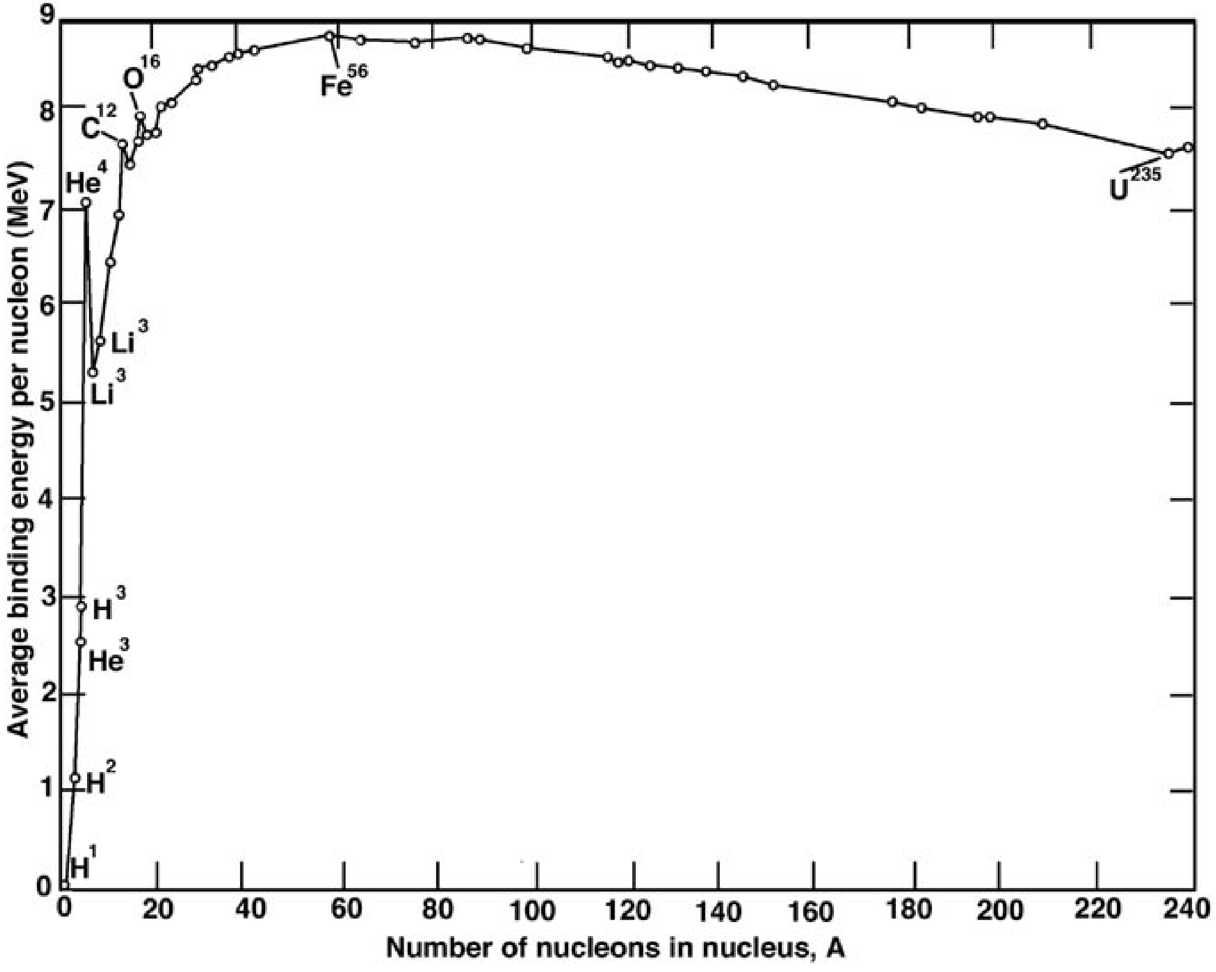
Neutron Binding Energy Measurements for a Direct Test of $E=mc^2$

Outline

- Framework of test
- Two crystal spectrometer
- Binding energy measurements
- Does $E=mc^2$?
- Towards 10^{-8} precision
- References
- Historical highlights of the program

Framework



Average binding energy per nucleon (MeV)
Number of nucleons in nucleus, A
0
1
2
3
4
5
6
7
8
9
0
20
40
60
80
100
120
140
160
180
200
220
240
H1
H2
He3
H3
Li3
Li3
He4
C12
O16
Fe56
U235

