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Mass measurement in the N=40 region with JYFLTRAP

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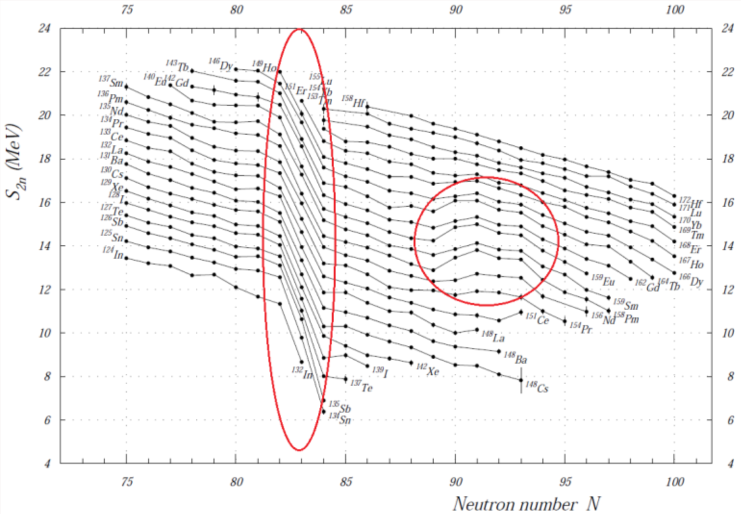
Nuclear Physics for Astrophysics X

Cern, 8th september 2022

Importance of nuclear mass

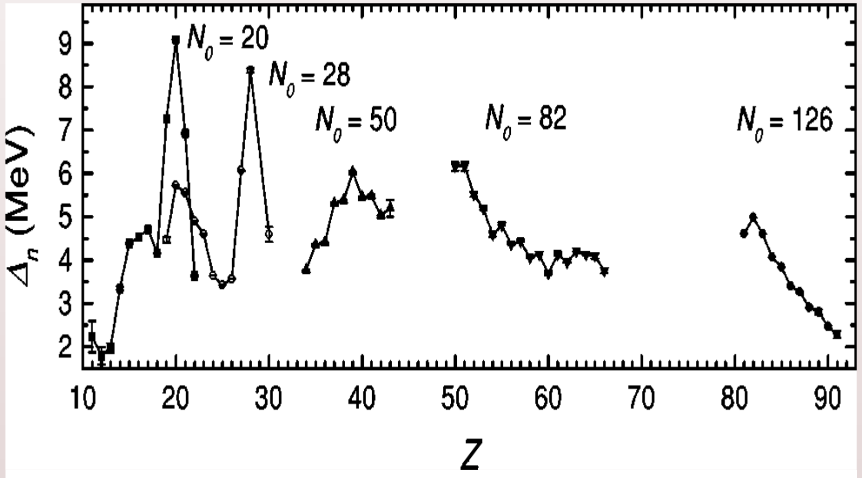
❖**NUCLEAR STRUCTURE**

Evolution and magnitude of shell and subshell closure, shape coexistence…



$$S_{2n}(Z,N) = \Delta(Z,N-2) + 2\Delta(n) - \Delta(Z,N)$$

AME2003



$$D_{2n}(N,Z) = S_{2n}(N,Z) - S_{2n}(N+2,Z)$$

D. Lunney et al, Rev. Mod. Phys., Vol. 75, No. 3, July 2003

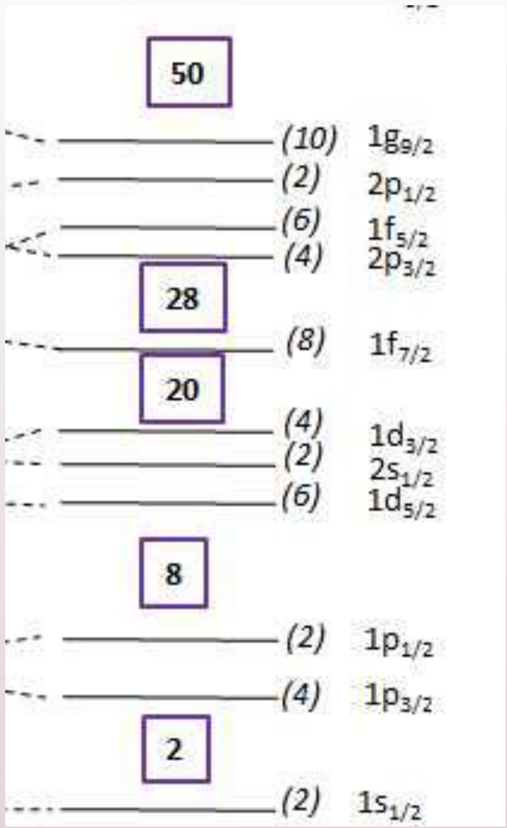
❖**NUCLEAR ASTROPHYSICS**

Reaction rate in r-process, rp-process, s-process ect…

$$N_A < \sigma v >_{res} = 1.54 \times 10^{11} (\mu T_9)^{-3/2} \sum_i (\omega\gamma)_i \times \exp\left(-\frac{11.605 E_{res,i}}{T_9}\right)$$

