Quasi-particle excitations far from the path of stability.

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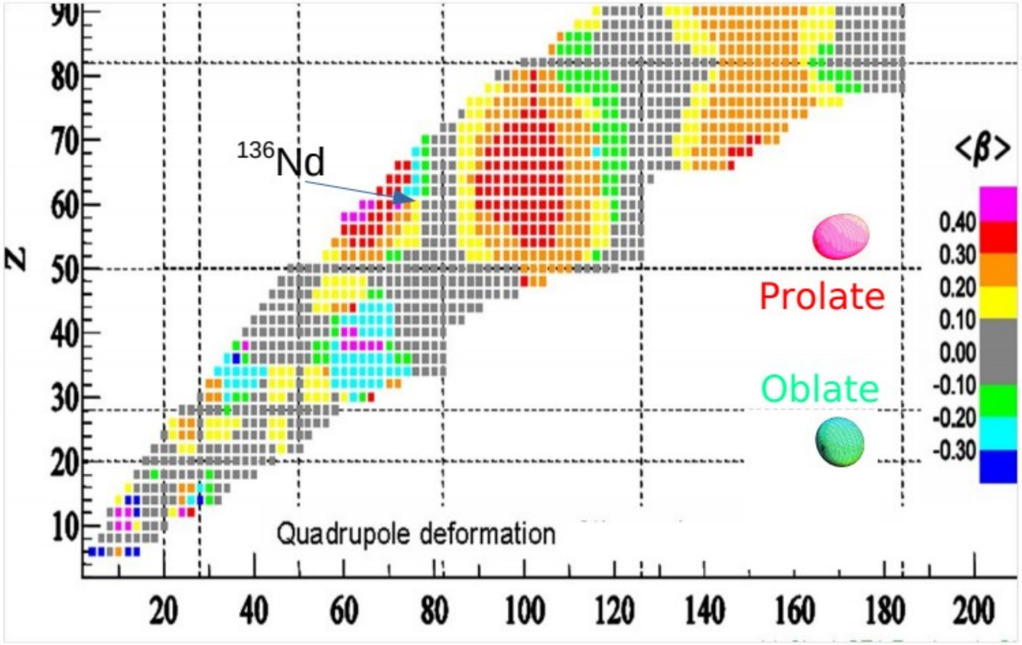
Area of interest



We based on the deformed Woods-Saxon single-particle potential and the Yukawa-plus-exponential macroscopic energy. Pairing implemented with usual BCS.

S. Cwiok, J. Dudek, W. Nazarewicz,
J. Skalski, and T. Werner,
Comput. Phys. Commun. 46,379(1987).
J.Skalski,J.Mizutori,W.Nazarewicz Nucl. Phys.A 617 (1997) 282-315

Prolate deformations (β>0) found for ^{136}Nd

Nuclear shape can change from prolate to oblate within the same nucleus and only with one pair breaking.

Nuclear states of different deformation, close in energy – their wave functions can mix ---> shape coexistance.

Why are single particle excitations important?

- Low-energy nuclear-structure properties show a strong dependence on the nuclear pairing force.
- govern the shape change of excited nuclei
- can tell about the properties and structure of nuclei far from the valley of stability
- bandheads of many collective bands at low excitation energy
- astrophysical nucleosynthesis studies, it is important to have available pairing models and pairing parameters that give reliable results far from the valley of β-stability.
- Rotationally align two proton excitation versus two neutron excitation from $h_{11/2}$ orbit are of particular interest for A ~ 130 mass region.

The Macro-Micro model

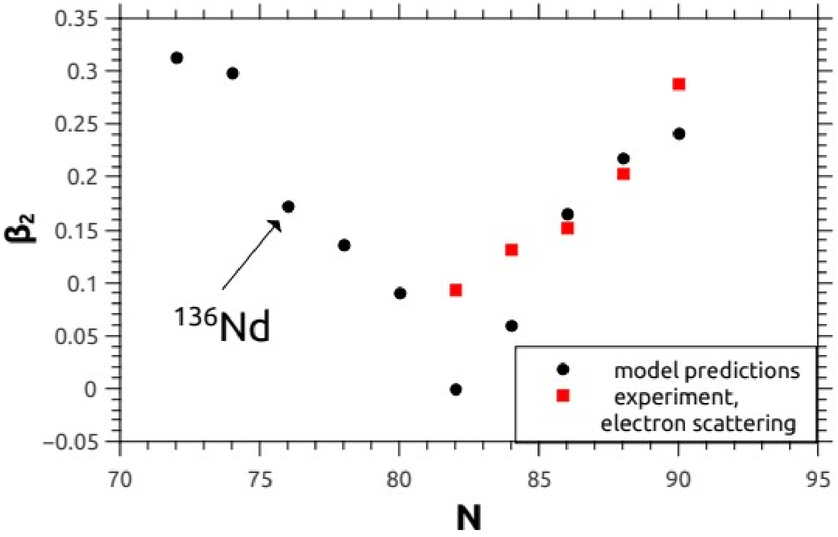
The macroscopic-microscopic method:

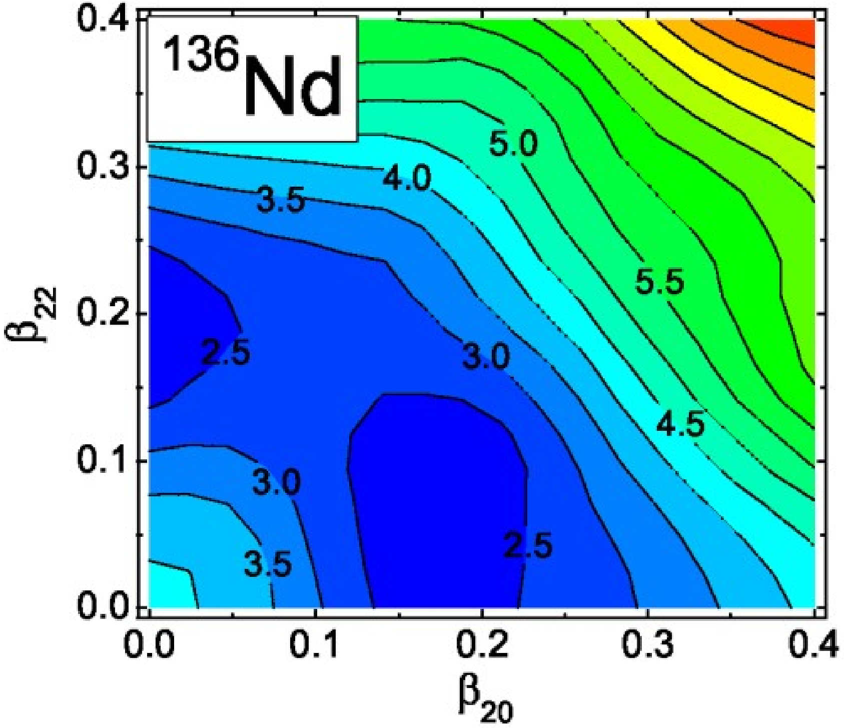
$$E = E_{macro} + E_{micro},$$

E_{macro} is the macroscopic energy. The Yukawa-plus-exponential model [finite range liquid-drop (FRLD) model] were applied.
E_{micro} is the microscopic energy calculated from a non-self-consistent average deformed Wood-Saxon potential.
Pairing as usual BCS*

* J. Dudek, A. Majhofer, and J. Skalski, J. Phys. G 6, 447 (1980).

Qudrupole deformation β_2 for Nd isotopes

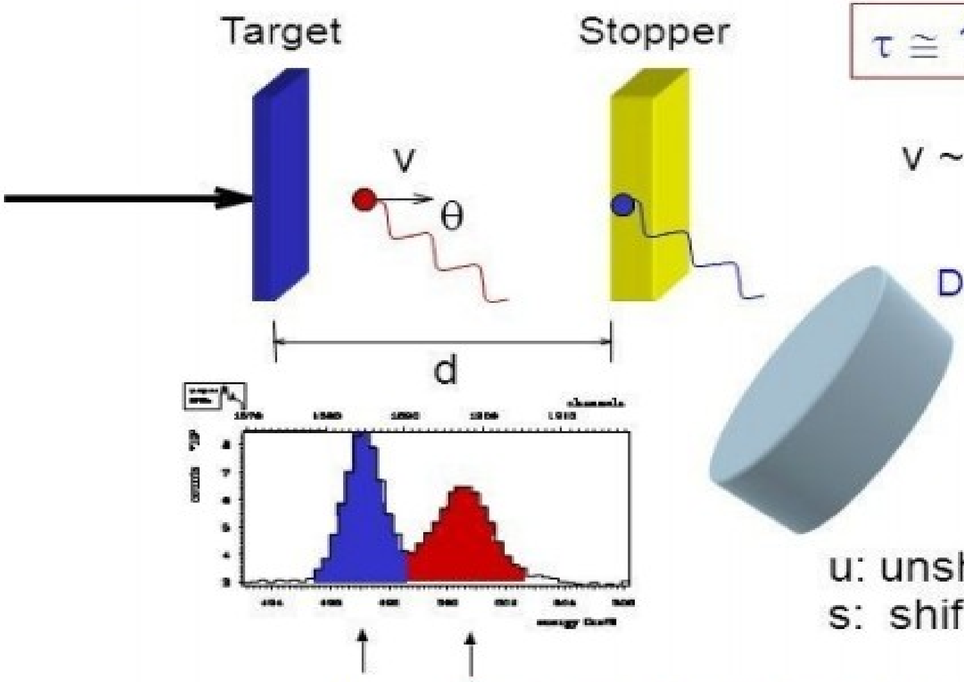




The experimental observables

- lifetime – measured by Recoil Distance Doppler-Shift (RDDS) method
- magnetic moments – measured by Recoil In Vacuum (RIV) method or Transient Field (TF) method
- quadrupole moments

The Recoil Distance Doppler-Shift Method



$\tau \cong 1 - 1000\text{ps}$

v ~ 1-2 % c

u: unshifted
s: shifted

E_u $\quad E_s = E_u\,(1 + v/c \cos\theta)$

Two observables by RDDS method:

- velocity of the compound nucleus
- lifetime of the nuclear level

Experiment in Warsaw at HIL

Lifetime measurements of 10^+ isomer in the ^{136}Nd nucleus

A. Tucholski,[1] Ch. Droste,[2] J. Srebrny,[1] C. M. Petrache,[3] J. Skalski,[4] P. Jachimowicz,[5] M. Fila,[2] T. Abraham,[1] M. Kisieliński,[1] A. Kordyasz,[1] M. Kowalczyk,[1] J. Kownacki,[1] T. Marchlewski,[1] P. J. Napiorkowski,[1] L. Próchniak,[1] J. Samorajczyk-Pyśk,[1] A. Stolarz,[1] A. Astier,[3] B. F. Lv,[3] E. Dupont,[3] S. Lalkovski,[6] P. Walker,[7] E. Grodner,[4] and Z. Patyk[4]

1 - Heavy Ion Laboratory, University of Warsaw, Pasteura 5a, 02-093 Warsaw, Poland
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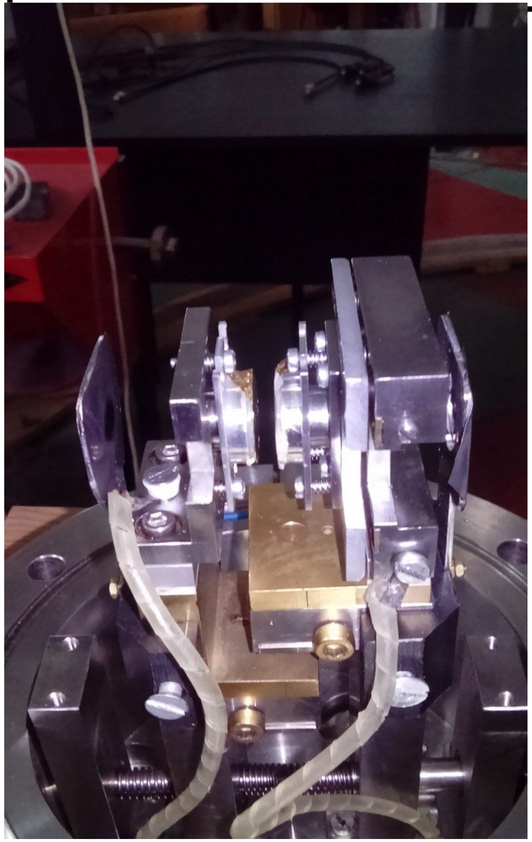
PHYSICAL REVIEW C 100, 014330 (2019)