Framework

$$n + {}^{A}\mathsf{X} \rightarrow {}^{A+1}\mathsf{X} + \gamma\text{'s}$$

Framework

$$A_{\mathrm{r}}(\mathrm{n}) + A_{\mathrm{r}}({}^{A}\mathrm{X}) - A_{\mathrm{r}}({}^{A+1}\mathrm{X}) = \left\{10^{-3}\frac{N_{\mathrm{A}}h}{c}\right\}_{\mathrm{SI}} \left\{\frac{1}{\lambda^{*}_{A+1}}\right\}_{\mathrm{SI}}$$

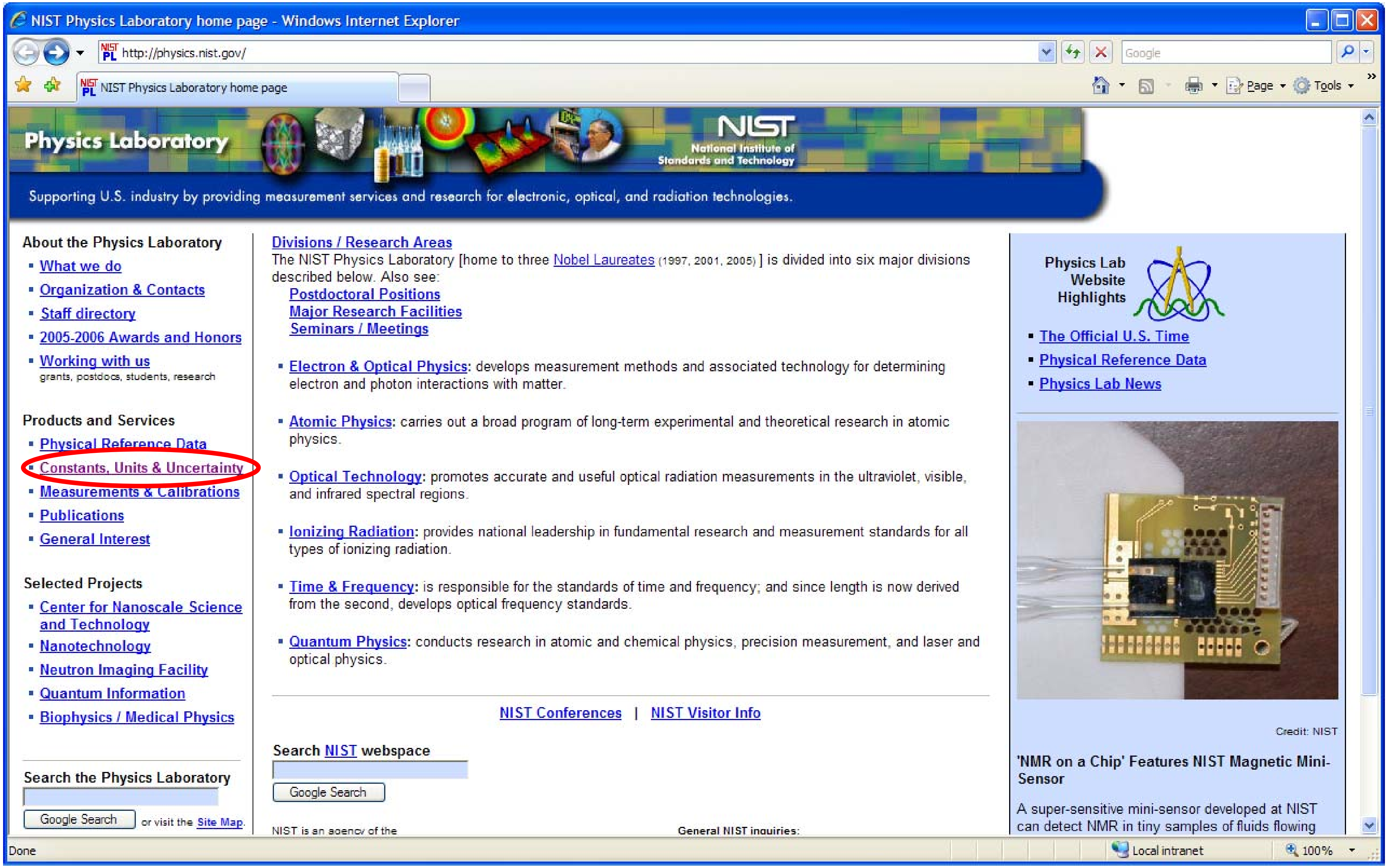
Framework

Penning trap ion mass measurement **(m)**

$$A_r(^{A+1}\mathrm{X}) + A_r(\mathrm{H}) - A_r(^{A}\mathrm{X}) - A_r(\mathrm{D}) = \left\{10^{-3}\frac{N_\mathrm{A}h}{c}\right\}_\mathrm{SI}\left\{\frac{1}{\lambda^*_\mathrm{D}} - \frac{1}{\lambda^*_{A+1}}\right\}_\mathrm{SI}$$

Molar Planck constant divided by c; $u_r = 1.4$ £ 10^{-9}

Gamma-ray measurements **(E)**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A super-sensitive mini-sensor developed at NIST can detect NMR in tiny samples of fluids flowing

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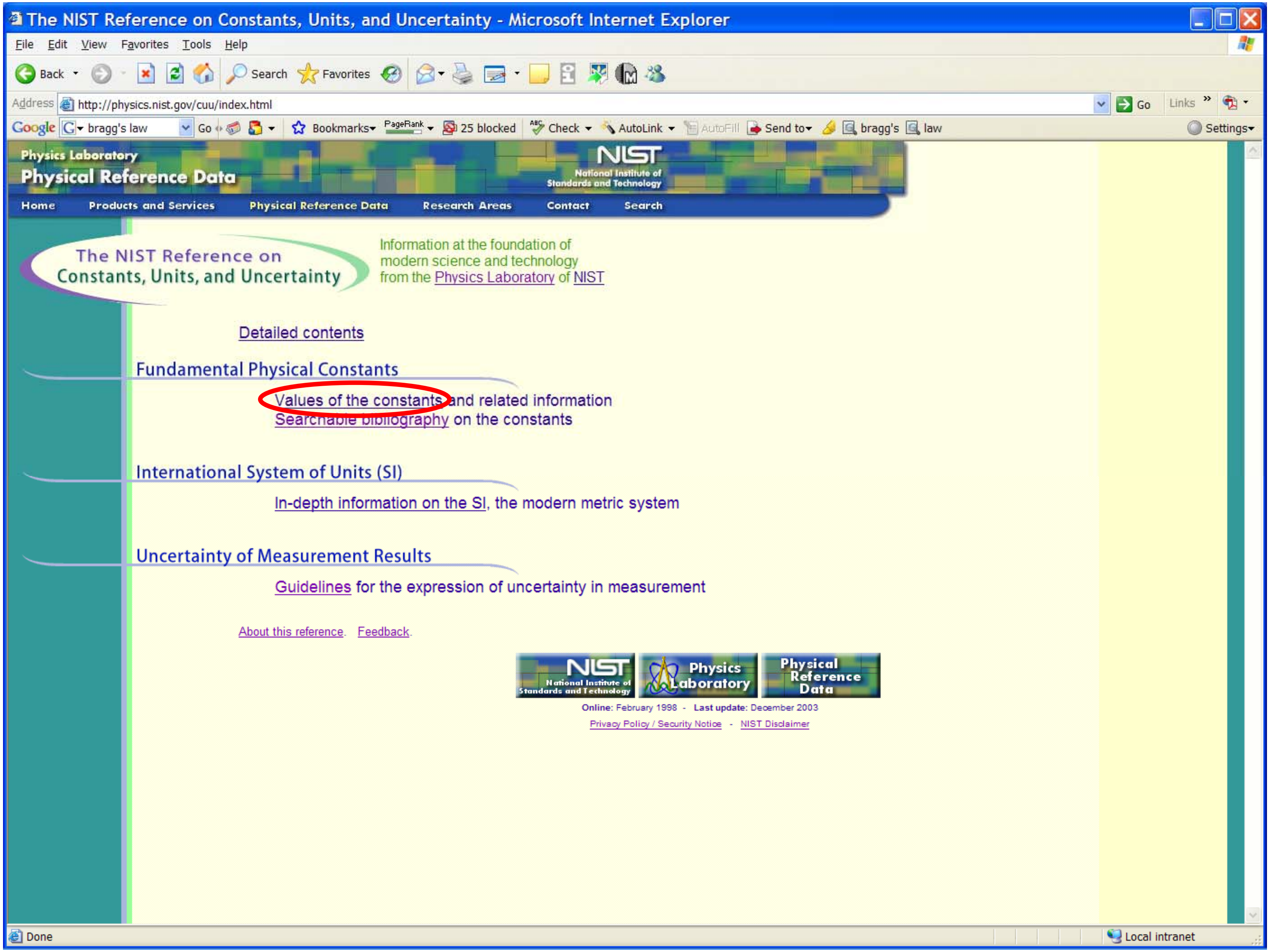
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CODATA Value: molar Planck constant - Windows Internet Explorer

