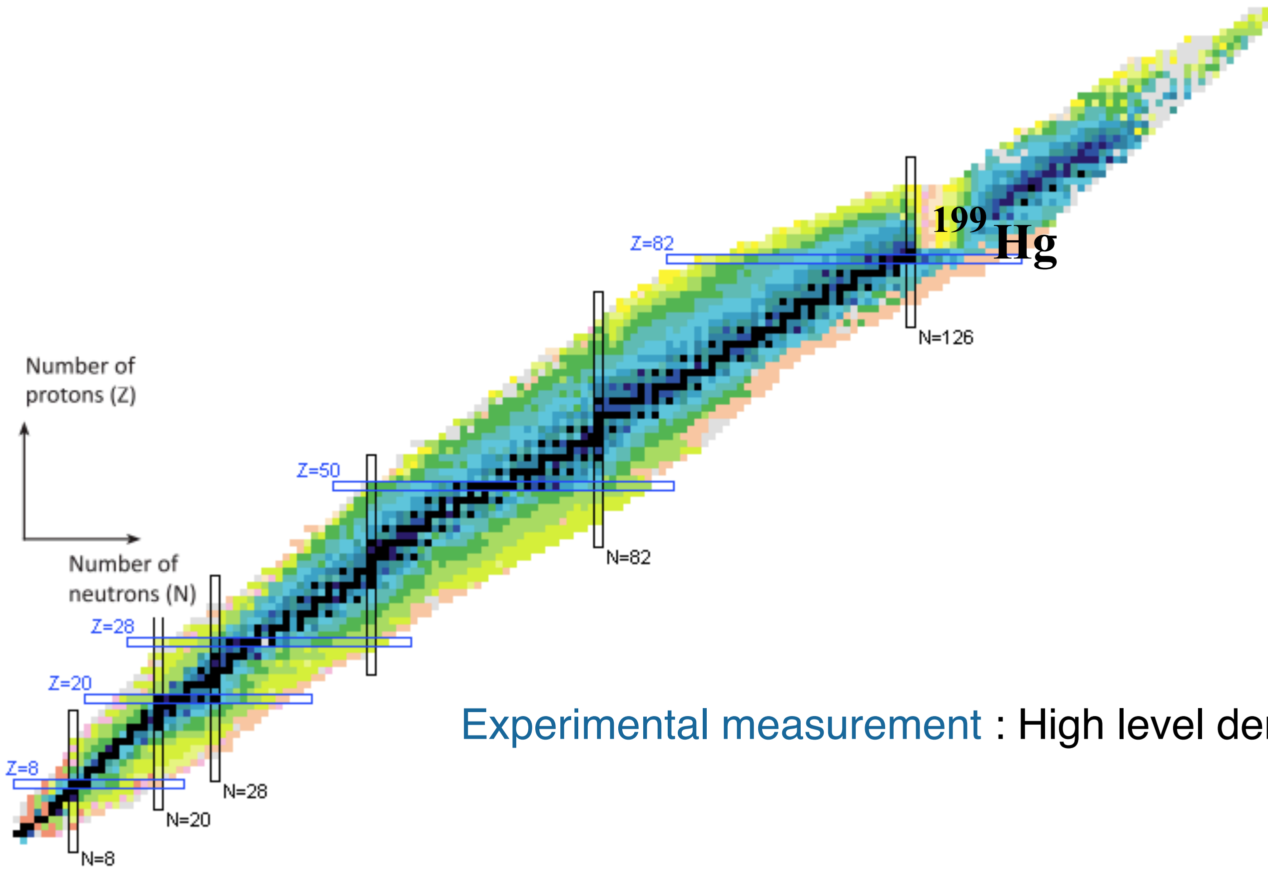
CHALLENGES IN ^{199}Hg



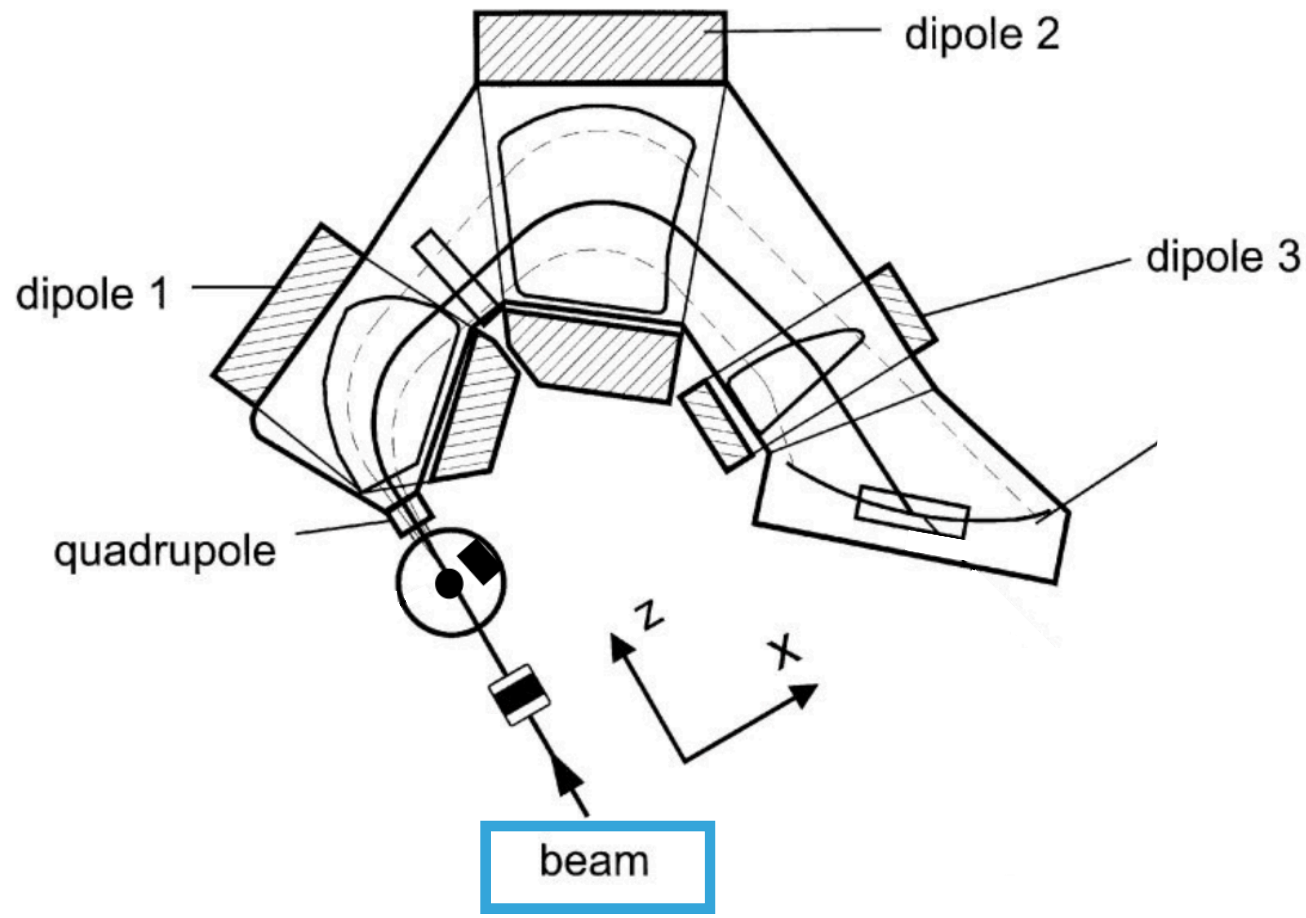
Experimental measurement : High level density of a heavy odd- A nucleus.

[1]

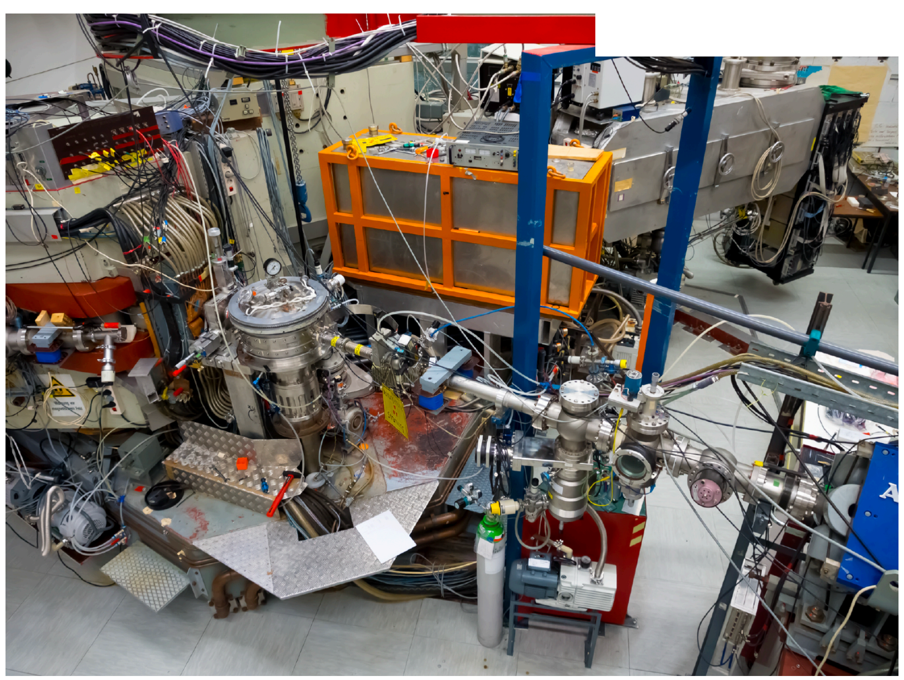
SOLUTION → Information from states in the neighbouring even-even isotopes of ^{198}Hg and ^{200}Hg

E2 and E3 strengths → Constrains present models.