$$E_{res,i} = E_{x,i} - \boldsymbol{Q_{p,\gamma}}$$

The N=40 region

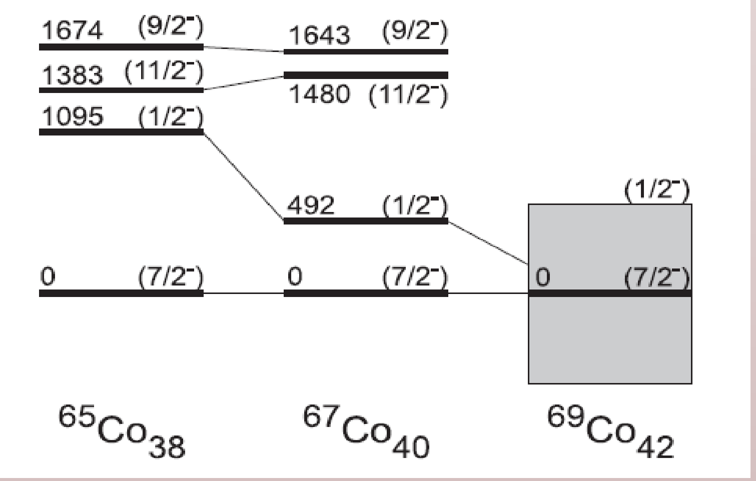


- ❖N = 40 region is known for shape coexistence

- ❖Magicity of N=40 (?)
  Example of ^{68}Ni (Z=28): The first 2+ state has a high excitation energy (2033 keV) and a low reduced transition probability (B(E2; $0^+_1 \rightarrow 2^+_1$)=260(50) e^2fm^4)

- ❖Overall trend above N = 40 has remained unclear, partly due to long-living isomers.

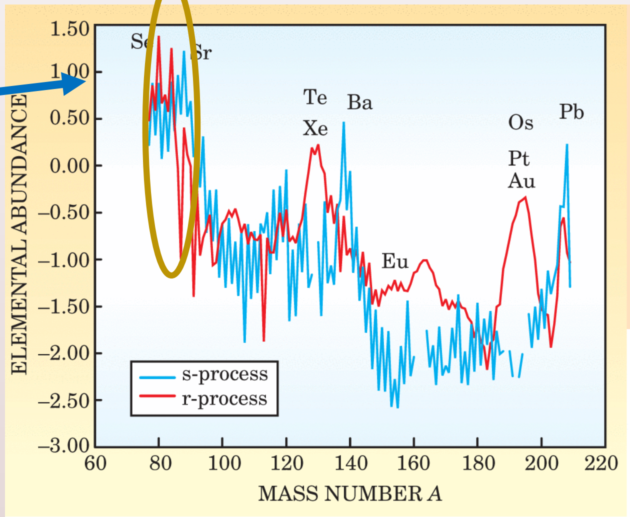
- ❖The neutron-rich Co isotopes are important for the evolution of the N=40 neutron shell gap at Z=27 . In the odd-A Co isotopes, the 1/2− level is suggested to be a deformed intruder.



A Gade and S N Liddick, J. Phys. G: Nucl. Part. Phys. 43 (2016) 024001

The weak r-process

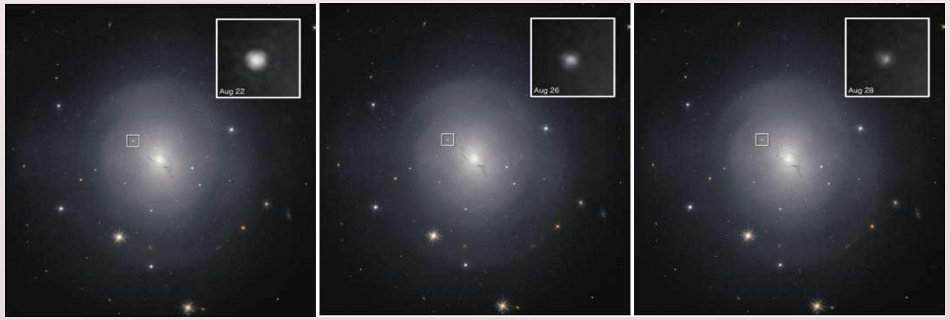
$A \sim 80$ *r*-process abundance peak.



J. Cowan, F.K. Thielemann, Physics Today **57**, 10, 47 (2004)

❖ Astrophysical conditions:

Neutrino wind associated with a core-collapse supernova or neutron star mergers



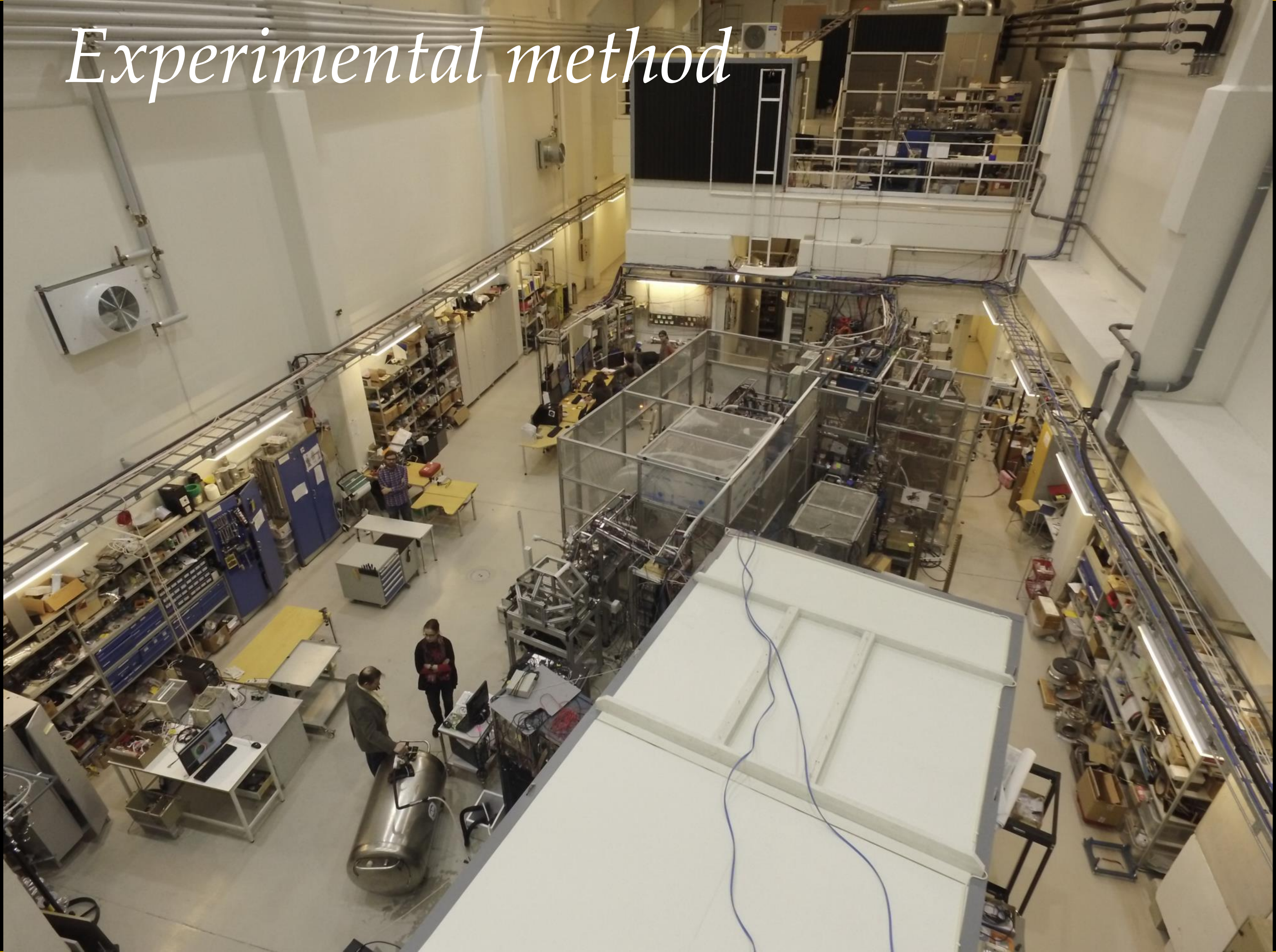
^{68}**Co(n, γ)**^{69}**Co** reaction is relevant for the weak r-process and its abundance pattern

TABLE II. Nuclei with maximum neutron capture rate sensitivity measures $F > 10$ from the combined results of fifty-five neutron capture rate sensitivity studies run under a range of distinct astrophysical conditions, from Fig. 7.