Experimental set-up

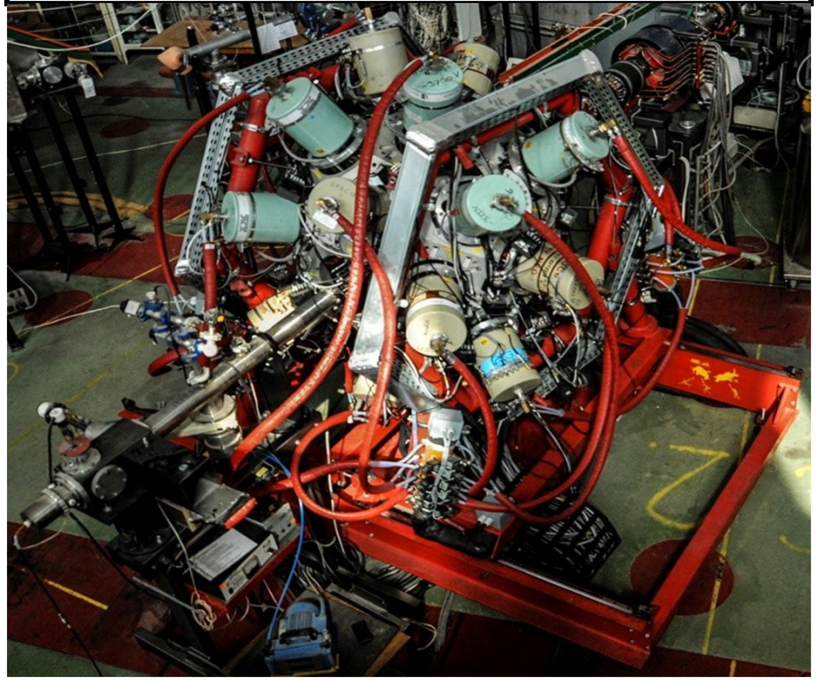
Plunger device

- Target to stopper distance change in micrometers



EAGLE, HIL Warsaw

- 15 HPGe
- anticompton shields
- 1% eff. for γ rays of 500 keV

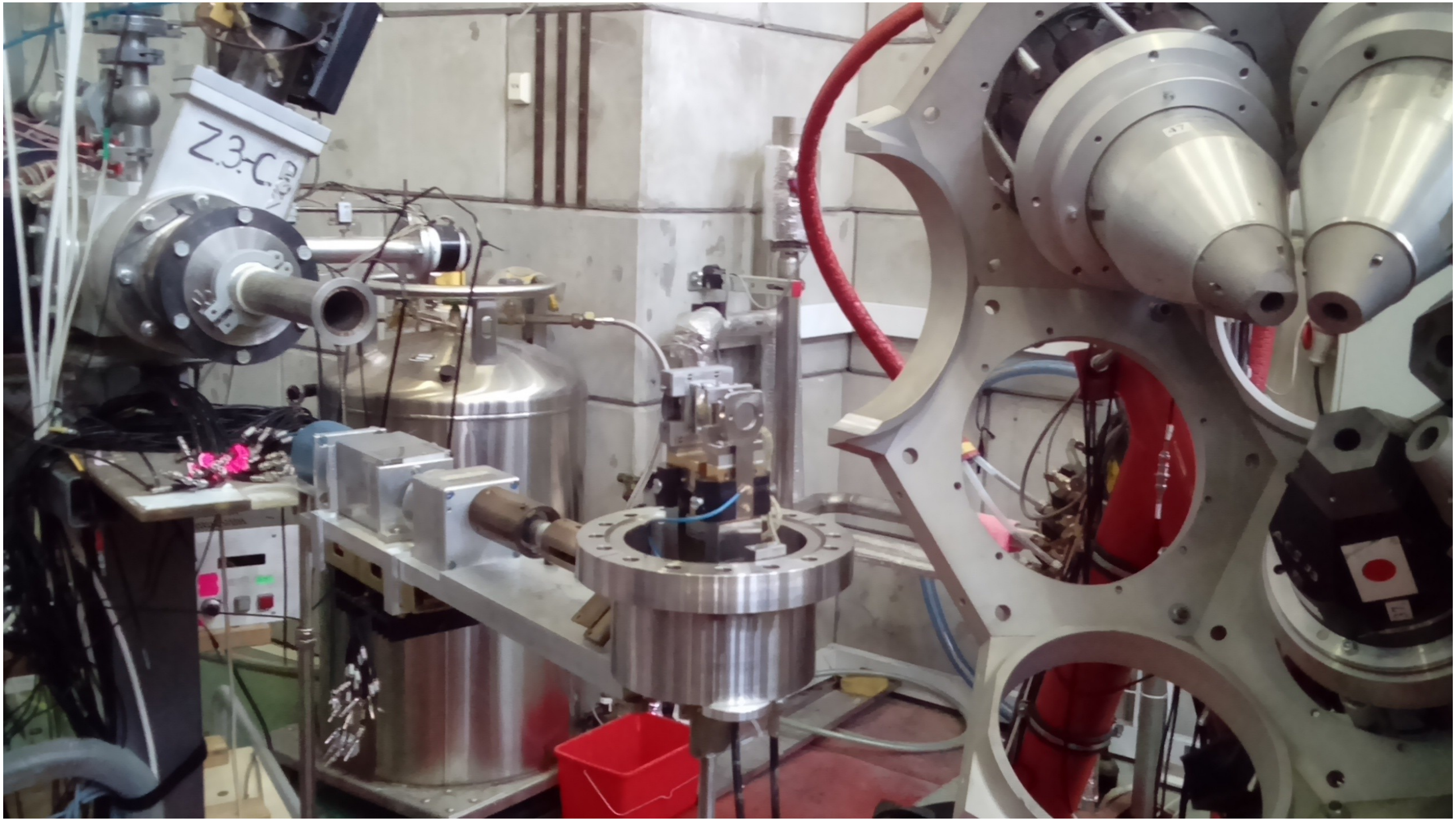


Reaction: $^{120}\mathrm{Sn}(^{20}\mathrm{Ne},4n)^{136}\mathrm{Nd}$

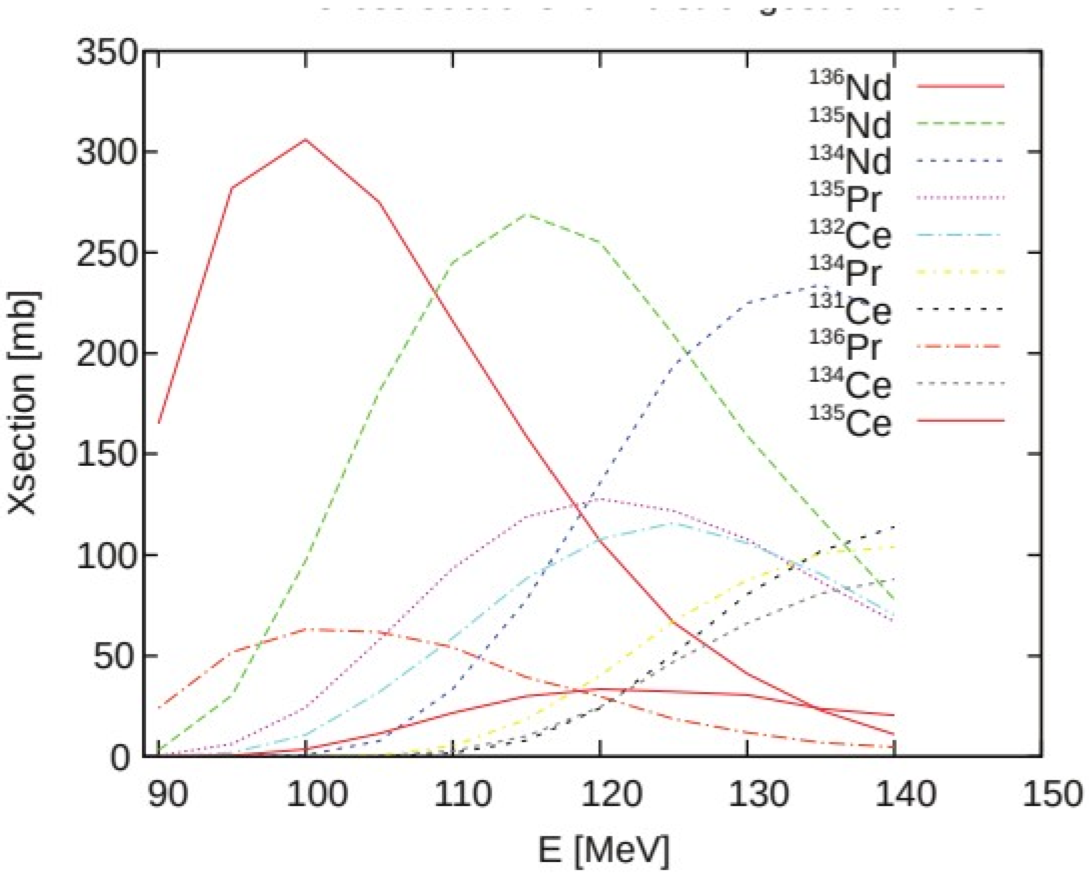
Beam energy: 97.5 MeV

Target thickness: 0.5mg/cm^2 of ^{120}Sn

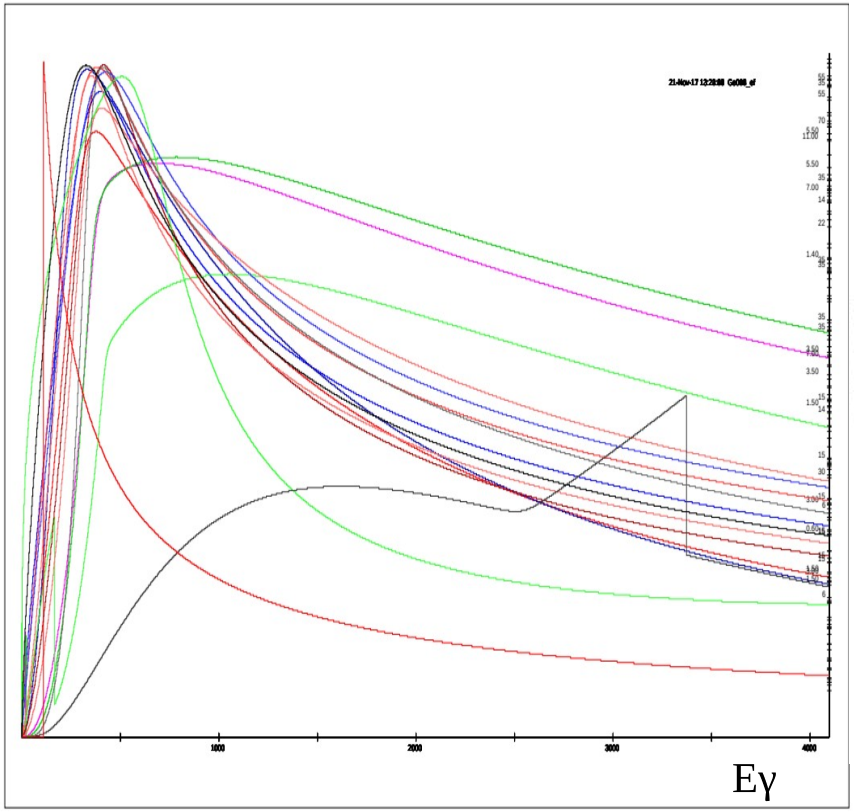
Plunger in EAGLE

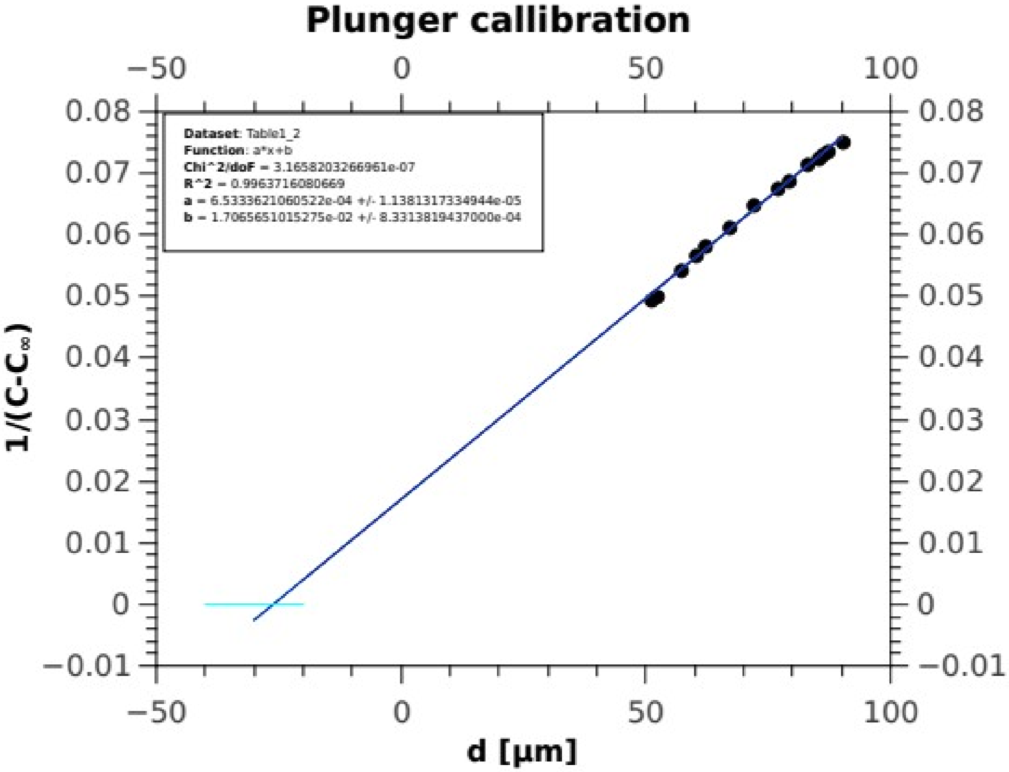


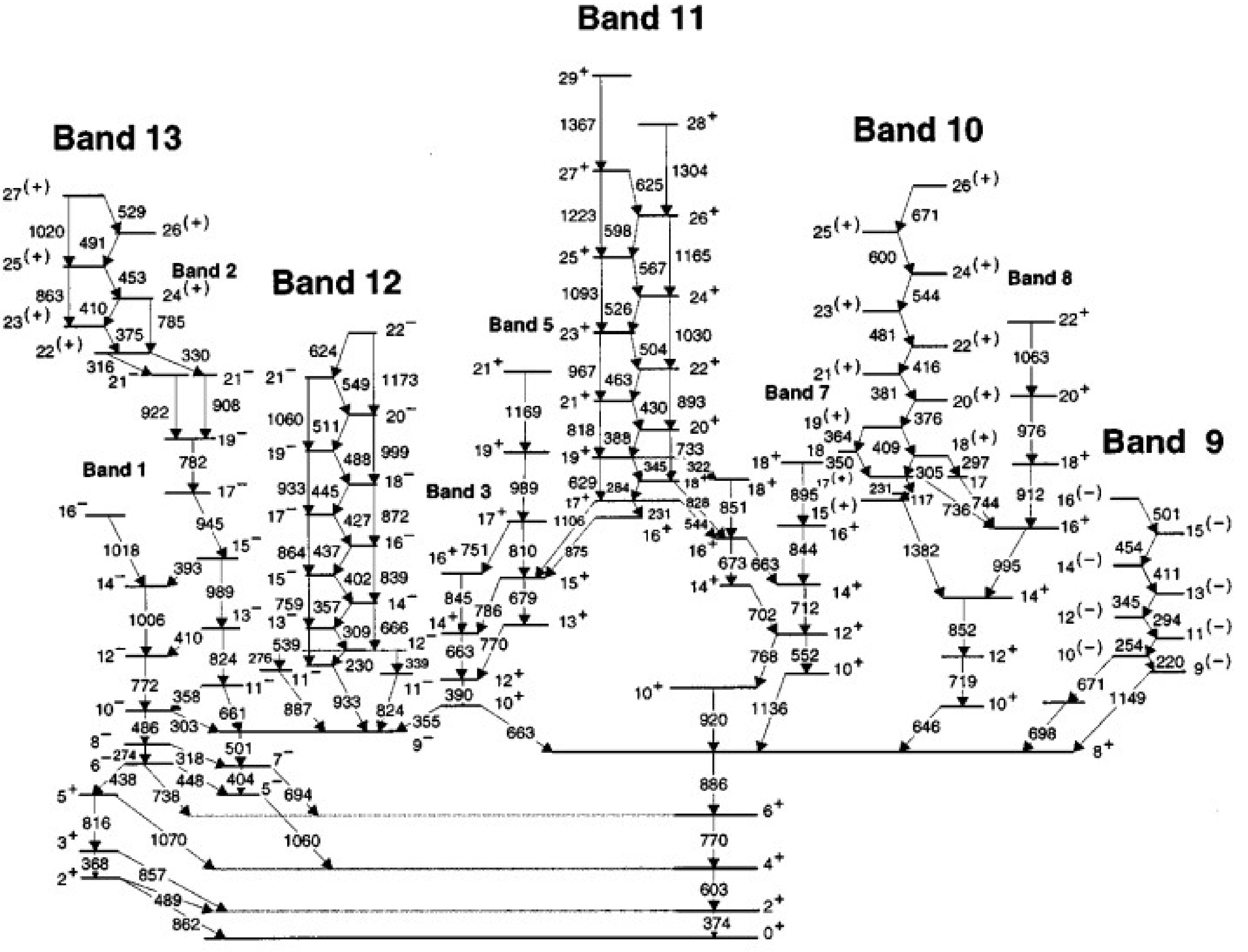
The cross section for the ^{120}Sn + ^{20}Ne reaction. It was assumed that the ^{120}Sn target and the Au backing foil are 0.5mg/cm 2 and 5mg/cm 2 thick, respectively.