Maier-Leibnitz Laboratorium of the Ludwig-Maximilians Universität München



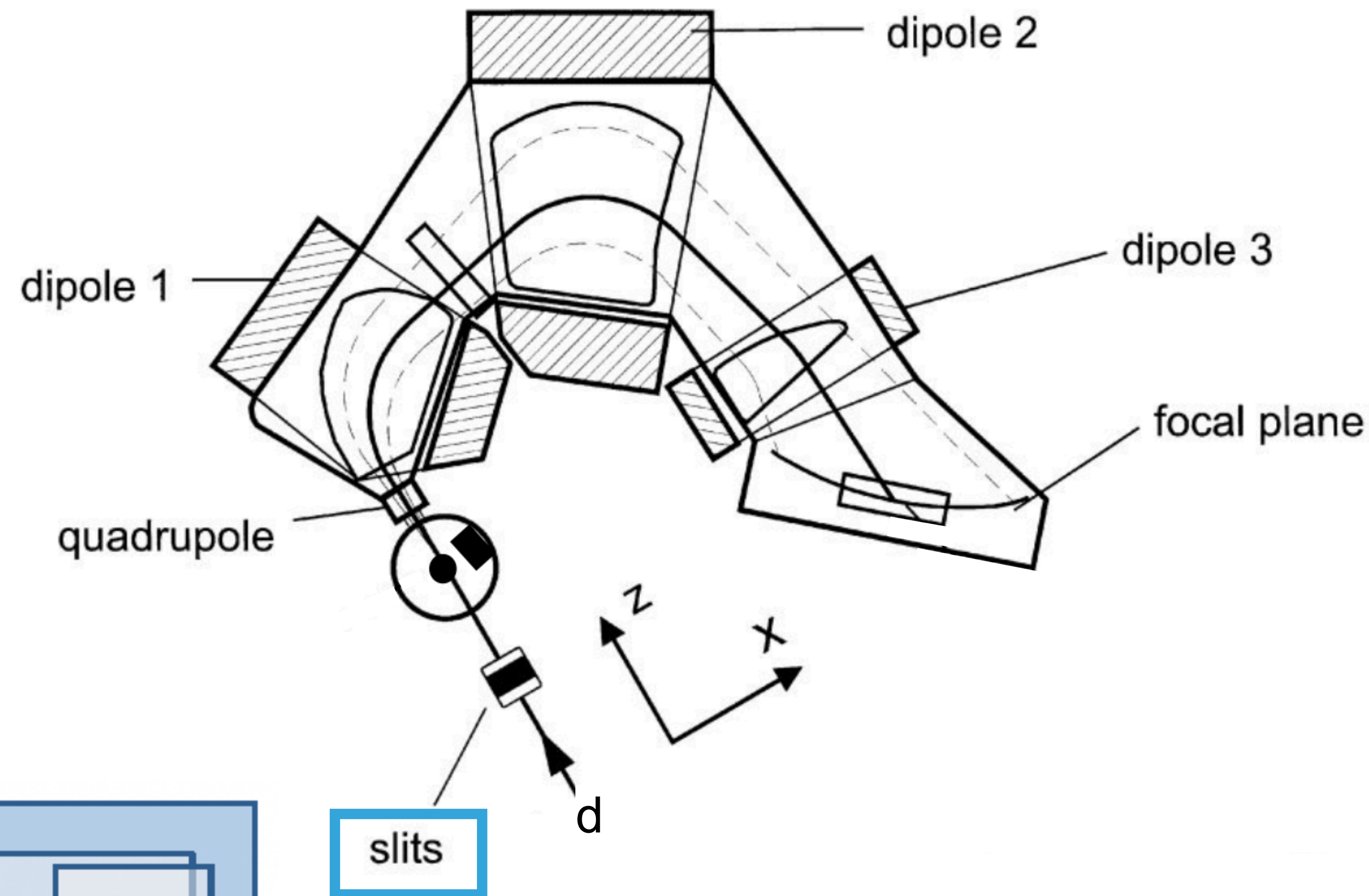
Q3D magnetic spectrograph at MLL

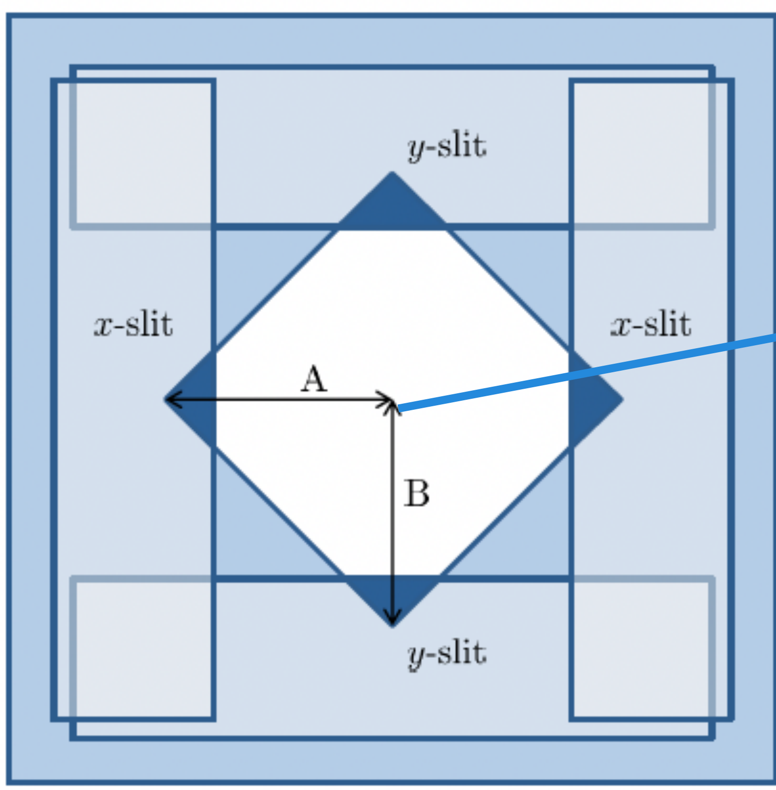


From E.T. Rand.

- Beam: d
- Beam energy: 22 MeV
- Beam current: 1 μA

SOLID ANGLE





Q3D acceptance solid angle

A=31.5 mm
B=36.75 mm

$$\Omega = \frac{(F(x,y) - \Delta F(x,y))}{D^2},$$

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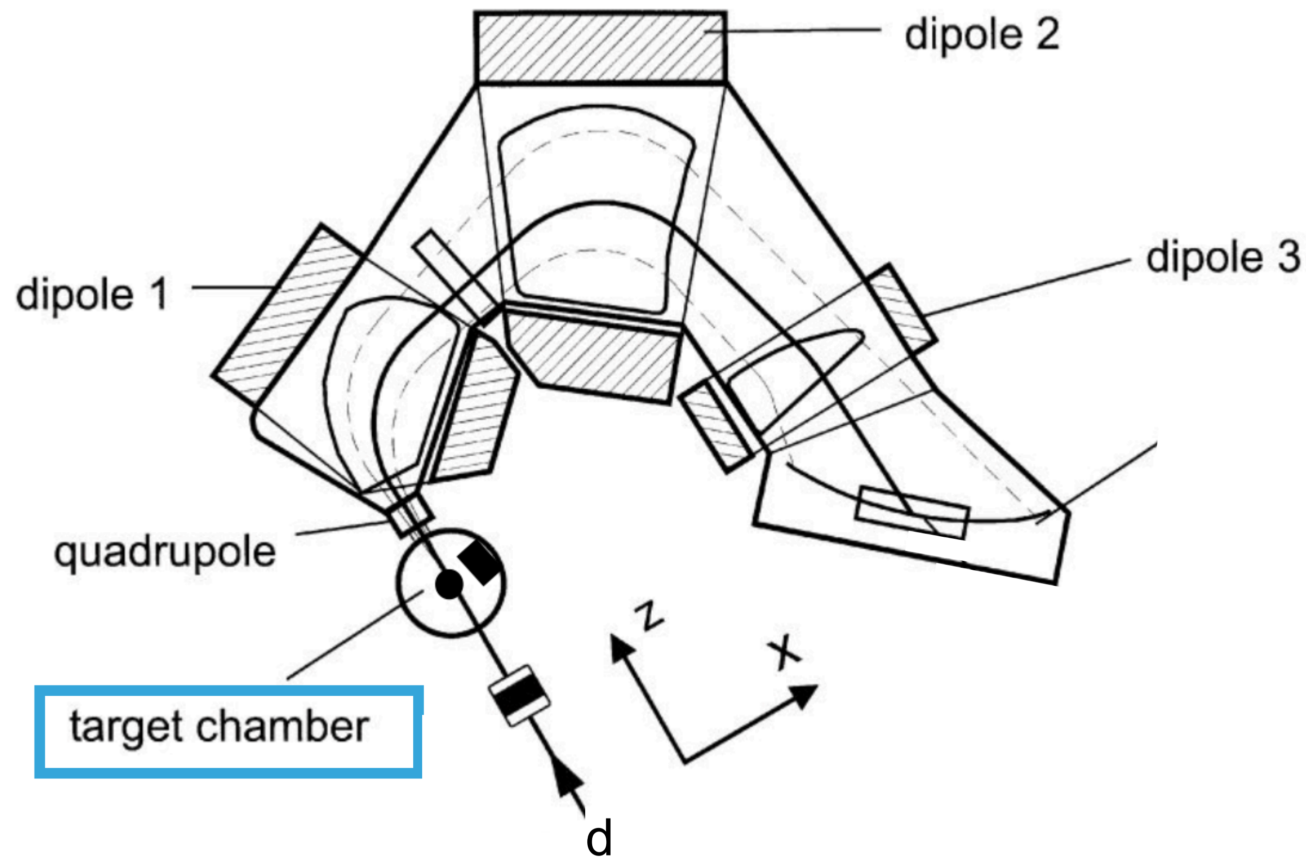
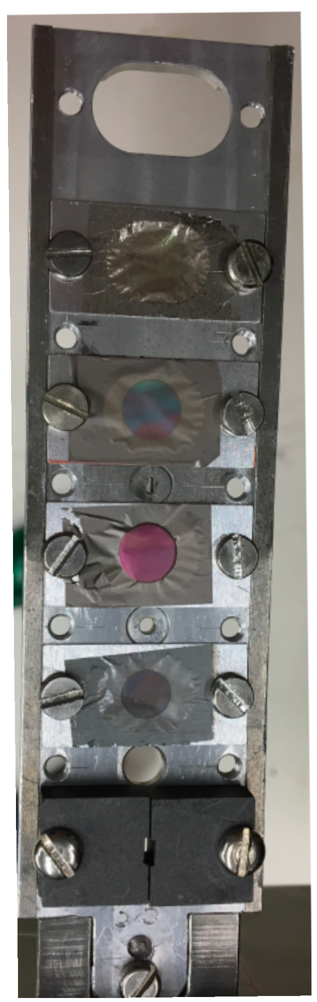
TARGET



Q3D magnetic spectrograph at MLL



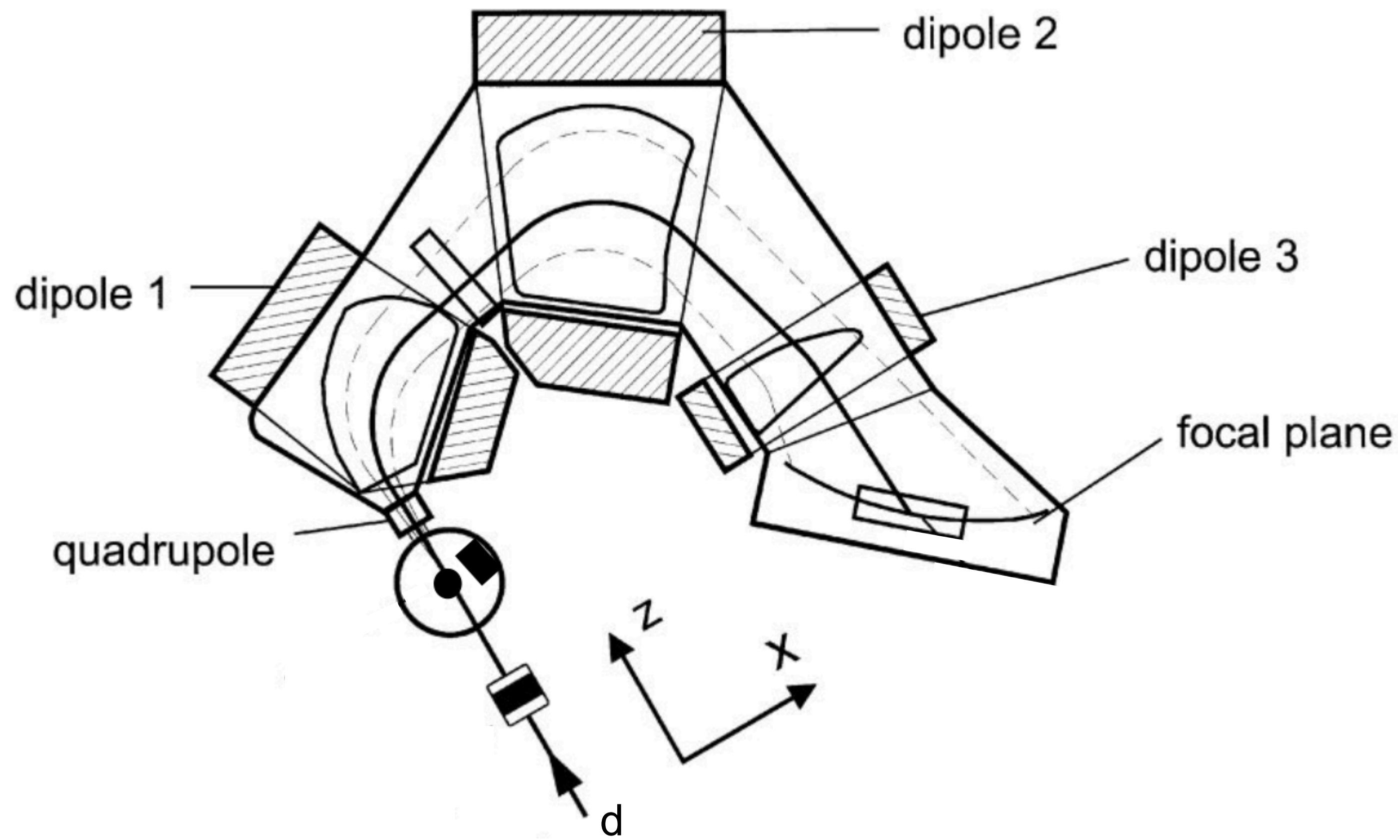
From C. Burbadge.