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molar Planck constant

$N_A h$

Value	3.990 312 6821 x 10^{-10} J s mol^{-1}
Standard uncertainty	0.000 000 0057 x 10^{-10} J s mol^{-1}
Relative standard uncertainty	1.4 x 10^{-9}
Concise form	3.990 312 6821(57) x 10^{-10} J s mol^{-1}

Click here for **correlation coefficient** of this constant with other constants

Source: 2006 CODATA recommended values | Definition of uncertainty | Correlation coefficient with any other constant

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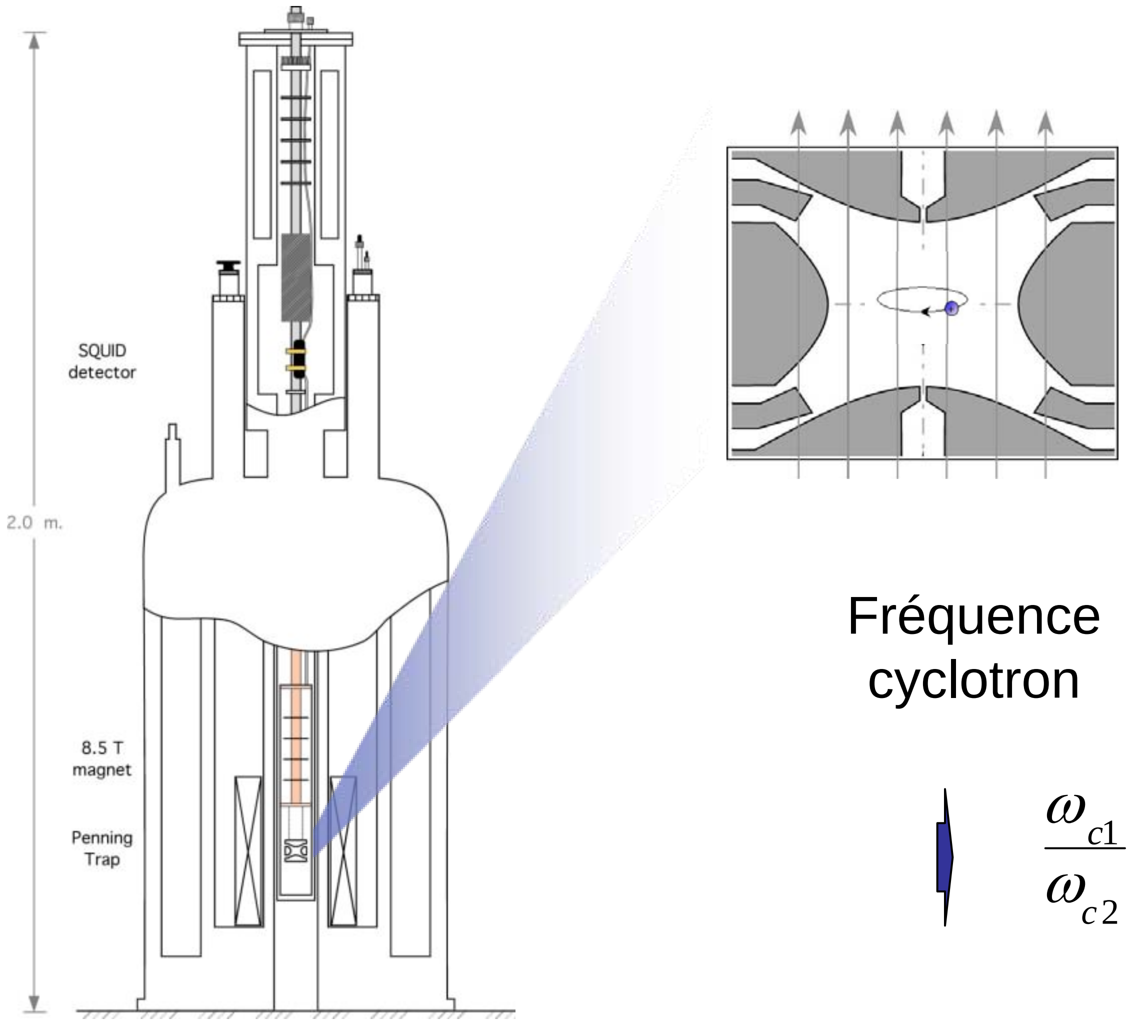
Piège de Penning