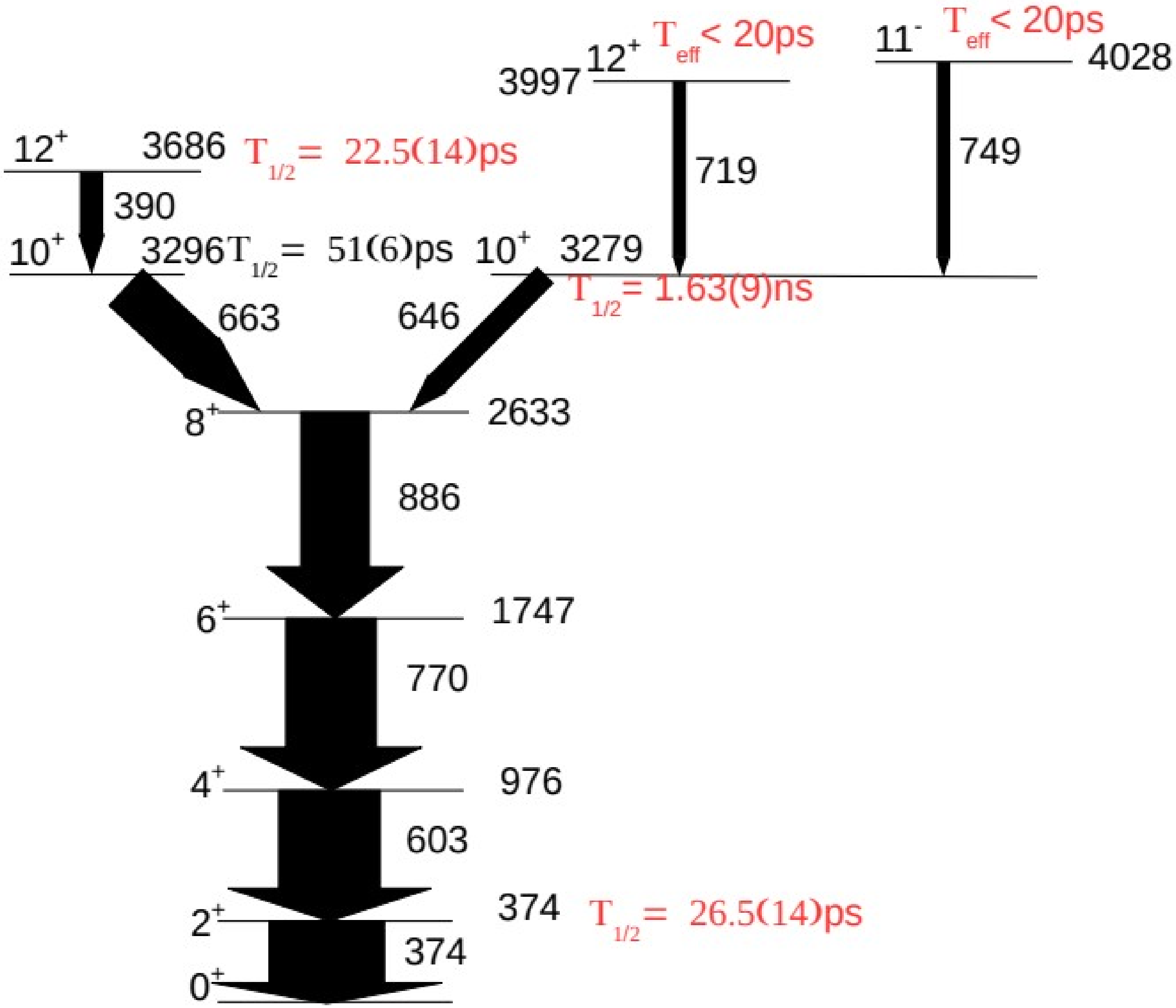
Efficiency of Ge detectors



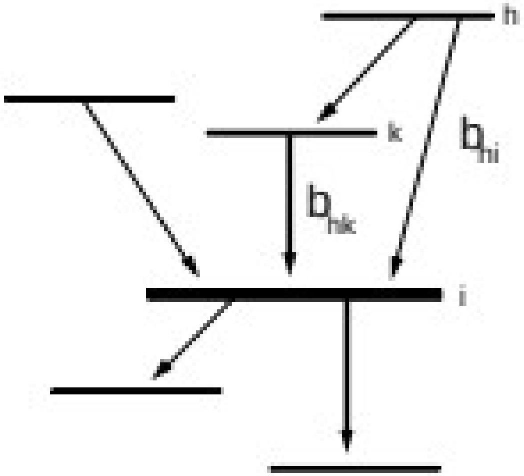



Band 11
Band 13
Band 10
Band 2
Band 12
Band 5
Band 8
Band 7
Band 9
Band 1
Band 3
29+
1367
28+
27+
625
1304
1223
26+
598
25+
567
1165
1093
24+
526
23+
1030
504
967
22+
463
21+
430
893
818
20+
388
19+
733
345
322
629
18+
284
17+
828
231
1106
16+
875
27(+)
529
26(+)
1020
491
25(+)
453
24(+)
863
410
23(+)
375
785
22(+)
330
316
21−
21−
922
908
19−
782
17−
16−
1018
945
15−
14−
393
989
1006
13−
410
12−
824
11−
772
358
10−
486
303
661
8−
501
7−
6−
274
318
438
448
404
5−
5+
738
694
816
6+
1070
1060
3+
368
857
2+
489
862
22−
624
21−
549
1173
20−
1060
511
19−
488
999
18−
933
445
17−
427
872
16−
864
437
15−
402
839
759
357
14−
13−
309
666
539
12−
276
230
339
11−
11−
887
933
824
355
9−
21+
1169
19+
989
17+
16+
751
810
845
15+
679
14+
786
13+
663
770
12+
390
10+
663
26(+)
25(+)
671
600
24(+)
544
23(+)
481
22(+)
21(+)
416
381
20(+)
19(+)
376
364
409
18(+)
297
18
350
305
17
17(+)
231
117
895
15(+)
736
744
16+
844
14+
712
12+
552
10+
851
544
673
663
702
768
1136
920
1382
995
14+
852
12+
719
10+
646
22+
1063
20+
976
18+
912
16(−)
501
15(−)
454
14(−)
411
13(−)
12(−)
345
294
11(−)
10(−)
254
220
9(−)
671
1149
698
8+
886
770
4+
603
2+
374
0+

^{136}Nd


11⁻ T_{eff}< 20ps 4028
3997 12⁺ T_{eff}< 20ps
749
719
12⁺ 3686 $T_{1/2}$= 22.5(14)ps
390
10⁺ 3296 $T_{1/2}$= 51(6)ps
10⁺ 3279 $T_{1/2}$= 1.63(9)ns
663
646
8⁺ 2633
886
6⁺ 1747
770
4⁺ 976
603
2⁺ 374 $T_{1/2}$= 26.5(14)ps
374
0⁺

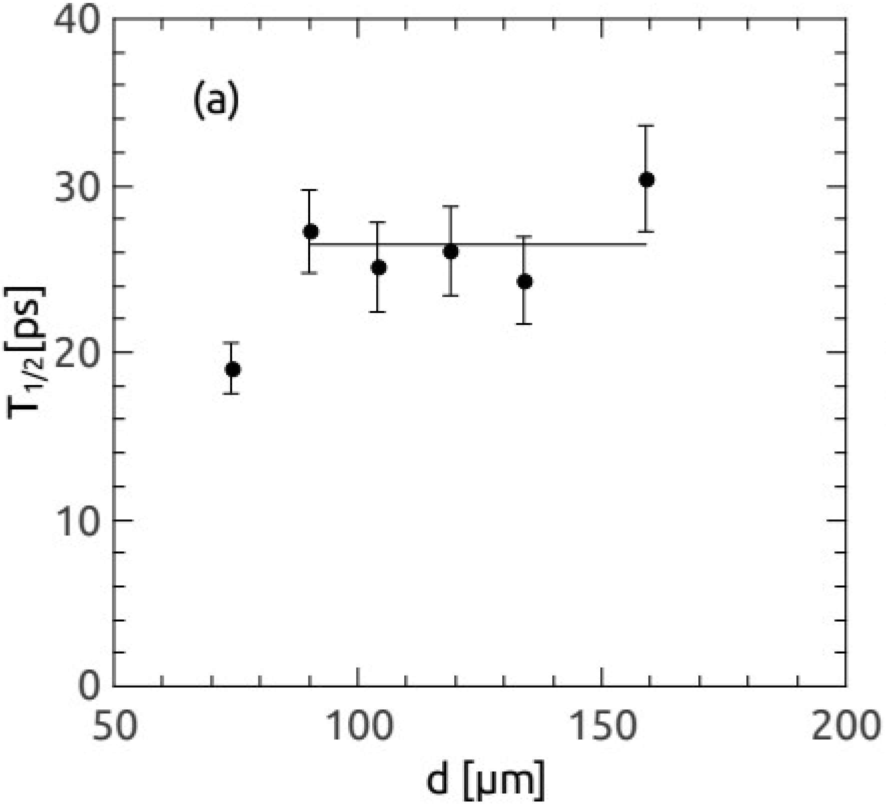
Differential Decay Curve Method



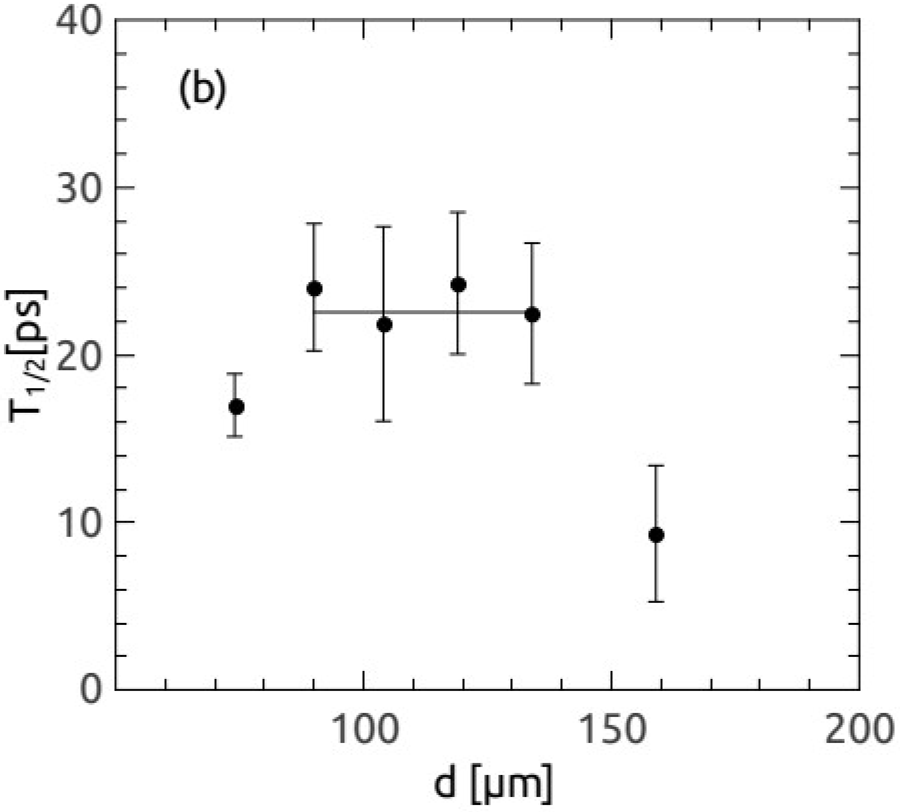
$$\frac{d}{dt}n_i(t) = -\lambda_i n_i(t) + \sum_h b_{hi}\lambda_h n_h(t)$$