- Target: $^{198}Hg^{32}S$ (thickness $\sim 40-95\mu g/cm^2$)
- Mounted to a target ladder.
- MLL's target ladder hold up five target.

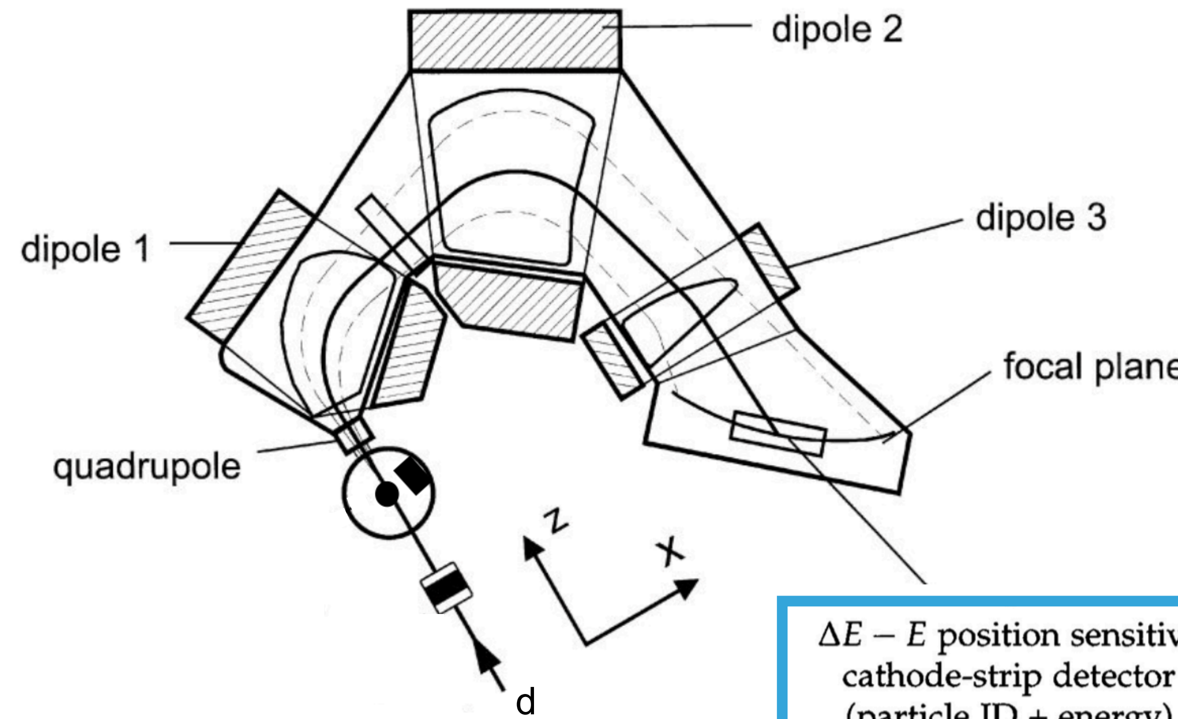
Q3D

Deuterons travel in a circular path:

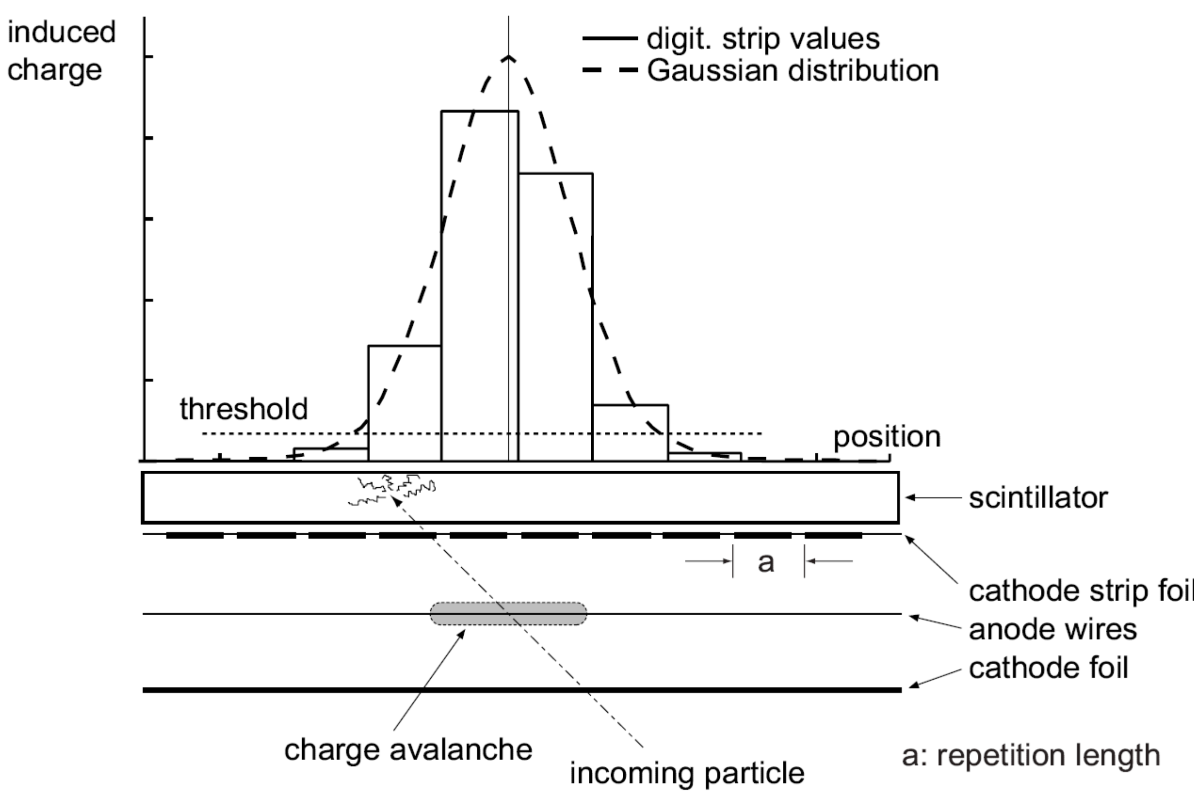
$$F = qvB = m\frac{v^2}{R},$$
$$R = \frac{mv}{qB},$$



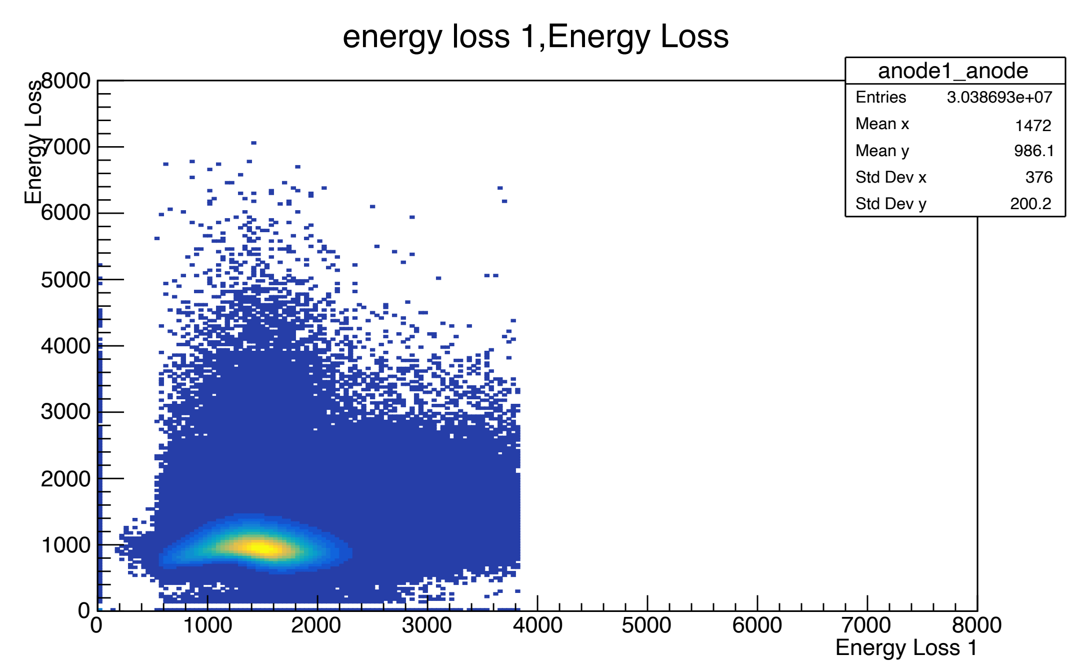
PARTICLE IDENTICATION



$\Delta E - E$ position sensitive cathode-strip detector (particle ID + energy)



[3]