Z	A	F
26	67	15.8
26	71	11.2
27	68	11.6
27	75	17.3
28	76	17.2
28	81	34.1
29	72	10.4
29	74	15.1
29	76	25.0
29	77	12.5

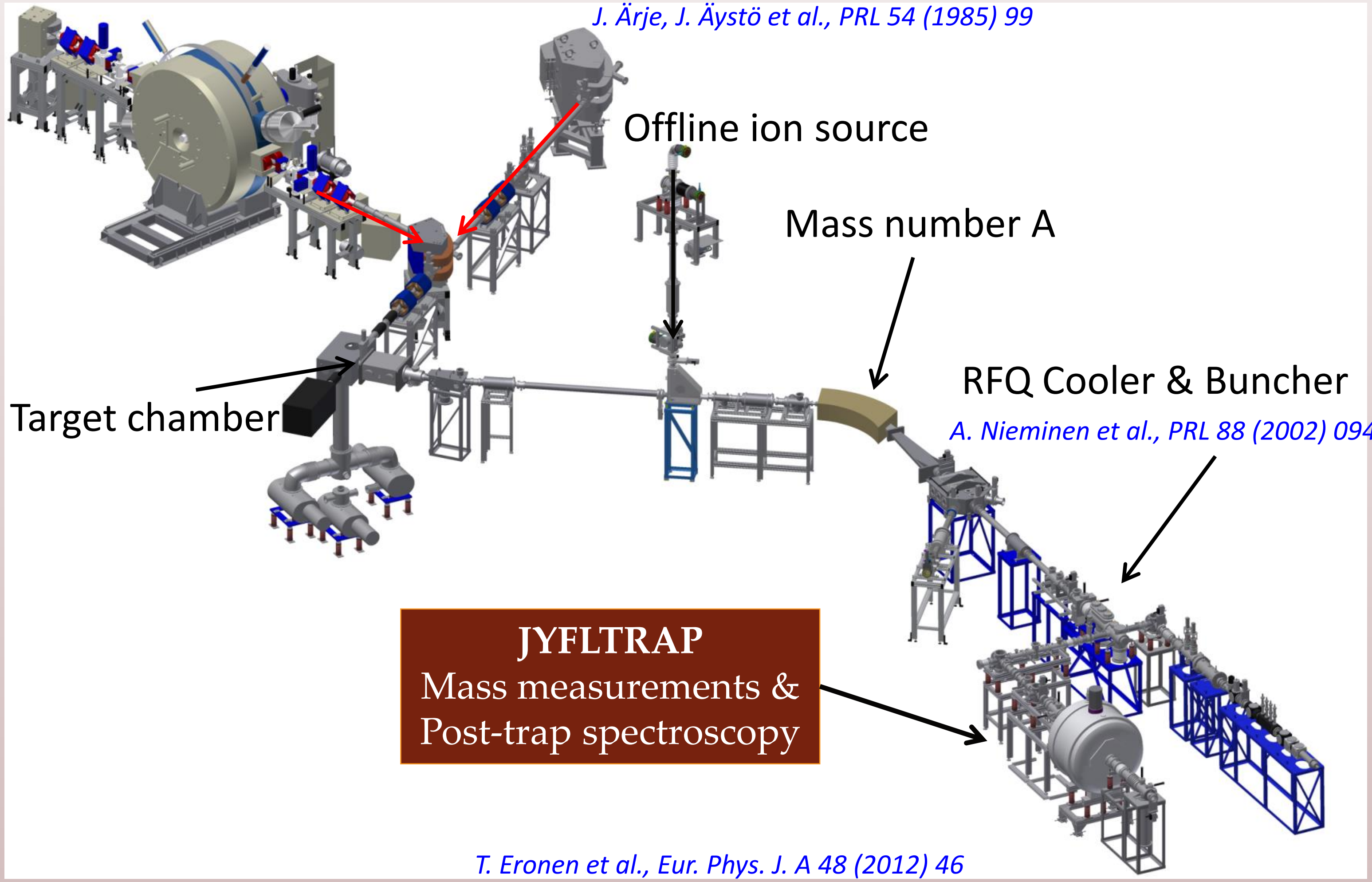
R. Surman et al., AIP Advances 4, 041008 (2014)