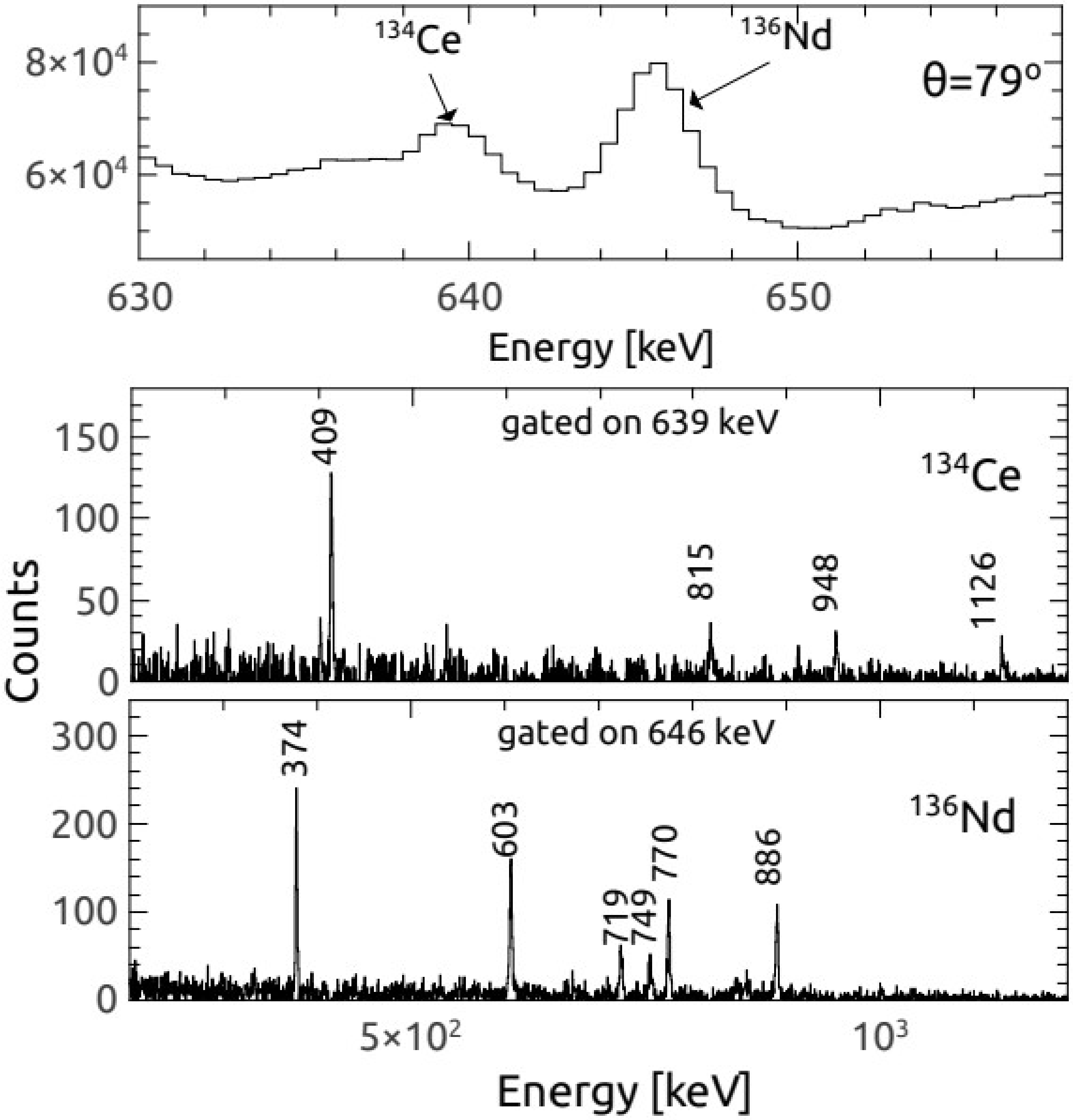
$$\tau_i(t) = \frac{-n_i(t) + \sum_h b_{hi} n_h(t)}{\frac{d}{dt}n_i(t)}$$

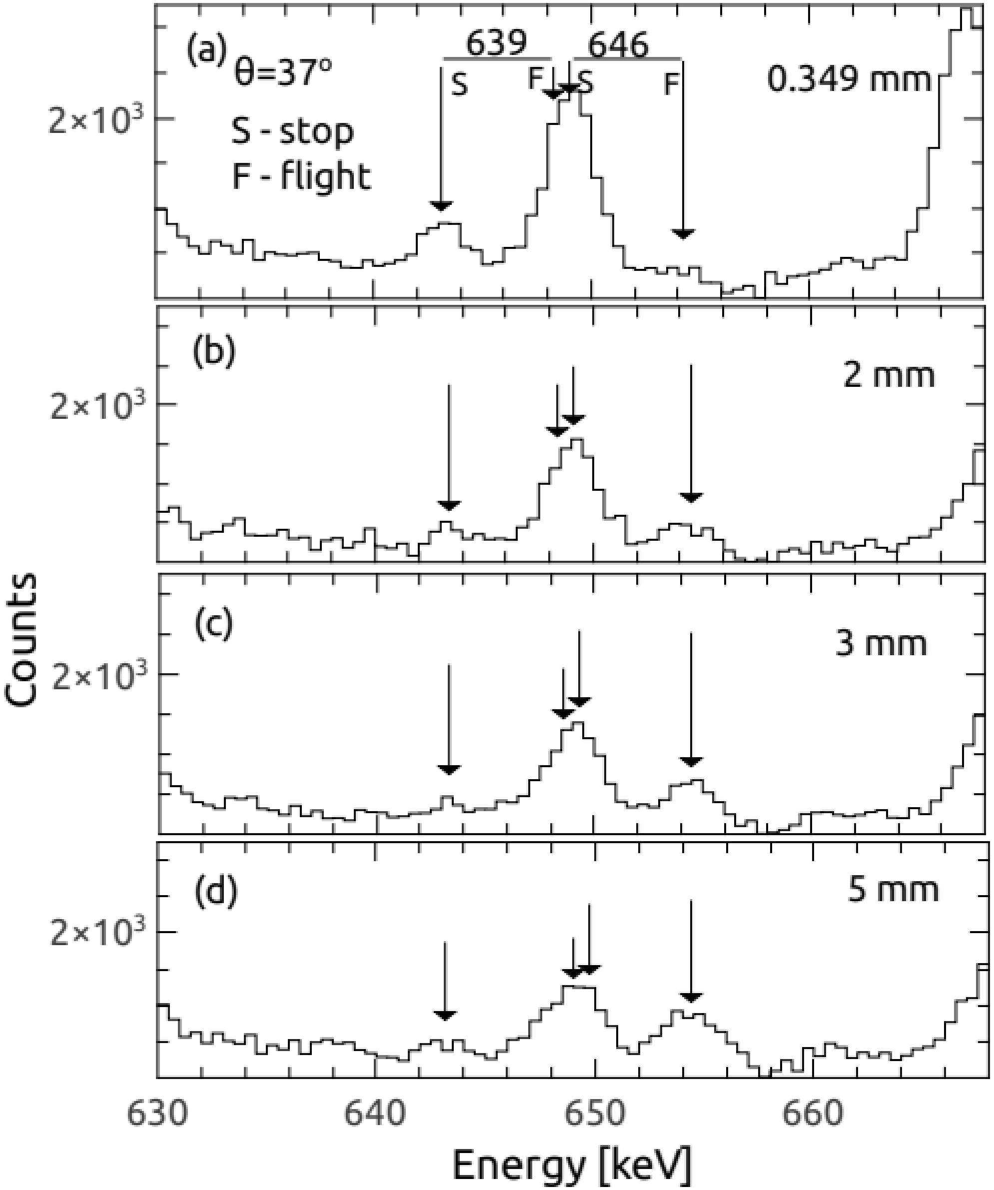
2^+ state 374 keV



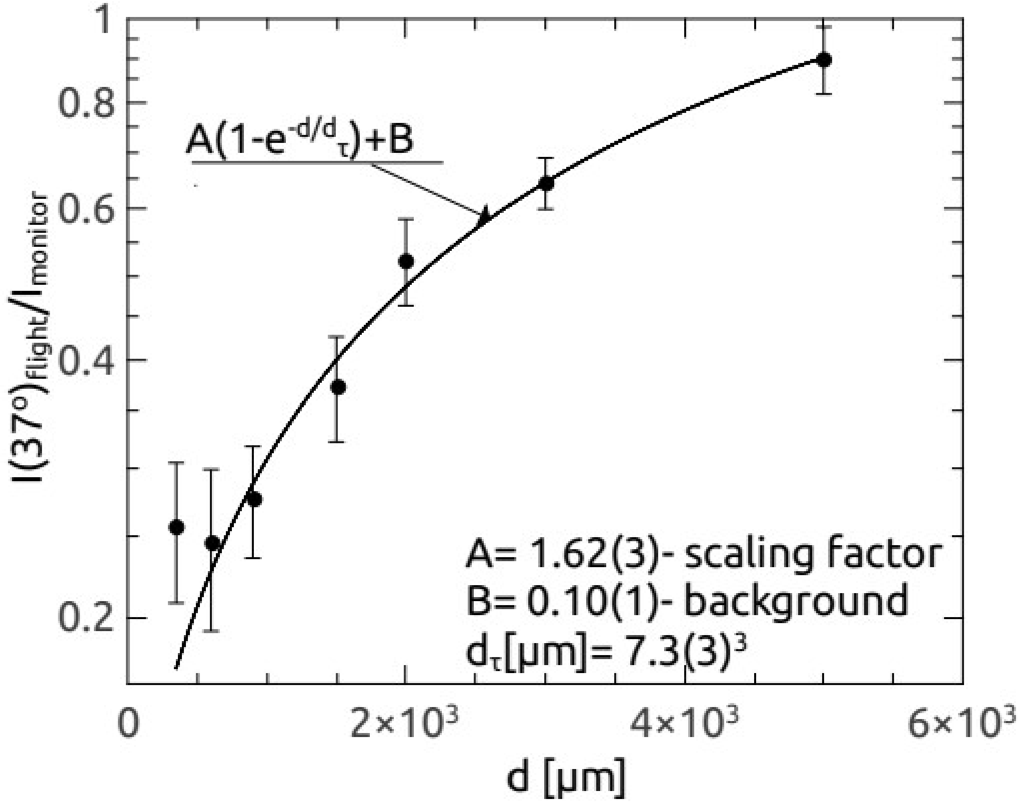
12^+ state 3686 keV




^{134}Ce
^{136}Nd
θ=79°
8×10^4
6×10^4
630
640
650
Energy [keV]
gated on 639 keV
^{134}Ce
409
815
948
1126
150
100
50
0
Counts
gated on 646 keV
^{136}Nd
374
603
719
749
770
886
300
200
100
0
5×10^2
10^3
Energy [keV]