Fréquence cyclotron $\omega_c = \dfrac{qB}{m}$

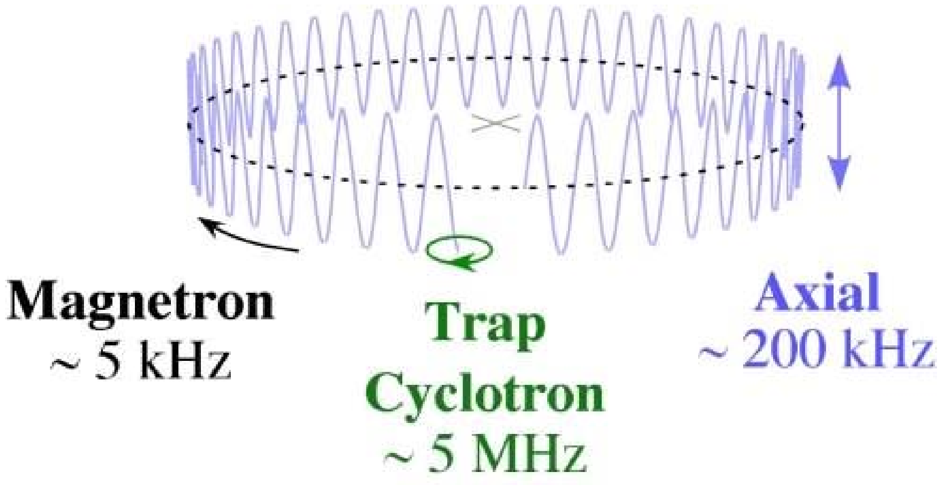
(5 MHz)

$$\Rightarrow \quad \frac{\omega_{c1}}{\omega_{c2}} = \frac{q_1}{q_2}\frac{m_2}{m_1}$$