Experimental method

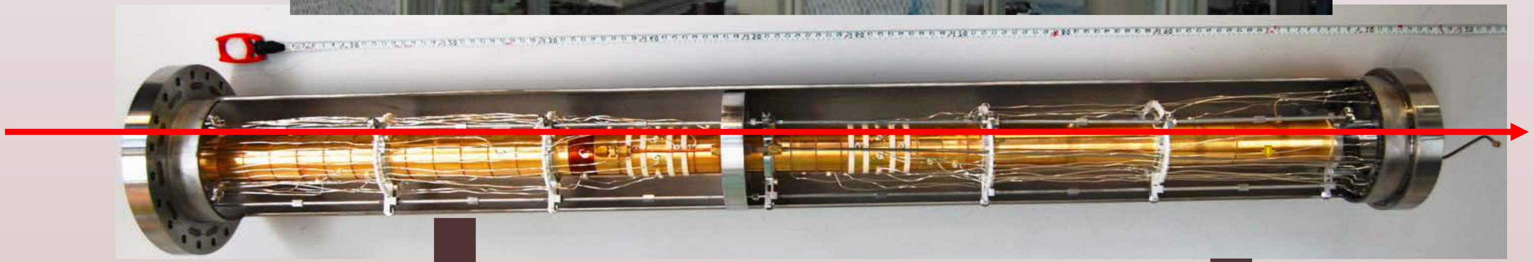


IGISOL: A fast and universal method to produce radioactive ion beams

35-MeV p beam
15-mg/cm2-thick
^{nat}U target



The double Penning traps JYFLTRAP

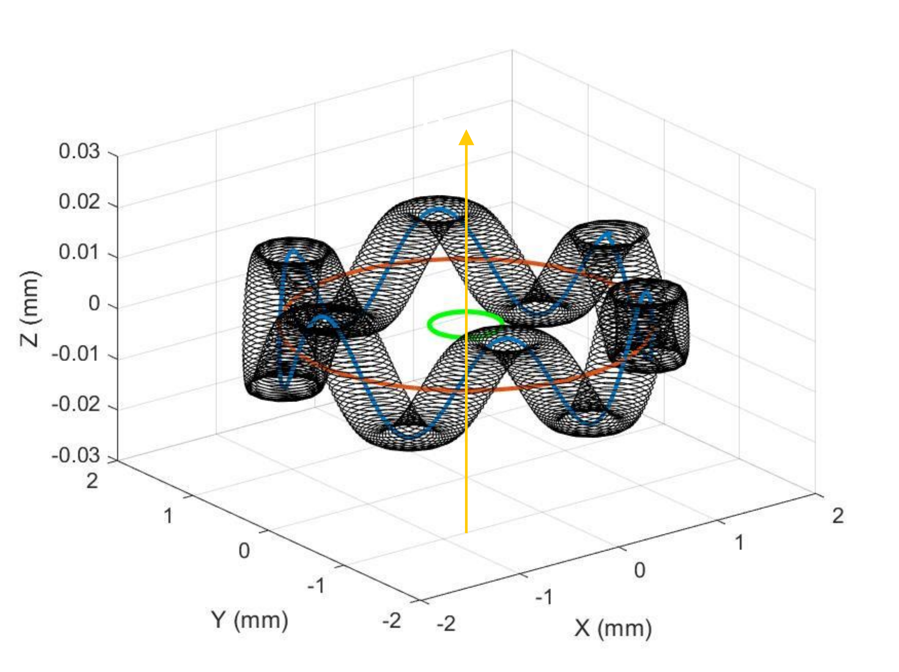


Purification trap
Filled with He gas (~10^{-4}mbar) to cool ions.

Precision trap
High vacuum (~$10^{-9}/10^{-8}$mbar)

Ion motions in a Penning trap

- In a quadrupolar electric field, the motion of an ion undergoes three eigenmotions : An axial oscillation v_z, and two radial oscillations v_+ and v_-

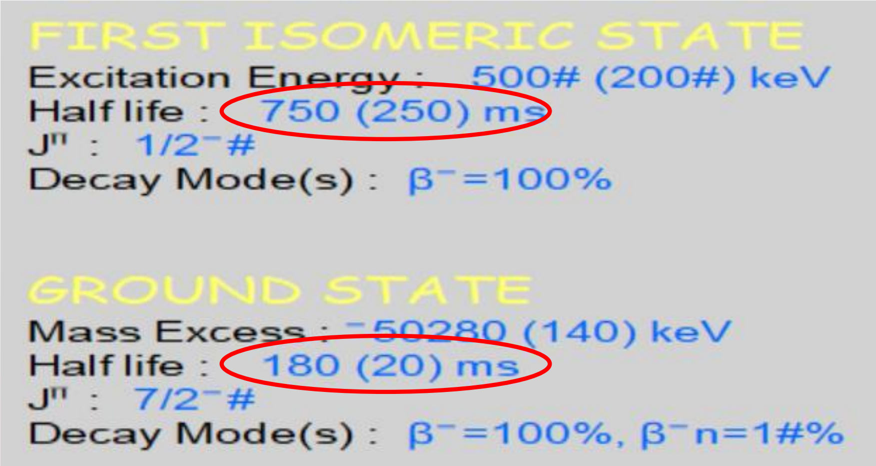


- By applying a quadrupolar excitation, a coupling of two eigenmotions can be excited: The magnetron motion can be converted to reduced cyclotron motion and vice versa

In an ideal trap :

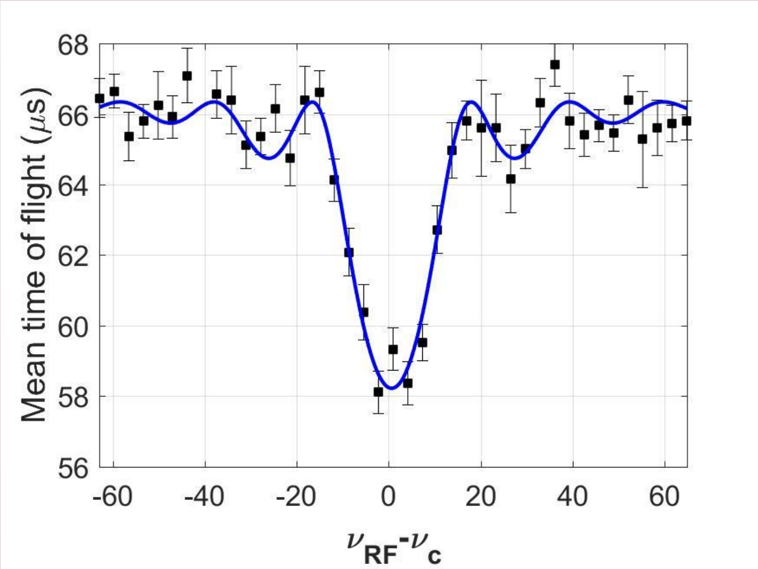
$$\vartheta_c = \vartheta_+ + \vartheta_- = \frac{1}{2\pi}\frac{qB}{m}$$

^{69}Co measurement


FIRST ISOMERIC STATE
Excitation Energy : 500# (200#) keV
Half life : 750 (250) ms
J^π : 1/2⁻#
Decay Mode(s) : β^-=100%

GROUND STATE
Mass Excess : −50280 (140) keV
Half life : 180 (20) ms
J^π : 7/2⁻#
Decay Mode(s) : β^-=100%, β^-n=1#%

- The proximity of the ground and isomeric states did not allow to separate them and fit the two states directly on the collected TOF-ICR spectra.



- The composition of the ion bunches was manipulated by changing the waiting time from the moment the ion-beam accumulation in the cooler was stopped to the extraction toward JYFLTRAP.
- When adding 500ms in the cooler, most of the short living state decayed.