(a)
θ=37°
639
646
S
F
S
F
S - stop
F - flight
0.349 mm
(b)
2 mm
(c)
3 mm
(d)
5 mm
2×10³
Counts
630
640
650
660
Energy [keV]

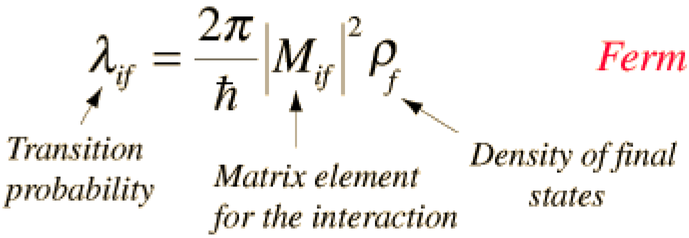
10^+ state 3279 keV



A= 1.62(3)- scaling factor
B= 0.10(1)- background
d_τ[μm]= $7.3(3)^3$

10^+ configuration structure

Transition Probability is given by the quantum mechanical Fermi-Golden rule



$$\lambda_{if} = \frac{2\pi}{\hbar} \left| M_{if} \right|^2 \rho_f$$

Fermi's Golden Rule

$$M_{if} = \langle f|H|i \rangle$$

Lifetime of 10^+ 3279 keV is 1.63ns what is 30 times longer then the lifetime of 10^+ 3296 keV which is 51 ps

10^+ at 3279 and 10^+ at 3296 have different structure

- Lifetime 10+ 3296 keV – 51 ps → B(E2) = 2 W.u., g-factor = 1 → $(h_{11/2})^2$ proton-aligned excitation
- Lifetime 10+ 3296 keV – 1.63 ns → B(E2) = 0.07 W.u., $f_\nu = 1.4$, ?? $(h_{11/2})^2$ neutron-aligned ?

Transition rate hindrance factor

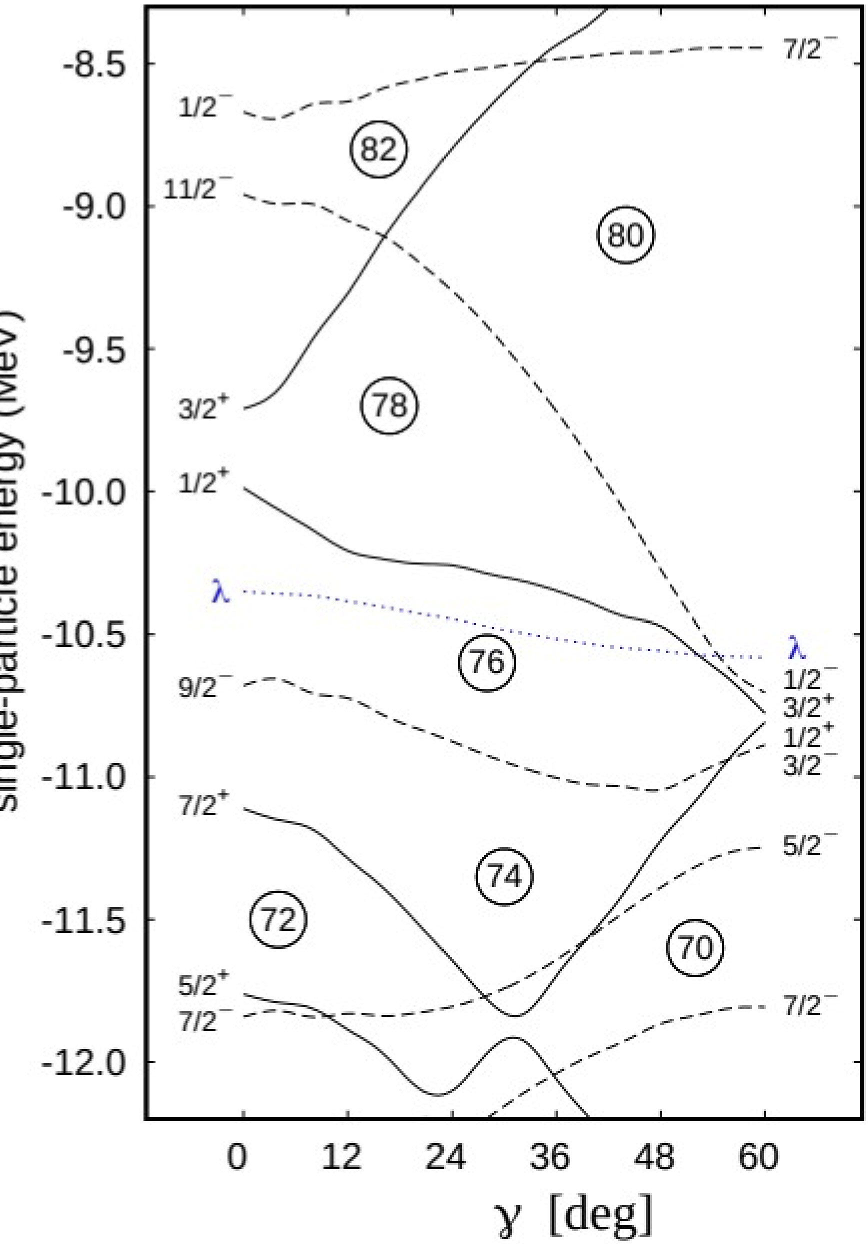
$F_W = T_{\gamma 1/2} / T_{W1/2}$ Weisskopf hindrance

$\nu = \Delta K - \lambda$ degree of K forbiddenness

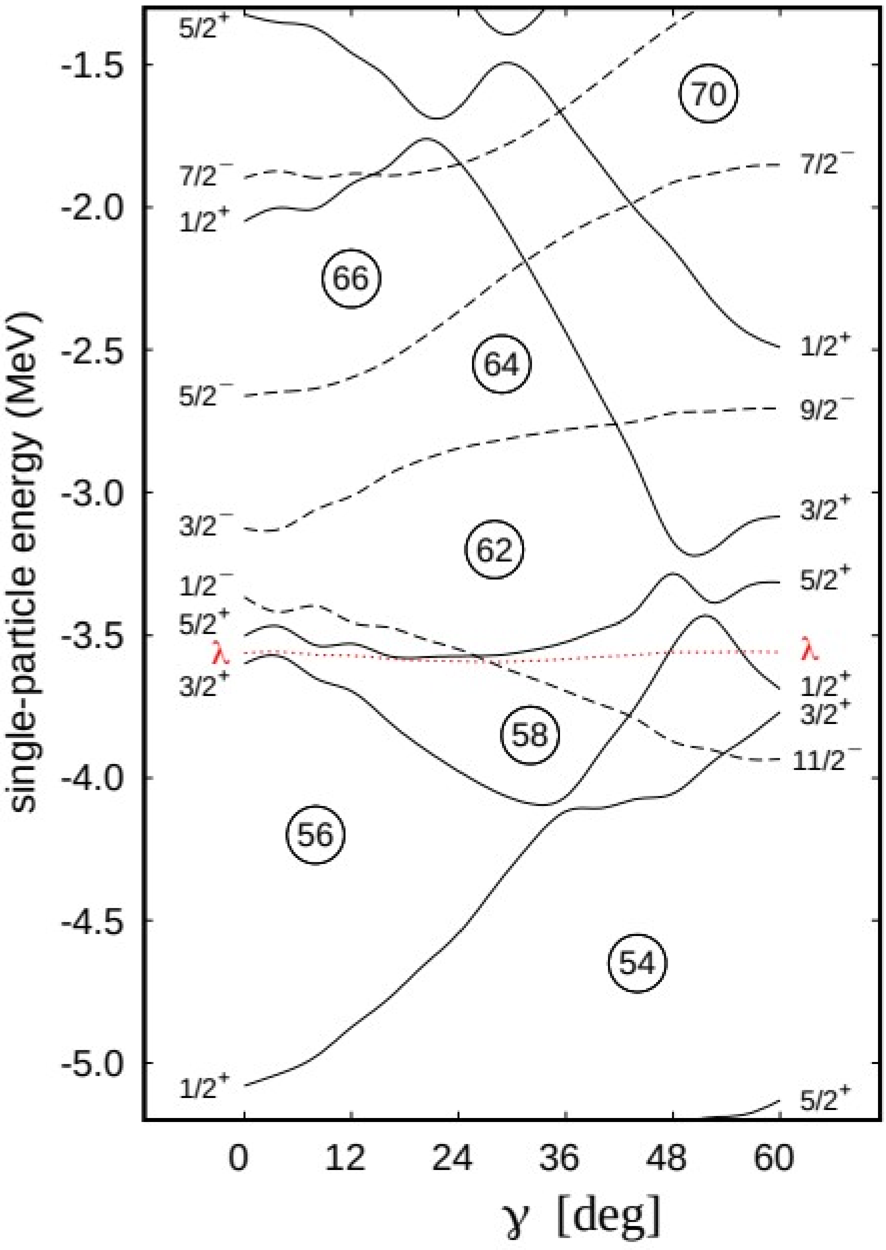
$f_\nu = (F_W)^{1/\nu}$ reduced hindrance (hindrance per degree of K forbiddenness)

A rather small reduced hindrance of the electromagnetic decay of the 10^+ state at 3279 keV, $f_\nu = 1.4$ for $\nu = 8$

neutrons



protons



1) two possible, relatively low lying 2 quasi-particle $K^\pi = 10^+$ configurations, one neutron, one proton, both build from the orbitals $\Omega^\pi = 9/2^-$ and $11/2^-$ of the intruder $h_{11/2}$ sub-shells.