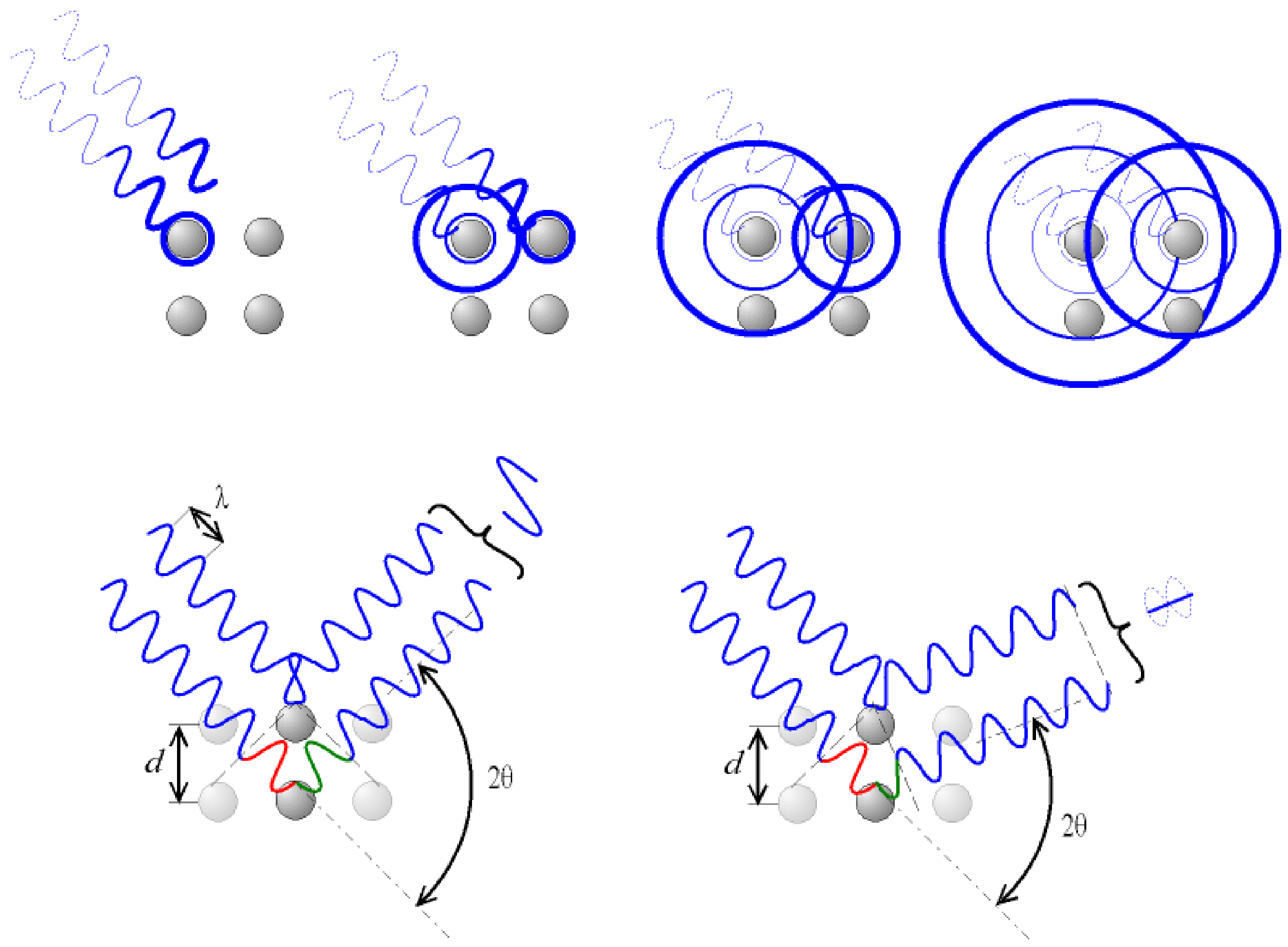
Exemples de résultat

$$\frac{m\left[{}^{33}S^{+}\right]}{m\left[H\,{}^{32}S^{+}\right]} = 0.999\;744\;164\;347\;(16) \qquad (1.6 \times 10^{-11})$$

$$\frac{m\left[{}^{29}Si^{+}\right]}{m\left[H\,{}^{28}Si^{+}\right]} = 0.999\;715\;124\;181\;3\;(67) \qquad (6.7 \times 10^{-12})$$