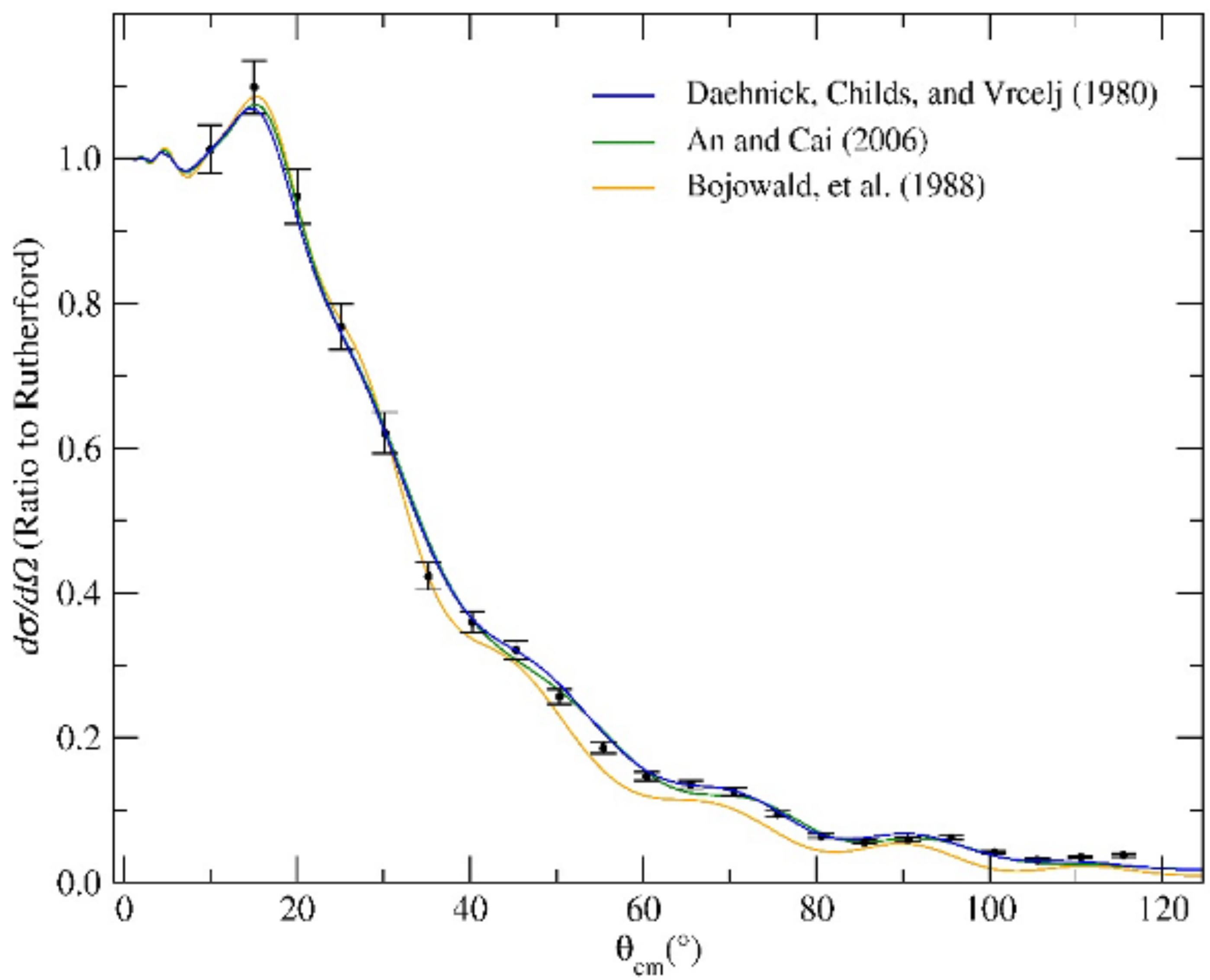


ELASTIC SCATTERING CROSS SECTIONS

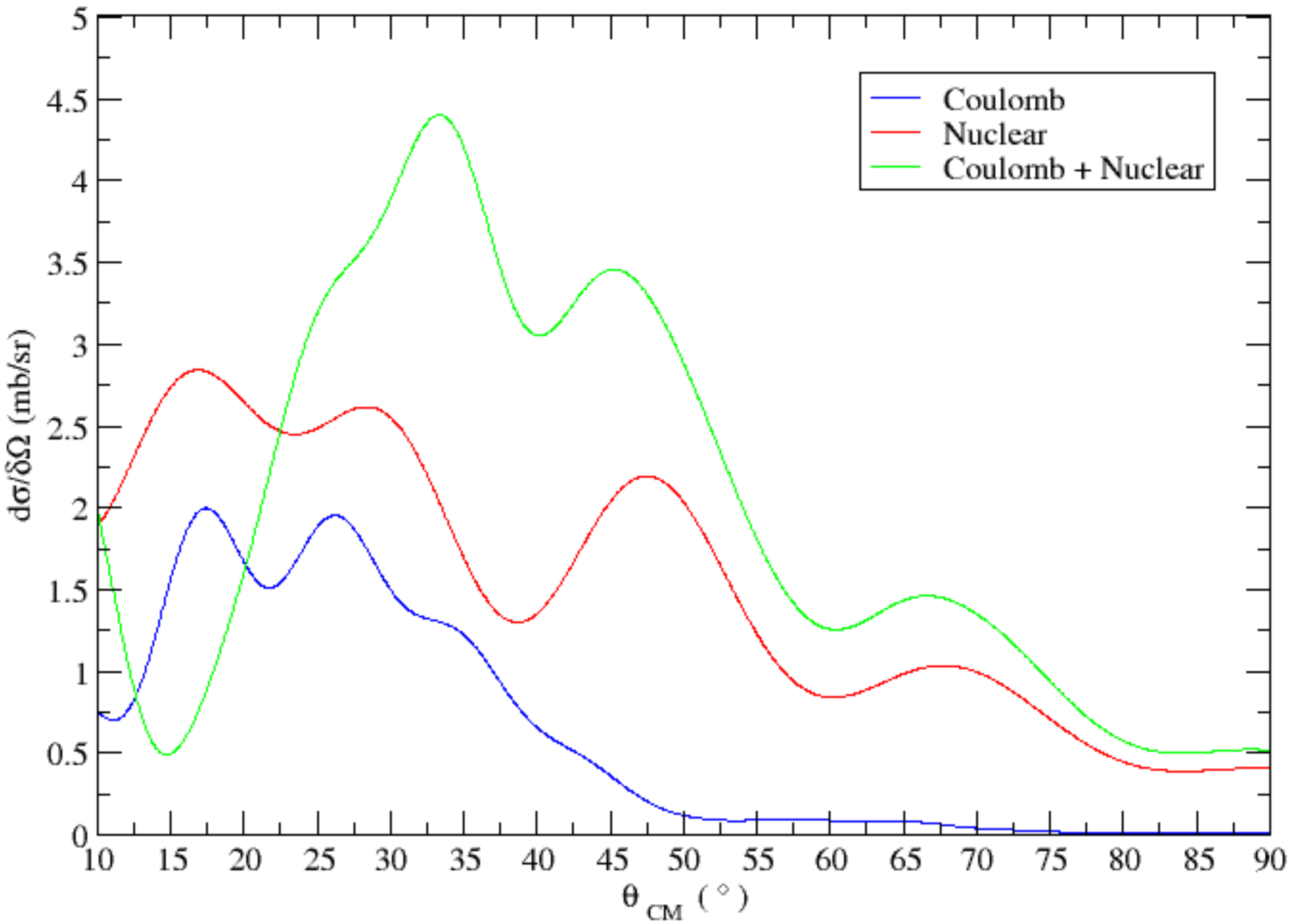
Experimental cross section measurements: $\left(\frac{d\sigma}{d\Omega}\right)_{\text{lab}} = \frac{N_{\text{c}}}{N_{\text{t,eff}} N_{\text{b}} \Omega LT_{\text{DAQ}} LT_{\text{DET}}} \times 10^{31} \left[\frac{\text{mb}}{\text{sr}}\right]$

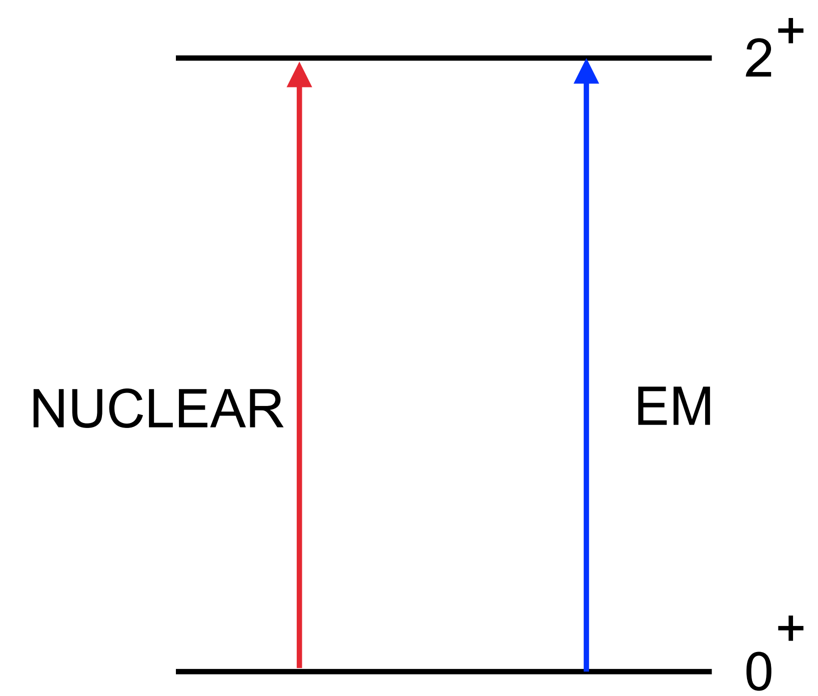
Optical potential by *An and Cai* [7]:

$$V(r) = -Vf_r(r) - iW_v f_v(r) + i4a_s W_s \frac{df_s(r)}{dr} + \lambda_\pi^2 \frac{V_{\text{so}} + W_{\text{so}}}{r} \frac{df_{\text{so}}(r)}{dr} \vec{\sigma} \cdot \vec{l} + V_C(r)$$