2) These lowest-Ω members of the $h_{11/2}$ intruder subshells lie much closer (less than 0.5 MeV) to the respective Fermi level - alignment

3) The deformation of the aligned configuration is driven towards the smaller $|\boldsymbol{\varepsilon}_\nu - \lambda|$, oblate collective rotation for the aligned neutrons and prolate for the aligned protons.

g-factor as a probe of single particle configuration

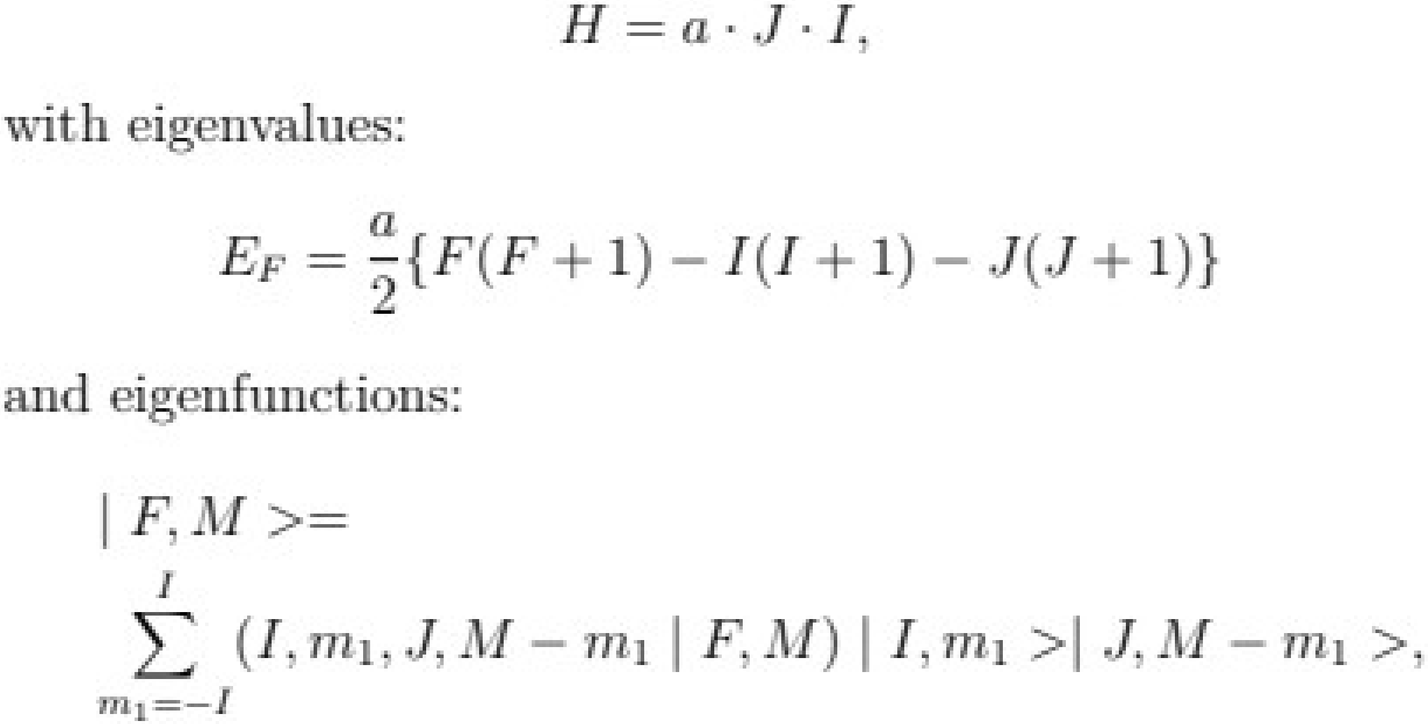
$$\mu(\nu) = g_l I + \frac{g(\nu) - g_l}{(I+1)}[\Omega^2 + \frac{1}{4}(2I+1)(-1)^{l+1/2} b(\nu)\delta_{1/2}]$$

$$g_l = \begin{cases} 1 & \text{for protons} \\ 0 & \text{for neutrons} \end{cases}$$

$$g(\nu) = \begin{cases} 5.82 & \text{for protons} \\ -3.82 & \text{for neutrons} \end{cases}$$

$$g(10^+) = \begin{cases} 1 & \text{for aligned protons} \\ -0.18 & \text{for aligned neutrons} \end{cases}$$

Hyperfine interactions



$$H = a \cdot J \cdot I,$$

with eigenvalues:

$$E_F = \frac{a}{2}\{F(F+1) - I(I+1) - J(J+1)\}$$

and eigenfunctions:

$$\mid F, M >= \sum_{m_1=-I}^{I} (I, m_1, J, M - m_1 \mid F, M) \mid I, m_1 >\mid J, M - m_1 >,$$

$$W(\theta) = a_0(1 + a_2P_2(\theta) + a_4P_4(\theta) + a_6P_6(\theta))$$

$$G_k(t) = \frac{a_2(t)}{a_0}$$

$$G_k(t) = \sum_{FF'} \frac{(2F+1)(2F'+1)}{(2J+1)} \left\{ \frac{FF'k}{IIJ} \right\}^2 e^{-i\omega_{FF'}t}$$

where $\omega_{FF'} = (E_F - E_{F'})/\hbar$

for $J = \frac{1}{2}$:

$$\omega = (2I+1)g\frac{\mu_N H(0)}{\hbar}$$

Two ways of g-factor measurements

Polarize electrons of the moving ion via spin exchange interactions with the polarized electrons of a ferromagnetic host

Transient Field (TF) method-precession

precession of nuclear spin about fixed axis (external field)

$$W(\theta,t)=1+a_2P_2[\cos(\theta-\omega_L t)]+a_4P_4[(\cos(\theta-\omega_L t)]$$

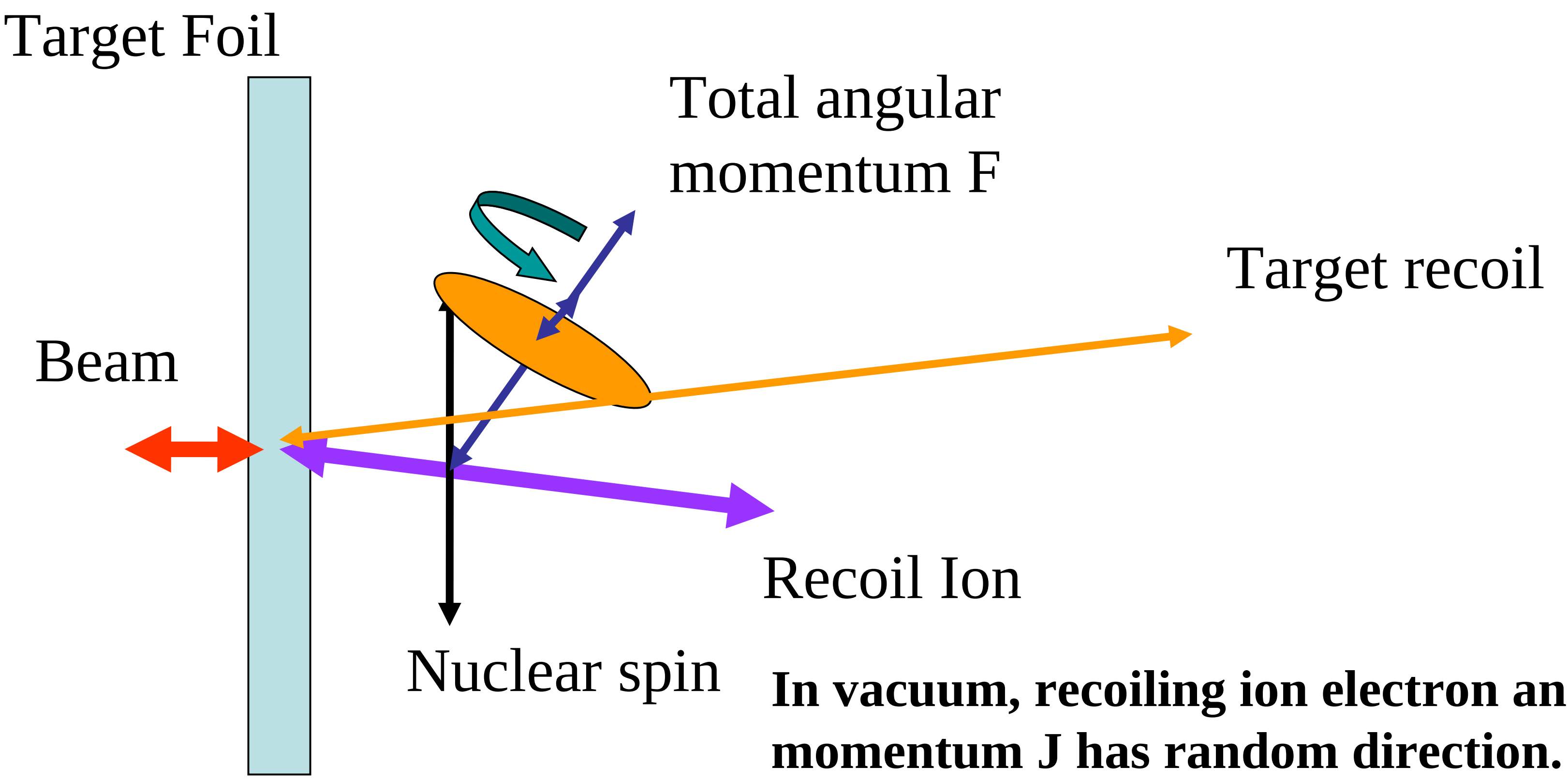
The moving ion recoil into vacuum (RIV)