Wavelength Determination Principle



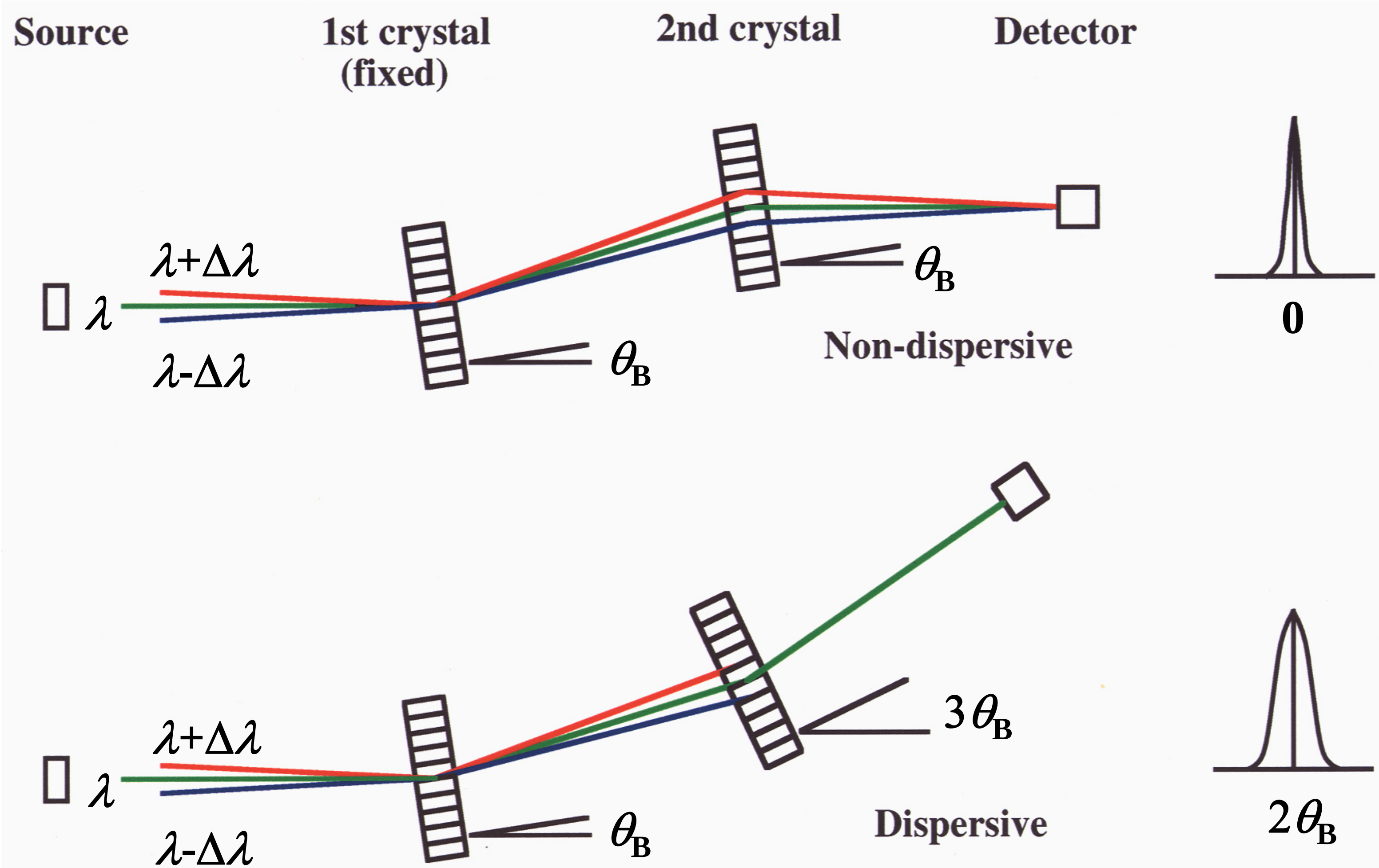
Wavelength Determination Principle

$$n\lambda = 2d\sin\theta_n$$

$$\frac{\Delta\lambda}{\lambda} \approx \sqrt{\left(\frac{\Delta d}{d}\right)^2 + \left(\frac{\Delta\theta_n}{\theta_n}\right)^2}$$