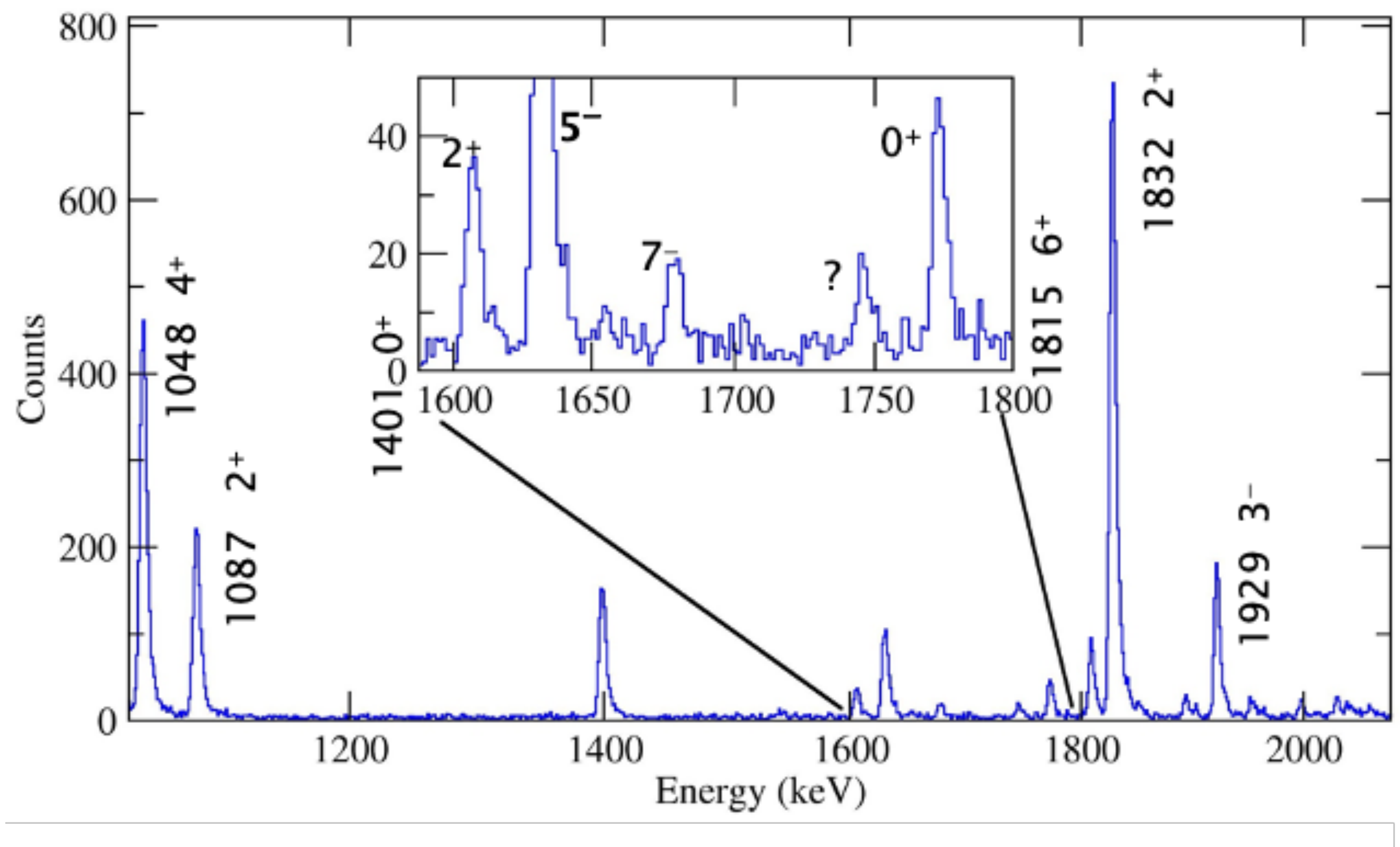


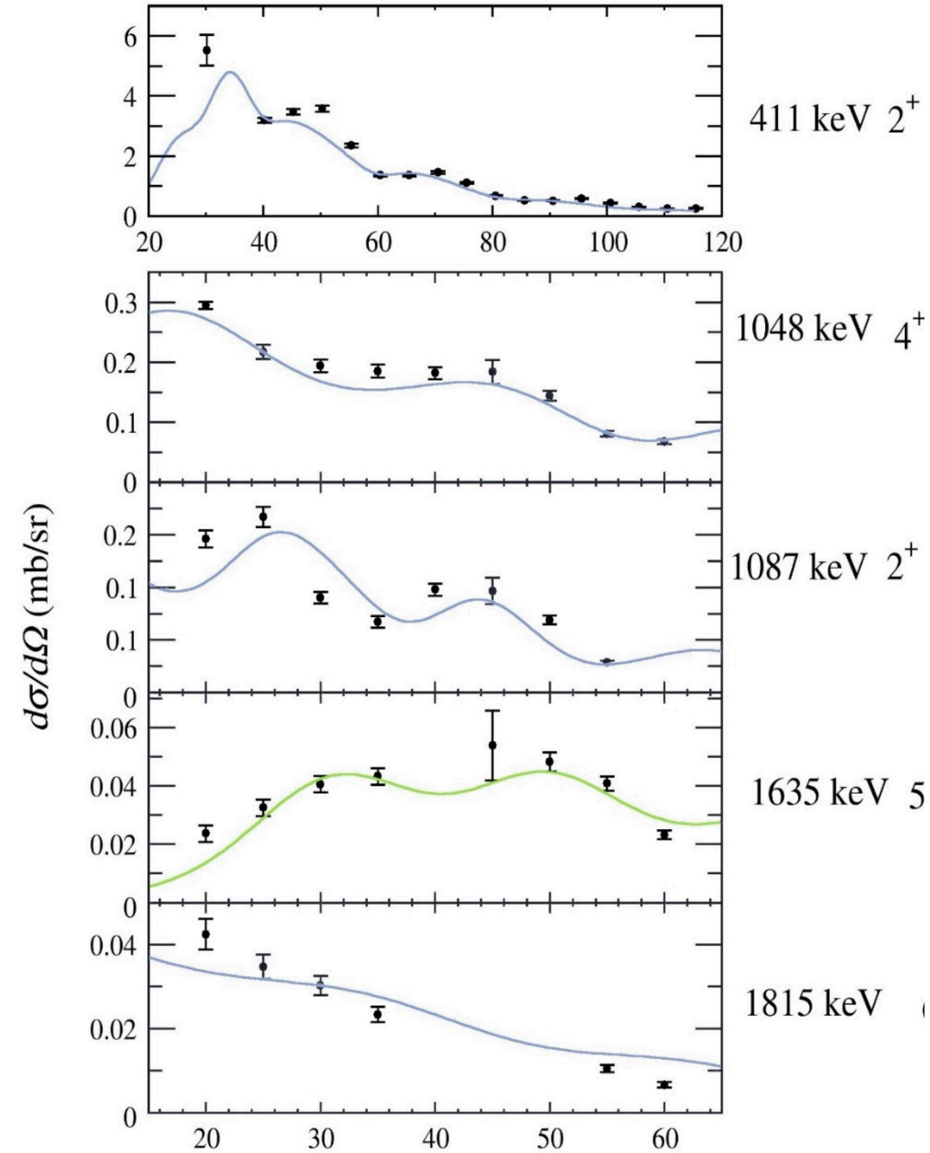
Coulomb and nuclear matrix elements





DEUTERON INELASTIC SCATTERING





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THANK YOU FOR THE ATTENTION

QUESTIONS?

BACKUP SLIDES

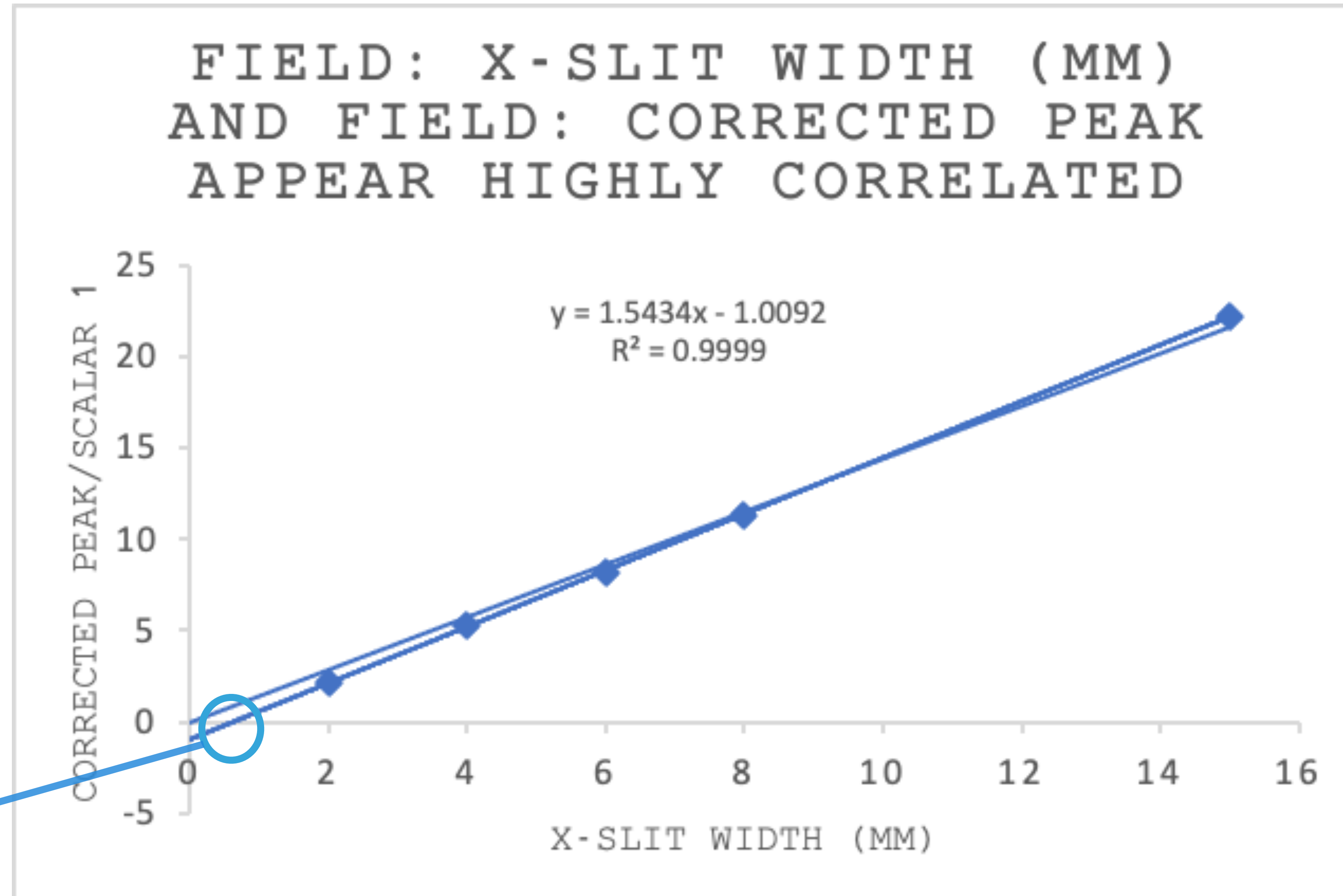
DATA COLLECTED FOR $^{198}Hg(d,d')^{198}Hg$ REACTION

Beginning date of Experiment	Momentum Bite	Number of Runs
January 23, 2014	730, 750	46
	1730, 1760	11
	3130, 3160	15
December 17, 2016	700	14
December 17, 2016 $^{138}Ba(d,d')$ data-Solid angle	500	6
July 14, 2017	750	8
July 24, 2017 $^{136}Ba(p,P)$ data-Solid angle	400	5

SOLID ANGLE

Angle 30^o	
x−slit×y−slit (mm)	corrected peak/Scalar 1
2 × 24.5	2.088784711
4 × 24.5	5.264463509
6 × 24.5	8.114882187
8 × 24.5	11.33647109
15 × 24.5	22.17004426
~~21.5 × 24.5~~	

A=31.5 mm
B=36.75 mm
D=354.8 mm
x_{slit}=0.654 mm
$x - x_{off}$=1.346 mm
y_{slit}=24.5