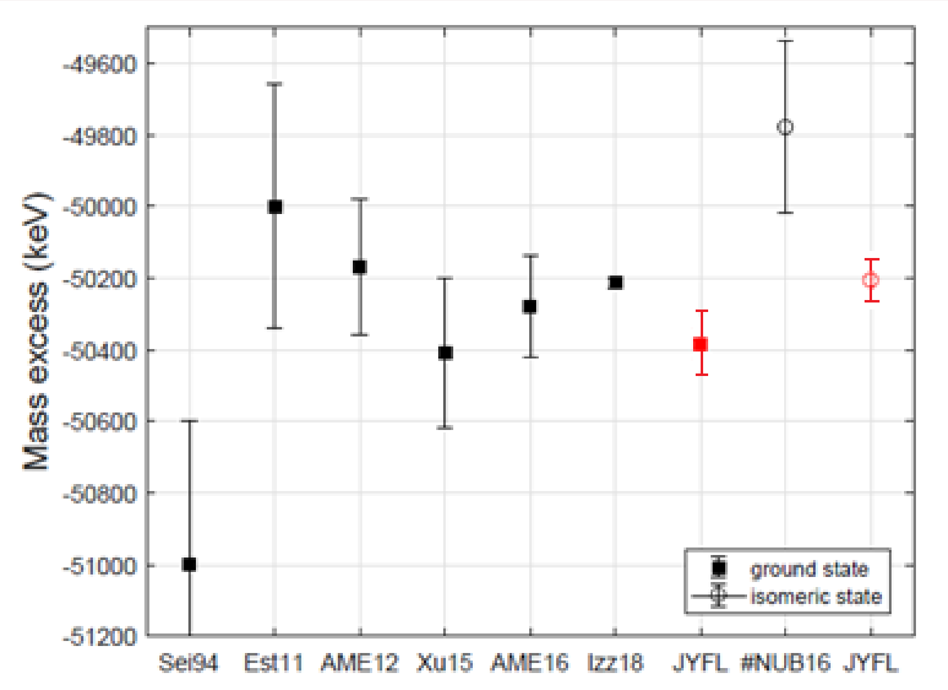
$$N_{short} = N_1 e^{-\lambda_1 t_{short}} + N_2 e^{-\lambda_2 t_{short}}$$

$$N_{long} = N_1 e^{-\lambda_1 t_{long}} + N_2 e^{-\lambda_2 t_{long}}$$

$$\Delta_{long} = f^{gs}_{long}\Delta_{gs} + f^{m}_{long}\Delta_m$$

$$\Delta_{short} = f^{gs}_{short}\Delta_{gs} + f^{m}_{short}\Delta_m$$

^{69}Co measurement



Δ(g.s.)=−50385(86) keV
Δ(i.m.)= −50203(50) keV

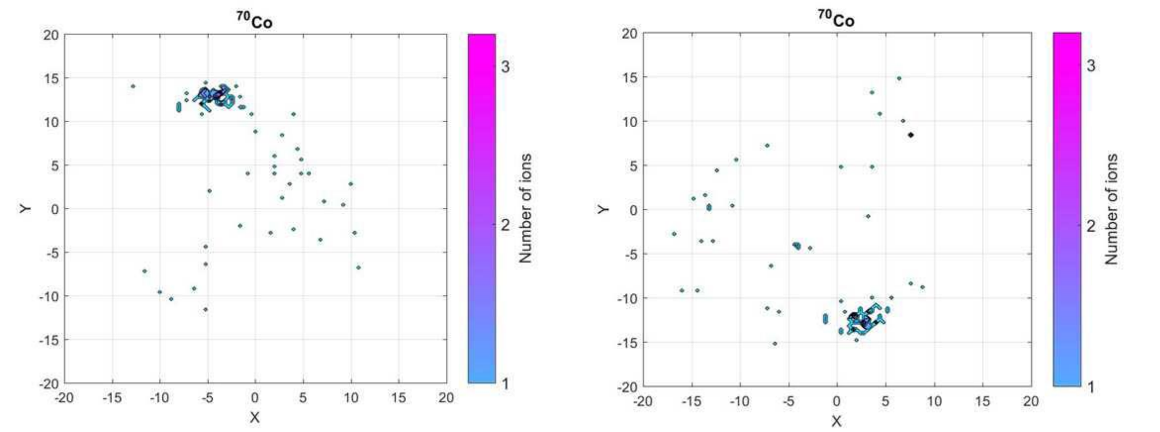
- The obtained mass-excess value for 69Co^{m}, −50 203(50) keV is in perfect agreement with the ground-state value of −50 214(14) keV reported from the LEBIT Penning trap, suggesting they have measured the isomer.