Neclear Deorientation

precession of nuclear spin about random axes

$$W(\theta,t)=1+a_2G_2(t)P_2[\cos(\theta)]+a_4G_4(t)P_4[(\cos(\theta)]$$

Recoil in Vacuum

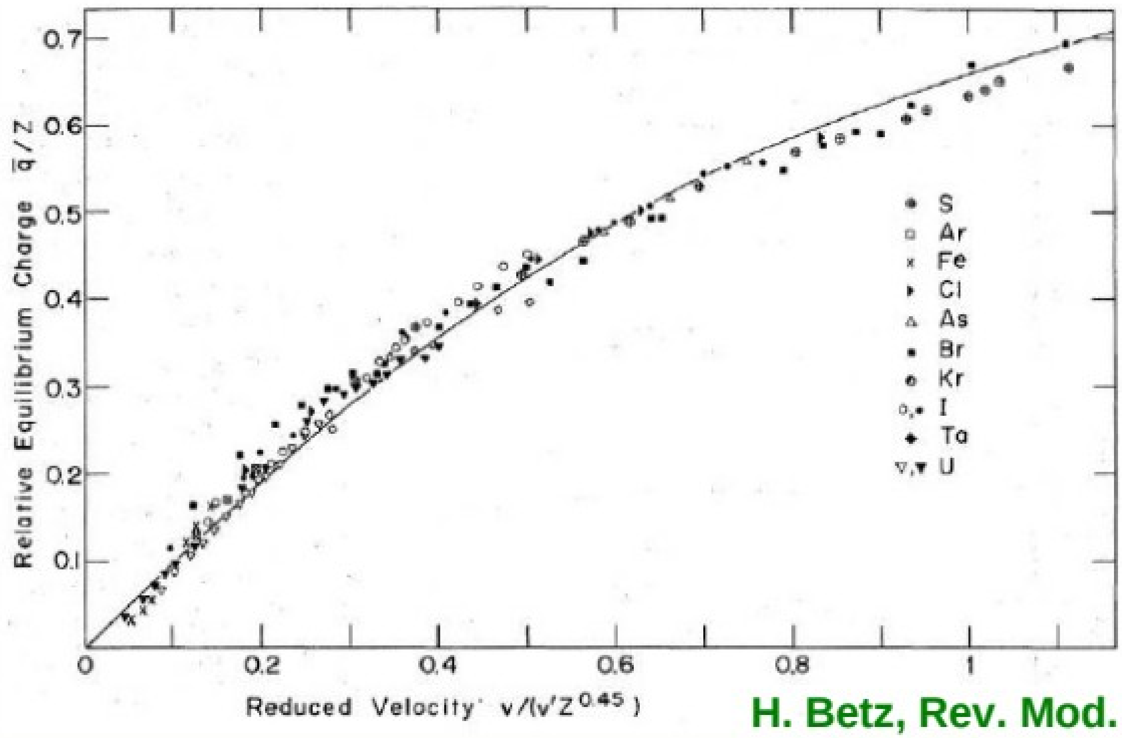


In vacuum, recoiling ion electron angular momentum J has random direction. Recoiling ion nuclear spin I, initially aligned in plane of target, precesses about resultant F=I+J. Anisotropy of angular distribution of decay gamma emission becomes attenuated.

Coulomb excitation ^{148}Nd as reference magnetic hyperfield measure for ^{136}Nd experiment

A.Tucholski, J.Srebrny, P.Napiorkowski, Ch.Droste, M.Kowalczyk, M.Palacz, K. Wrzosek-Lipska, K.Hadyńska, G.Jaworski, J.Puśk-Samorajczyk, A.Stolarz, T.Abraham, C.Fransen, A.Blashev

Warsaw University, HIL



H. Betz, Rev. Mod. Phys. 44, 465 (1972)

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)

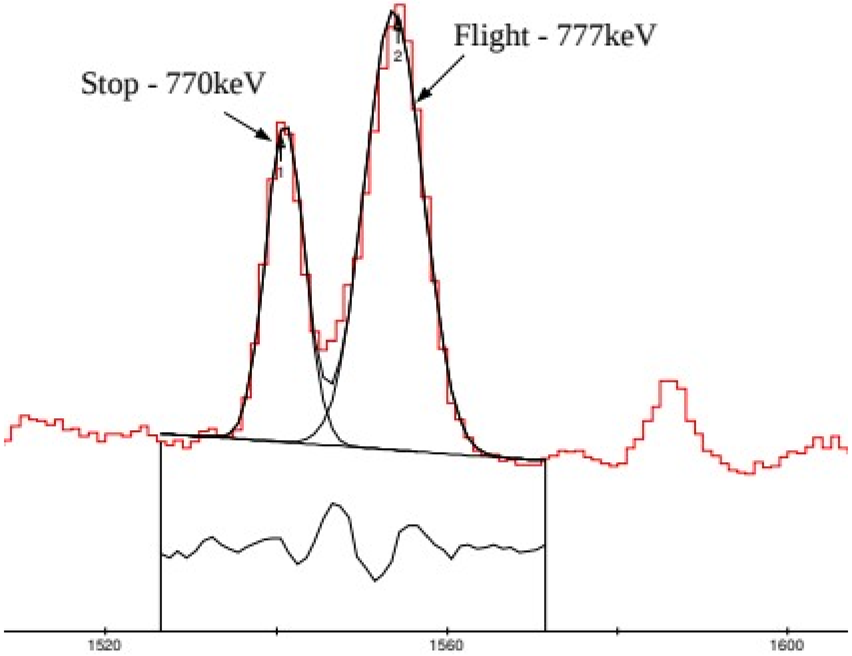
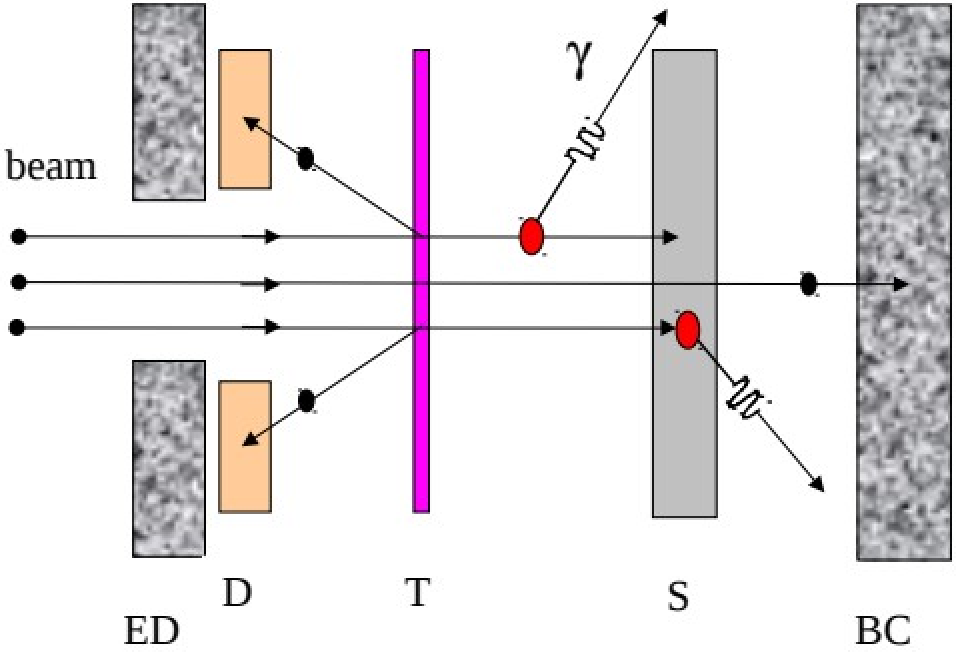


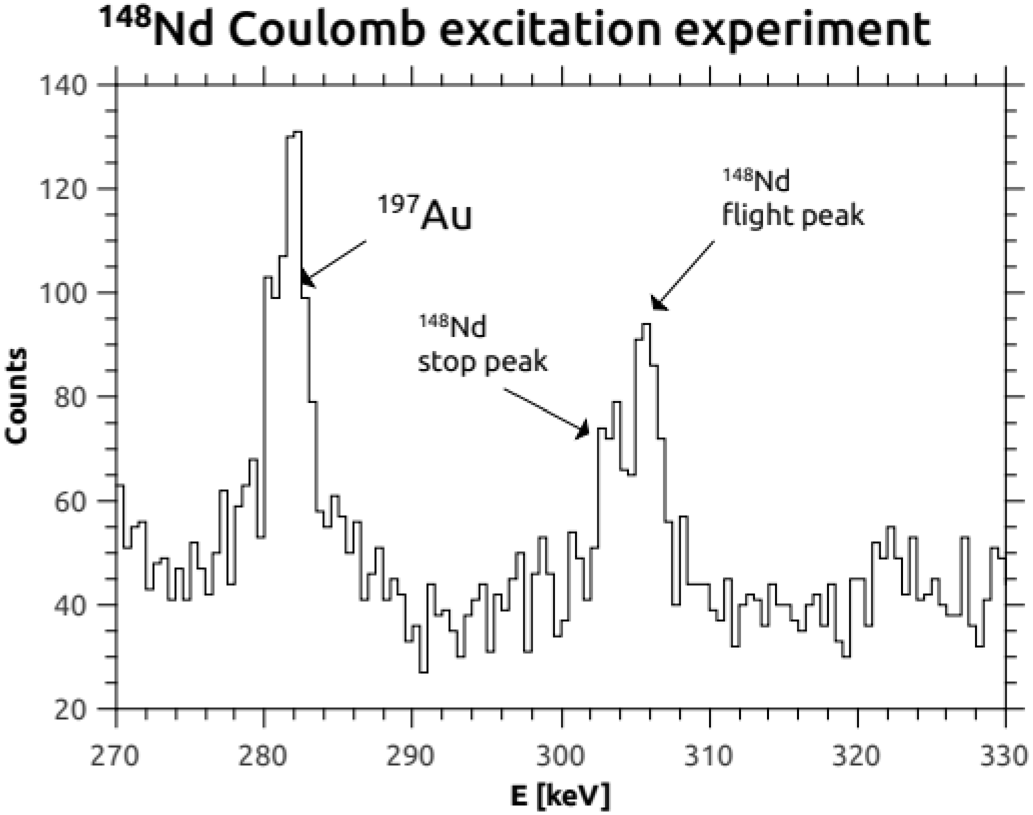
Figure: The line 770keV and its Doppler shifted flight component of 777keV of the transition 6 + → 4 + of the reaction ^{120}Sn(^{20}Ne, 4n) ^{136}Nd.

Experimental set-up



The ED stands for entrance diaphragm, D stands for Si annular detector, T - for target with backing foil, S - for stopper, BC - beam dumper, black circles - red circles - ^{148}Nd recoils.

First experimental results of gamma spectrum in coincidence with beam (^{10}B) in Si backscattering detector



Conclusions

- A rather small reduced hindrance of the electromagnetic decay of the 10^+ state at 3279 keV, $f_\nu = 1.4$ for $\nu = 8$, would be consistent with its K-mixed character.
- The moment of inertia of the band built on it , smaller than the one of the g.s. band, would be compatible either with a decrease in β deformation for a two-neutron configuration or with a close-to-oblate deformation of the two-proton one.
- Magnetic properties of 10+ will determine about the character of excitation due to different magnetic properties on neutrons against protons
- Next experiment in

collaboration with

Koln University, IKP

Christoph Fransen