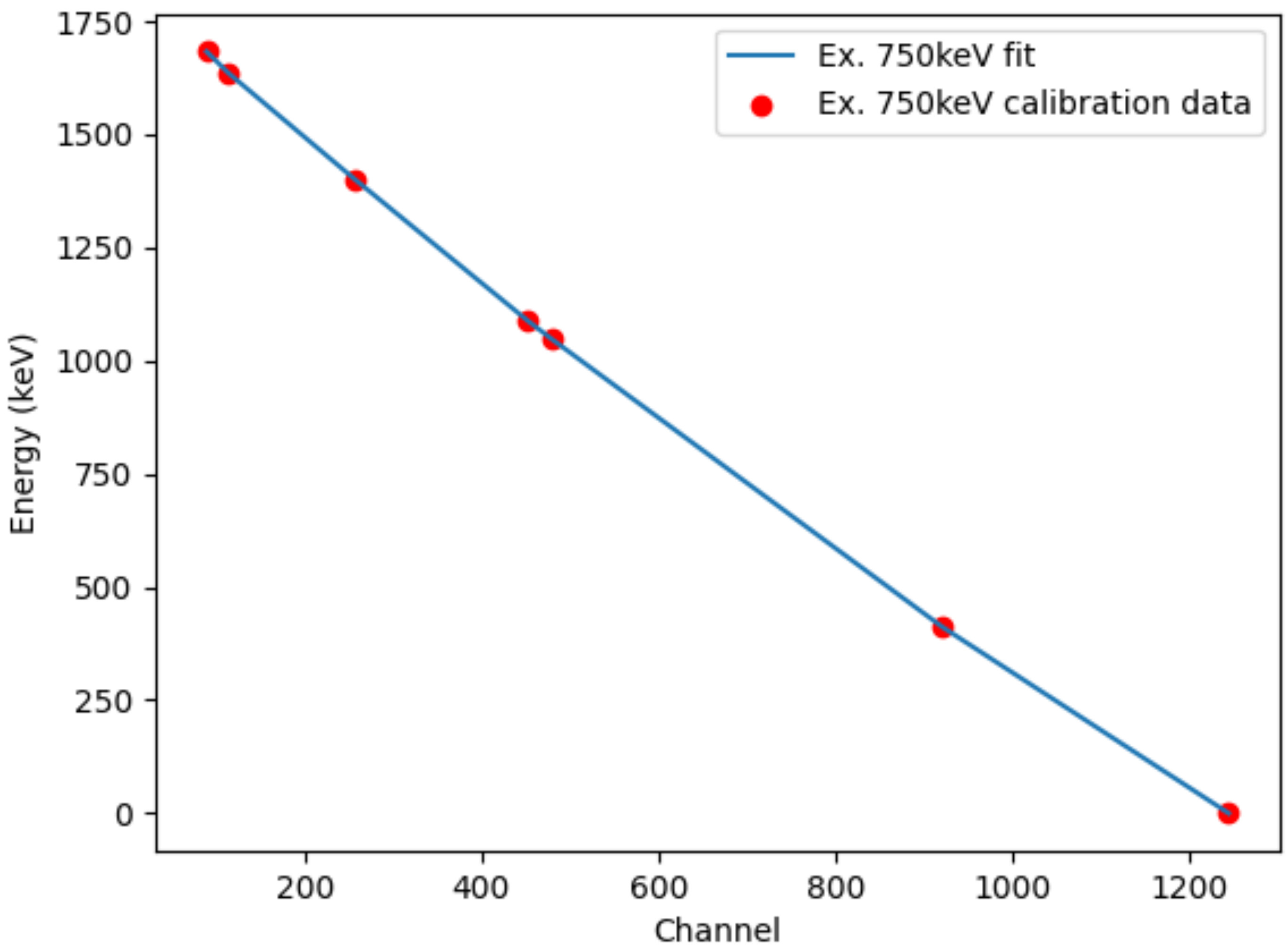


ENERGY CALIBRATION 750 keV MB

Beginning date of Experiment	Momentum Bite	Number of Runs
January 23, 2014	730, 750	46

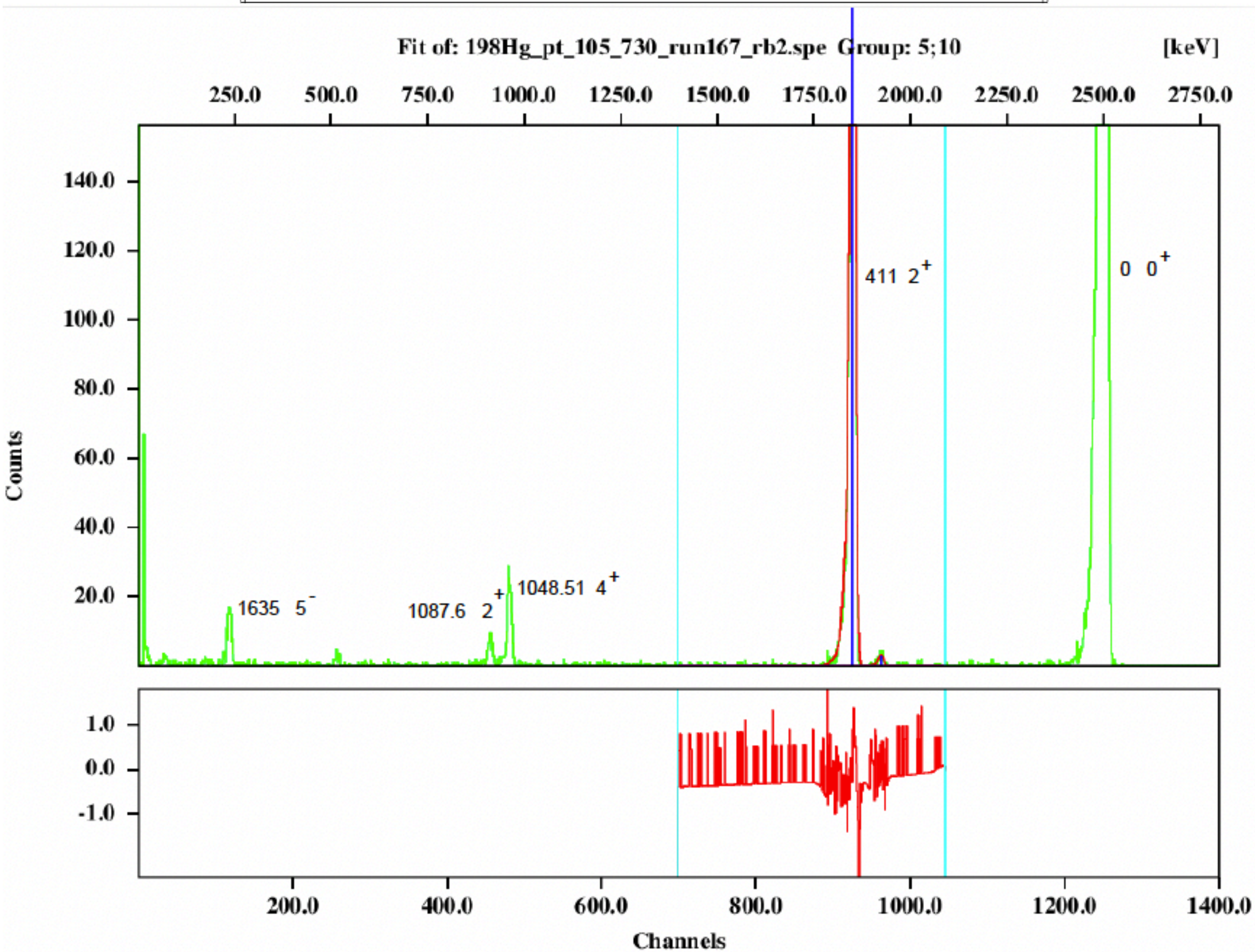
~1.27 keV per channel

Position (centroid)/channel	Energy (keV)	J^π
1245	0	0^+
921	411.8025	2+
478.85	1048.51	4^+
452.56	1087.6874	2^+
256.1615	1401.52	0^+
167.49	1550	0^+
114	1635	5^-
89.02	1683	7^-



PEAK FITTING

Beginning date of Experiment	Momentum Bite	Number of Runs
January 23, 2014	730, 750	46



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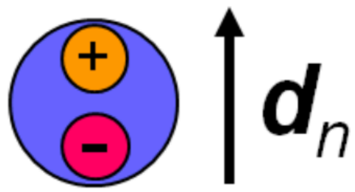
Coulomb and nuclear matrix elements

$$
\begin{aligned}
STR_{\mathrm{Coul}} &= M(E\lambda) \\
&= (-1)^{\frac{I-I'+|I-I'|}{2}} \langle I' \| M(E\lambda) \| I \rangle \\
&= (-1)^{\frac{I-I'+|I-I'|}{2}} \sqrt{(2I+1)B\left(E\lambda; I \rightarrow I'\right)}
\end{aligned}
$$

$$
\begin{aligned}
STR_{\mathrm{Nuc}} &= \mathrm{RDEF}\left(\lambda; I \rightarrow I'\right) \\
&= (-1)^{\frac{I-I'+|I-I'|}{2}} \langle I' \| \delta_\lambda \| I \rangle \\
&= (-1)^{\frac{I-I'+|I-I'|}{2}} \sqrt{2I+1} \langle I K \lambda 0 \mid I' K \rangle \beta_\lambda R_0
\end{aligned}
$$

EDM

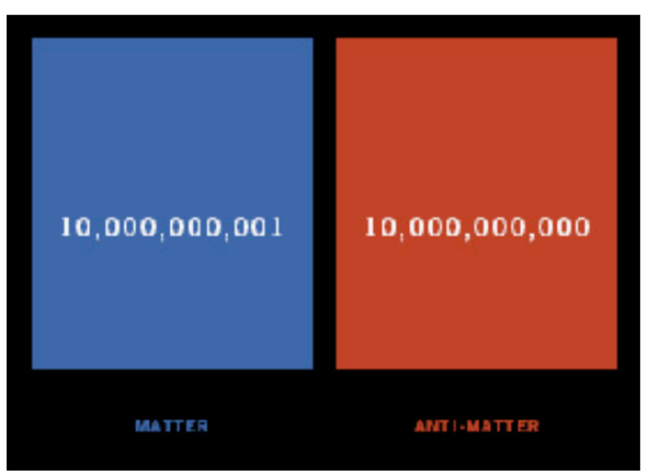
What is an EDM?



Neutron Electric Dipole Moment

A bar magnet is an example of a "magnetic dipole" with a north pole at one end and a south pole at the other. Although the neutron has no net electric charge, it is made of positive and negative quarks. If the positive charges were slightly to one side and the negative charges were slightly to the other, it would create an "electric dipole". The "electric dipole moment", or EDM, is the product of the electric charges and the distance between them. The neutron EDM is usually given in e-cm, the electronic charge times the distance in cm. [1]

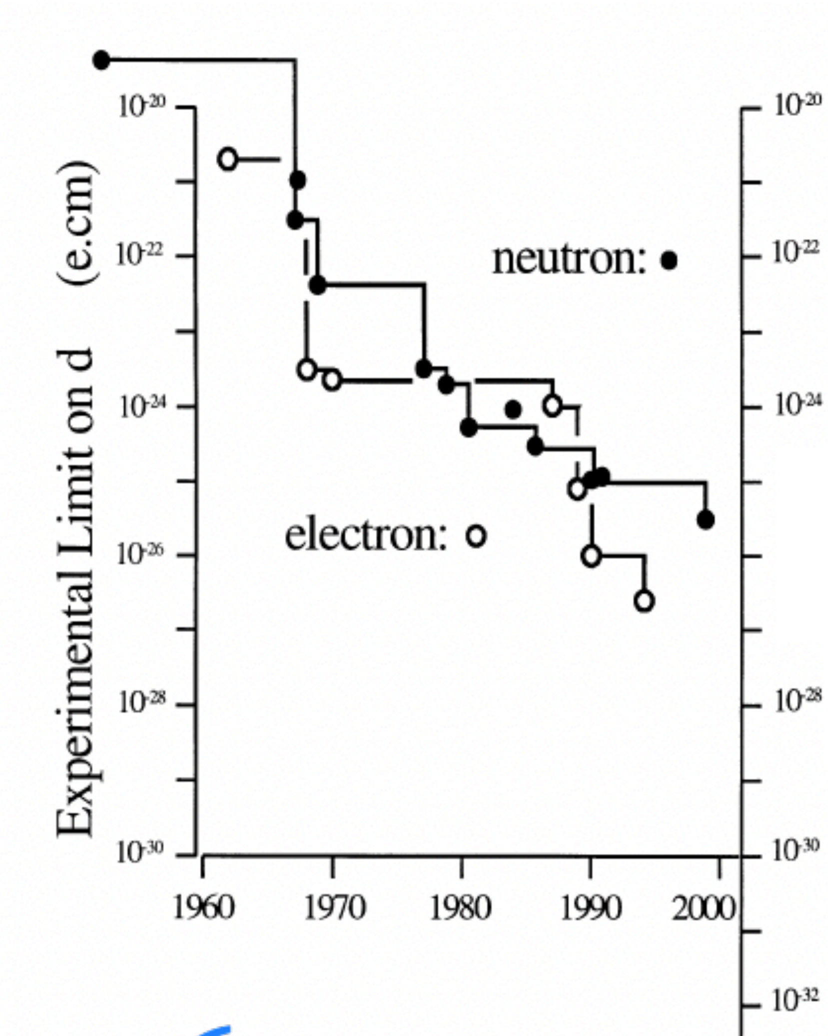
Why measure the Neutron EDM?