^{70}Co measurement

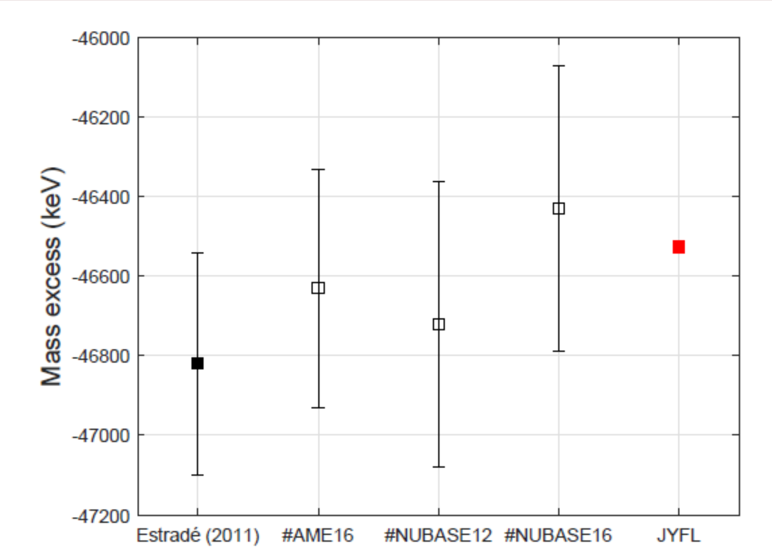
FIRST ISOMERIC STATE
Excitation Energy : 200# (200#) keV
Half life : 470 (50) ms
J^{π} : 3^{+}#
Decay Mode(s) : $\beta^{-}\approx$100%, IT?, β^{-}n=3#%, β^{-}2n=0#%

GROUND STATE
Mass Excess : $-$46630# (300#) keV
Half life : 112 (7) ms
J^{π} : $(6^{-},7^{-})$
Decay Mode(s) : β^{-}=100%, β^{-}n=3#%, β^{-}2n=0#%

- The production rates and determined mass-excess values for ^{70}Co changed only moderately when the measurement cycle was increased
- The phase-imaging ion-cyclotron-resonance was used to determine the composition of the ^{70}Co beam.

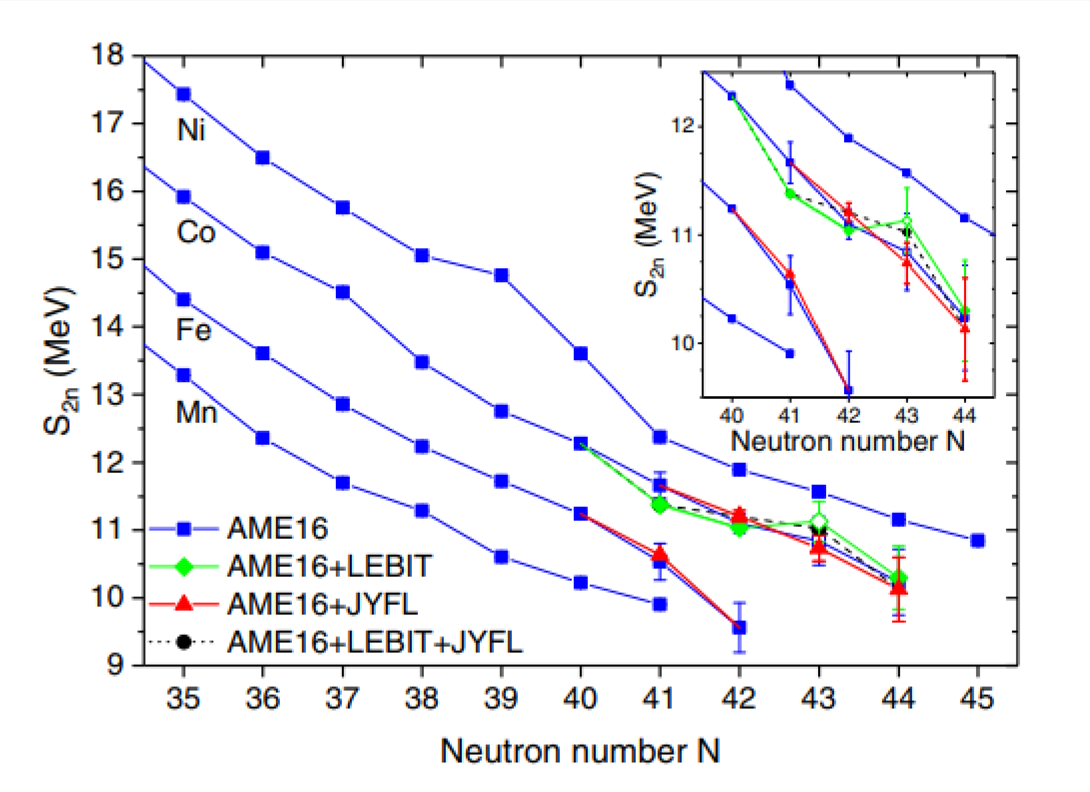


Unfortunately, there was no sign of another long-lived state at a statistically significant level.