Matter and Antimatter in the Early Universe

EDM

- Increased electric polarizability: a molecule or an atomic nucleus with octuple collectivity.



SM

Specie	d 95% u.l. (e cm)
Paramagnetic Systems	
Xe^m	3.1×10^{-22}
Cs	1.4×10^{-23}
	1.2×10^{-25}
	2×10^{-5}
	$2.6 \times 10^{-7}\ \mu_N R C_s$
Tl	1.1×10^{-24}
	1.9×10^{-27}
YbF	1.2×10^{-27}
ThO	9.7×10^{-29}
	6.4×10^{-9}
HfF^+	1.6×10^{-28}
Diamagnetic System	
^{199}Hg	7.4×10^{-30}
^{129}Xe	6.6×10^{-27}
^{225}Ra	1.4×10^{-23}
TIF	6.5×10^{-23}
n	3.6×10^{-26}
Particle Systems	
μ	1.8×10^{-19}
τ	3.9×10^{-17}
Λ	1.6×10^{-16}

[2], [3] [4]

OPTICAL POTENTIAL PARAMETERS

Optical potential by *An and Cai* [7]*:*

$$V(r) = -Vf_r(r) - iW_v f_v(r) + i4a_s W_s \frac{df_s(r)}{dr} + \lambda_\pi^2 \frac{V_{so} + W_{so}}{r} \frac{df_{so}(r)}{dr} \vec{\sigma} \cdot \vec{l} + V_C(r)$$

Saxon-Woods form factor: $$f_i(r) = \left\{ 1 + \exp\left[\frac{(r - r_i A^{1/3})}{a_i}\right] \right\}^{-1}$$

Parameter	An and Cai [1]	Bojowald et al. [2]	Deehnick, Childs and Vrcelj [3]	Han, Shi and Shen [4]
r_C (fm)	1.303000	1.300000	1.3000	1.6980
V_r (MeV)	95.240100	95.667800	94.8586	86.336100
r_r (fm)	1.150670	1.180000	1.170000	1.174000
a_r (fm)	0.792439	0.839997	0.746400	0.809000
W_V (MeV)	2.472400	0.000000	0.603400	3.043564
r_V (fm)	1.322100	-	1.325000	1.563000
a_V (fm)	0.272200	-	0.937993	0.962281
W_S (MeV)	10.156800	13.861600	12.168600	10.892290
r_S (fm)	1.360080	1.270000	1.325000	1.328000
a_s (fm)	0.892366	0.890398	0.937993	0.727281
V_{SO} (MeV)	1.778500	3.000000	3.346000	1.851500
r_{SO} (fm)	0.972000	1.001480	1.070000	1.234000
a_{SO} (fm)	1.011000	1.001480	0.660000	0.813000
W_{SO} (MeV)	0.000000	0.000000	0.000000	-0.103000

Edm

appropriate to express the combination of contributions to a measured atomic EDM for paramagnetic systems, diamagnetic systems, and nucleons as

$$d_i = \sum_j \alpha_{ij} C_j, \qquad (9)$$

where i labels the system, and j labels the specific low-energy parameter (*e.g.*, d_e, C_S, *etc.*). The $\alpha_{ij} = \partial d_i / \partial C_j$

imental results. In the global analysis, paramagnetic systems are used to set limits on the electron EDM d_e and the nuclear spin-independent electron-nucleus coupling C_S. Diamagnetic systems set limits on four dominant parameters: two pion-nucleon couplings $(\bar{g}_\pi^{(0)}, \bar{g}_\pi^{(1)})$, a specific isospin combination of nuclear spin-dependent couplings, and the "short distance" contribution to the

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EDM AND CP VIOLATION

- Search for EDM in Atoms with octuple-deformed nuclei

  - EDM = 0 if there is invariance under P and T

  - **d same orientation of I angular momentum,** d must change sign the same way under P and T

$$\begin{cases} \mathbf{d} \xrightarrow[P]{} -\mathbf{d} \\ \mathbf{I} \xrightarrow[P]{} \mathbf{I} \\ \mathbf{d} \xrightarrow[T]{} \mathbf{d} \\ \mathbf{I} \xrightarrow[T]{} -\mathbf{I} \end{cases}$$

[1]

d=q**r**

I=**r**x**p**

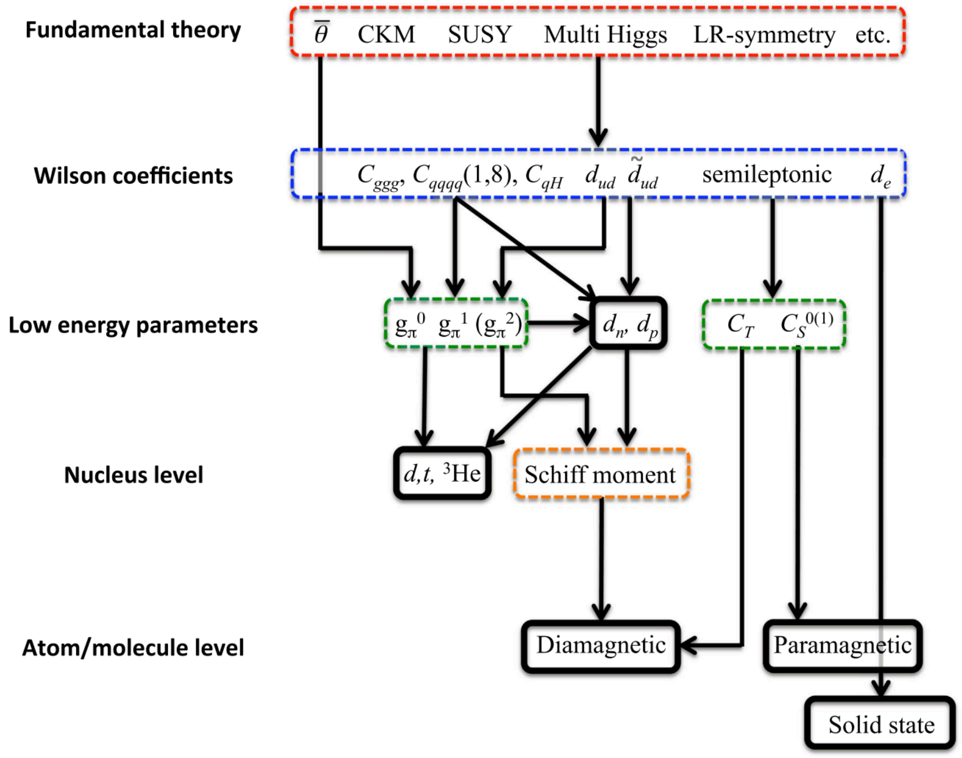
All particle and atomic EDMs are odd under P and T symmetry

Schiff Moments

- The observable EDM in the electron cloud is induced by the Schiff Moment of the nucleus.
- Schiff Moment ⟶ $\vec{S}_{int} = \frac{1}{10}[\vec{O_0} - \frac{5}{3}\vec{d_0}\langle r^2 \rangle_{ch}]$
- Large nuclear gs EDMs (large Schiff moments) ⟶ The action of a P- and T- violating $\hat{V}_{PT}$

$$S \equiv \langle S_z \rangle = \sum_{i \neq 0} \frac{\langle \Psi_0 | S_z | \Psi_i \rangle \langle \Psi_0 | \hat{V}_{PT} | \Psi_i \rangle}{\Delta E} + \ldots$$

- In the laboratory frame: $S \approx -2\frac{I}{I+1}\hat{S}_{int}\frac{\langle \Psi^+ | \hat{V}_{PT} | \Psi^- \rangle}{\Delta E}$
- The most direct ways to measure E2 and E3 matrix ⟶ Inelastic scattering.



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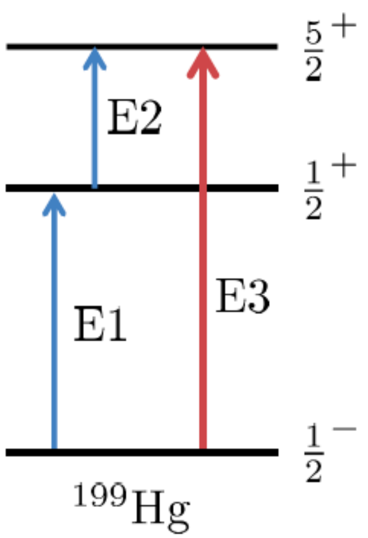


[3]

CP AND IMBALANCE

- WEAK INTERACTION VIOLATES C, P and T transformations.

- **Charge Conjugation** ⟶

$$\left|p\right\rangle \underset{C}{\longrightarrow} (-1)^{1/2+1/2}\left|\bar{p}\right\rangle = -\left|\bar{p}\right\rangle$$

$$\left|n\right\rangle \underset{C}{\longrightarrow} (-1)^{1/2+1/2}\left|\bar{n}\right\rangle = +\left|\bar{n}\right\rangle$$

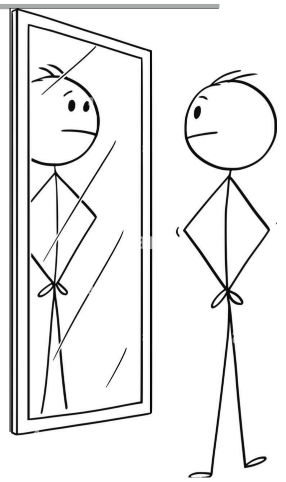
- **CP violation** ⟶ First observed in the decay of K^0 meson.

$$K_L^0 \rightarrow \begin{cases} \pi^{+} + e^{-} + \bar{\nu}_e \\ \pi^{-} + e^{+} + \nu_e \end{cases}$$

$$CP\left|K^0\right\rangle = \left|\bar{K}^0\right\rangle$$

CP violation - The standard model of elementary particle suggests that when the universe was less than 10-12 sec old, the condition was ripe for the production of more matter than antimatter with CP violation to provide the mechanism for different reaction rate (to produce matter and antimatter).

C and P Symmetries



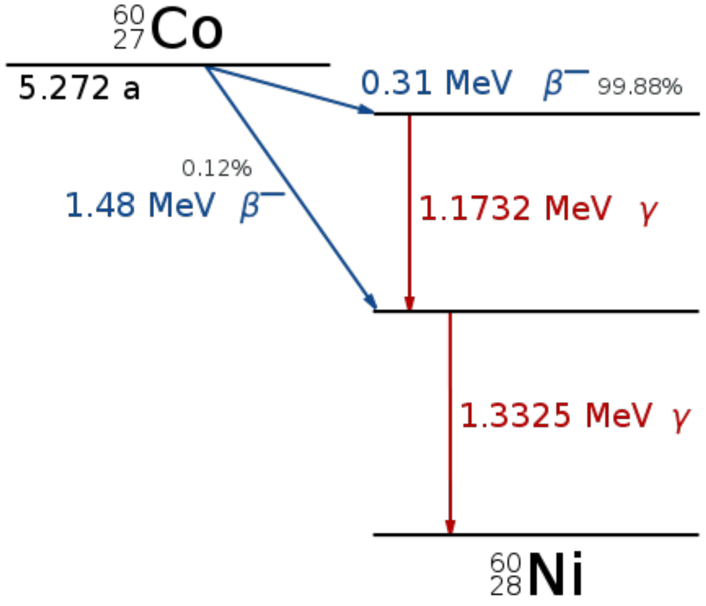
- WEAK INTERACTION VIOLATES C, P and T transformations.

- **Parity** → $(x, y, z) \underset{P}{\longrightarrow} (-x, -y, -z)$

Violation of Parity → $K^+ \rightarrow \begin{cases} \pi^+ + \pi^0 \\ \pi^+ + \pi^- + \pi^+ \end{cases}$

β^- decay of ^{60}Co → First evidence that confirmed parity nonconservation.

$^{60}_{27}\mathrm{Co} \rightarrow ^{60}_{28}\mathrm{Ni} + e^- + \bar{\nu}_e + 2\gamma$



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ELECTROMAGNETIC TRANSITIONS

Reduced transition probabilities in terms of intrinsic moments

- E1 transition → $B(E1; I_i \rightarrow I_f) = \frac{3}{4\pi} Q_1^2 (I_i K_i 10 | I_f K_f)^2$

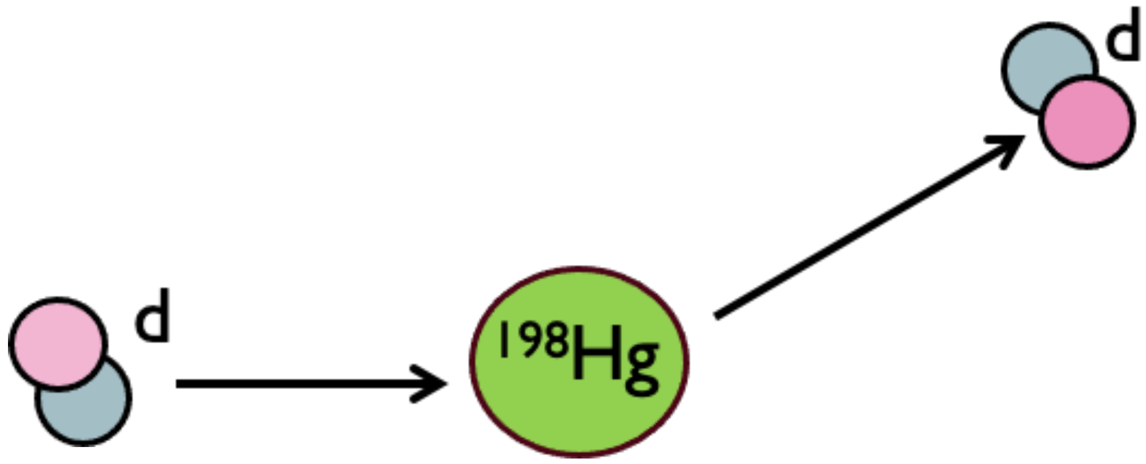
  - γ -ray studies

- Higher order transitions → $B(E\lambda; I_i \rightarrow I_f) = \frac{1}{2I_i + 1} < I_i || M(E\lambda) || I_f K_f >$

$$= \frac{2\lambda + 1}{16\pi} Q_\lambda^2 (I_i K_i \lambda 0 | I_f K_f)^2, \quad Q_\lambda = \frac{3}{\sqrt{2\lambda + 1)\pi Z R_0^\lambda \beta_\lambda}}$$

  - E2 and E3 transitions → Inelastic scattering, Coulomb excitation

ANGLES θ_{CM} and θ_{Lab}



$$\cos\theta_{cm} = \cos\theta_{lab}[x\cos\theta_{lab} + \sqrt{1 - x^2\sin^2\theta_{lab}}] - x$$

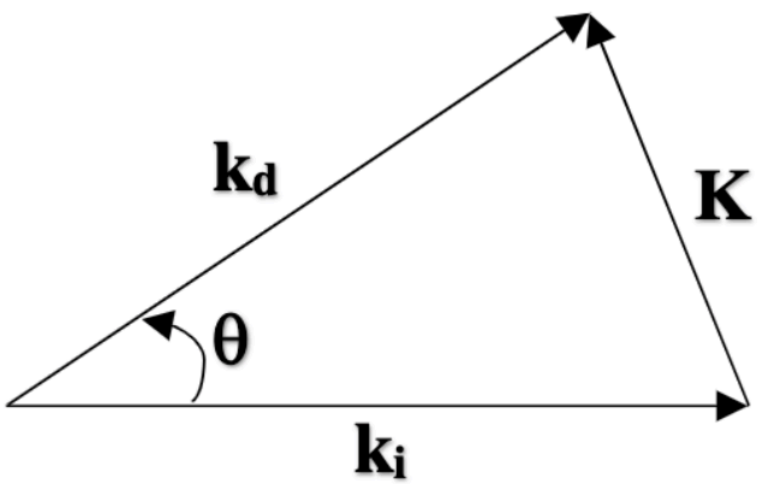
Elastic scattering $$x = \frac{m_p}{m_t}$$

Inelastic scattering $$x = \left[\frac{m_a m_b}{m_A m_B}\frac{1}{1+\frac{Q}{E_{cm}}}\right]^{1/2}$$

COULOMB SCATTERING CROSS SECTION

For spherically symmetric potential:

$$f(\theta) \cong -\frac{2m}{\hbar^2 K}\int_0^\infty dr\, r_o V(r_o)\sin(Kr_0)$$

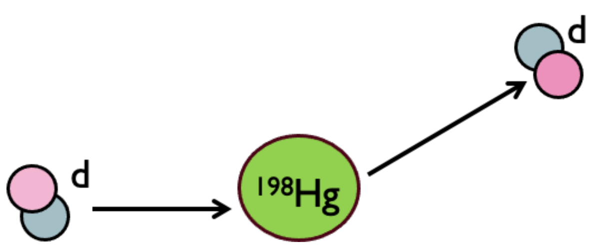


$$f(\theta) = -\frac{2mV_o}{\hbar^2\mu(\mu^2+K^2)}$$

In the limit $\mu \longrightarrow 0$, the Yukawa potential tends to the Coulomb potential $V(r) \sim \frac{Z_1 Z_2 e^2}{r}$

$$\frac{d\sigma}{d\Omega} = \frac{Z_1 Z_2 e^4}{16E^2\sin^4\frac{\theta}{2}}$$

In MKSA units:



$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Rutherford}} = \frac{d\sigma}{d\Omega} = \frac{1}{4\pi\epsilon_o}\frac{Z_1 Z_2 e^4}{16E^2\sin^4\frac{\theta}{2}}$$

$$= 17.408\frac{1}{\sin^4\frac{\theta}{2}}\ \text{mb/sr.}$$

TARGET THICKNESS CORRECTION

Beginning date of Experiment	Momentum Bite	Number of Runs
December 17, 2016	700	14

$$N_{t,\ \mathrm{eff}} = \frac{N_t}{\cos\theta_{\mathrm{target}}} [\mathrm{mb}^{-1}]$$

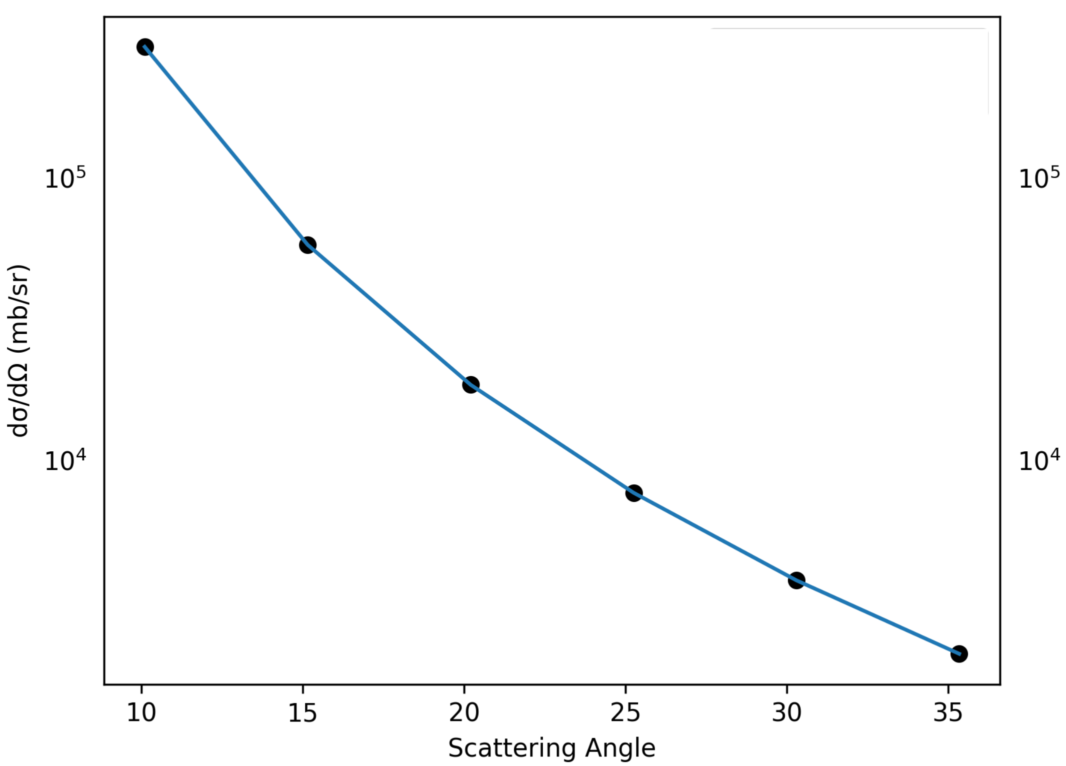
$$N_t = \frac{\rho t}{M} N_A$$

Beginning date of Experiment	Nominal Target Thickness ρt ($\mu g/cm^2$)
January 23, 2014	95
December 17, 2016	70
July 24, 2017	40

DIFFERENTIAL CROSS SECTION AS RATIO TO RUTHERFORD-FRESCO

Beginning date of Experiment	Momentum Bite	Number of Runs
December 17, 2016	700	14

$$N_{\text{t,eff}} = 0.980639890 \left(\frac{N_{\text{c}}}{\frac{\left(\frac{d\sigma}{d\Omega}\right)_{\text{DWBA}}}{\left(\frac{d\sigma}{d\Omega}\right)_{\text{Rutherford}}} N_{\text{b}} \Omega LT_{\text{DAQ}} LT_{\text{DET}} \left(\frac{d\sigma}{d\Omega}\right)_{\text{Rutherford}}} \right)$$



RUTHERFORD CROSS SECTION-FRESCO:

$$\frac{\left(\frac{d\sigma}{d\Omega}\right)_{\text{DWBA}}}{\left(\frac{d\sigma}{d\Omega}\right)_{\text{Rutherford}}} = 1.065.$$

UNIVERSITY of GUELPH

DETECTOR