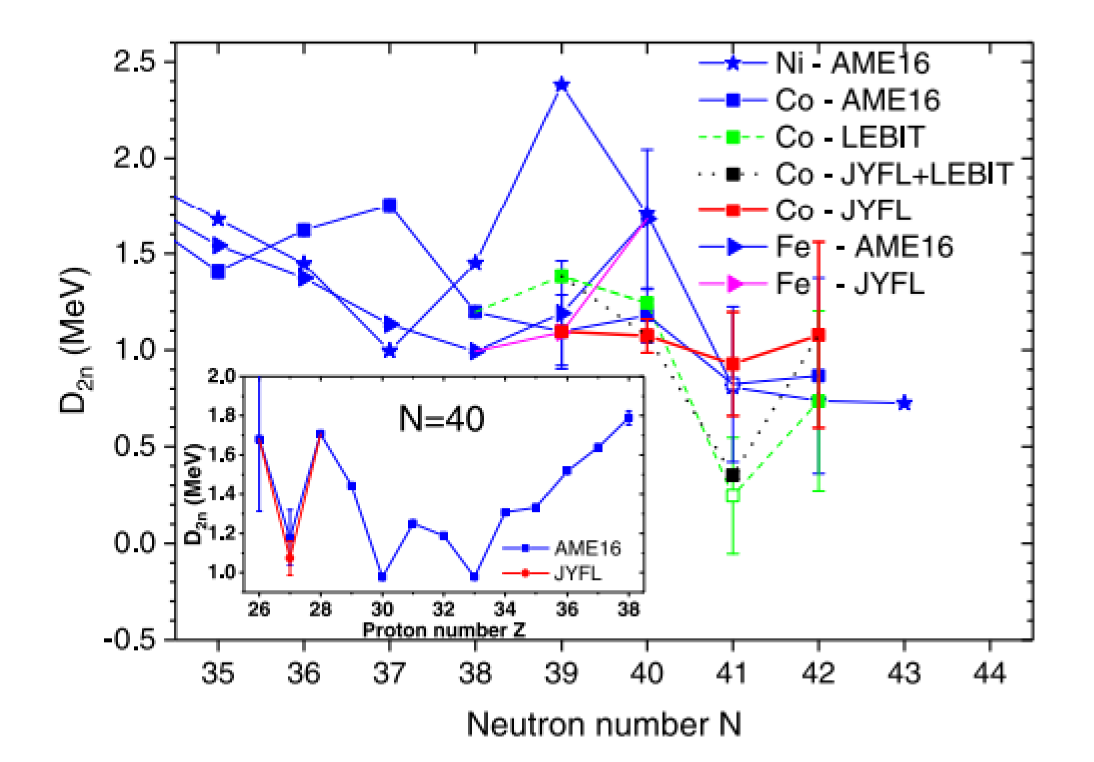


Δ=−46525(11) keV

N=40 subshell gap



The S_{2n} in the studied cobalt isotopic chain do not drop significantly after $N = 40$.



The D_{2n}energy, is about 0.7 MeV lower for $N = 40$ at ^{67}Co than at ^{68}Ni.

This is consistent with earlier spectroscopic studies and mass measurements of $^{58\text{-}63}Cr$ indicating increased collectivity below nickel.

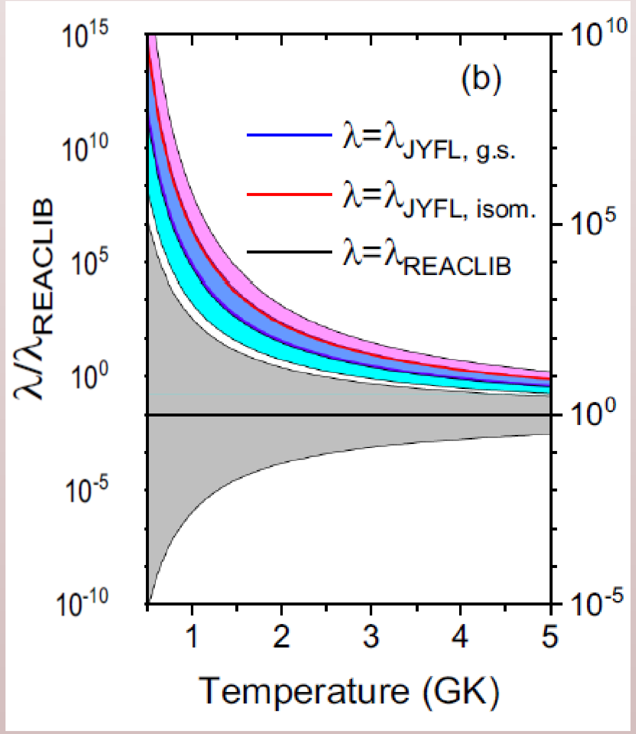
Neutron capture rates for the r-process

- ❖ Although mass values impact somewhat on the neutron capture rates the biggest impact of the reaction Q value is on the photodisintegration rate:

$$\lambda_{\gamma,n} \propto \exp\left(-Q_{n,\gamma}/kT\right)$$

❖ The photodisintegration rates calculated with the JYFLTRAP mass value for ^{69}Co are estimated to be around 7400 times higher than the REACLIB rates at 1 GK.

❖If the isomeric-state mass had been used for ^{69}Co the rate would be four times higher at 1.5 GK.



Summary

- We have performed the first precision mass measurements of ^{70}Co.

- The position of the (1/2−) proton intruder state in ^{69}Co was determined for the first time.

- The present data confirm that the $N = 40$ subshell closure gets weaker below nickel.

- No strong N = 40 subshell closure is observed below nickel, and the S2n values follow a smooth trend, favoring the spherical 7/2− orbital as the ground state also for ^{69}Co.

- The Q value for ^{68}Co(n, γ) ^{69}Co, $Q = 6.52(21)$ MeV is also much lower than the value used in REACLIB V1.0 $Q = 7.29(50)$ MeV. As a result, the new calculated photodissocation rate value is much higher.

Kiitos!

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