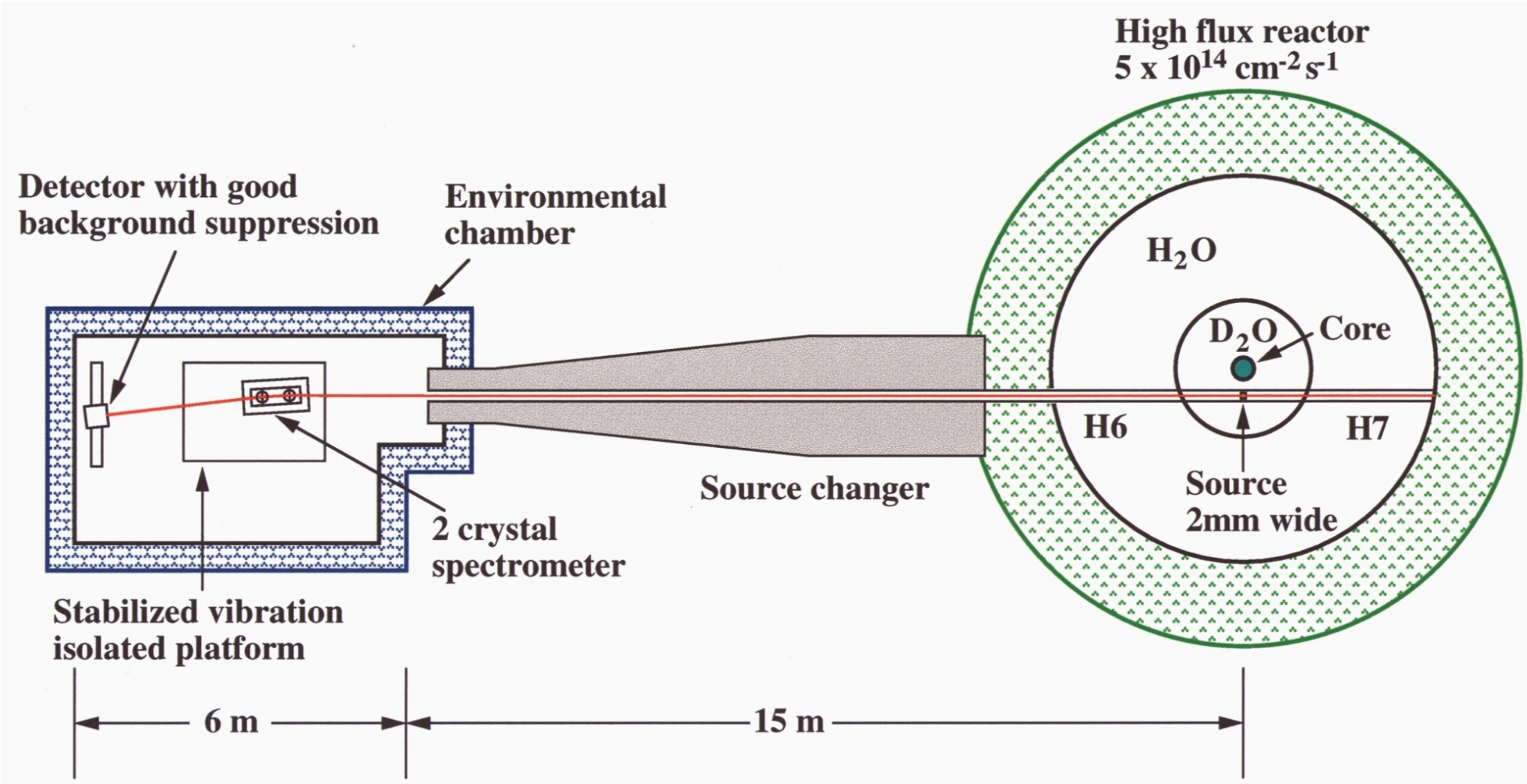
$$\frac{\Delta d}{d} \approx 5 \times 10^{-8} \qquad \frac{\Delta\theta_n}{\theta_n} \approx ?$$

Two Crystal Geometry

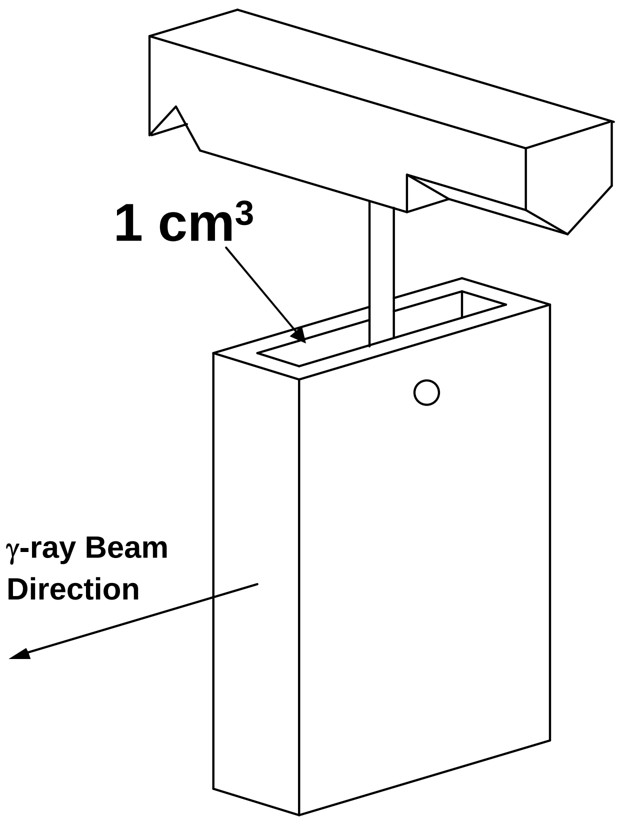


Grenoble - the scientific centers, ILL, and ESRF, together with Belledonne

NIST-ILL Gamma-ray Facility



Gamma-ray Sources



Activity depends upon:

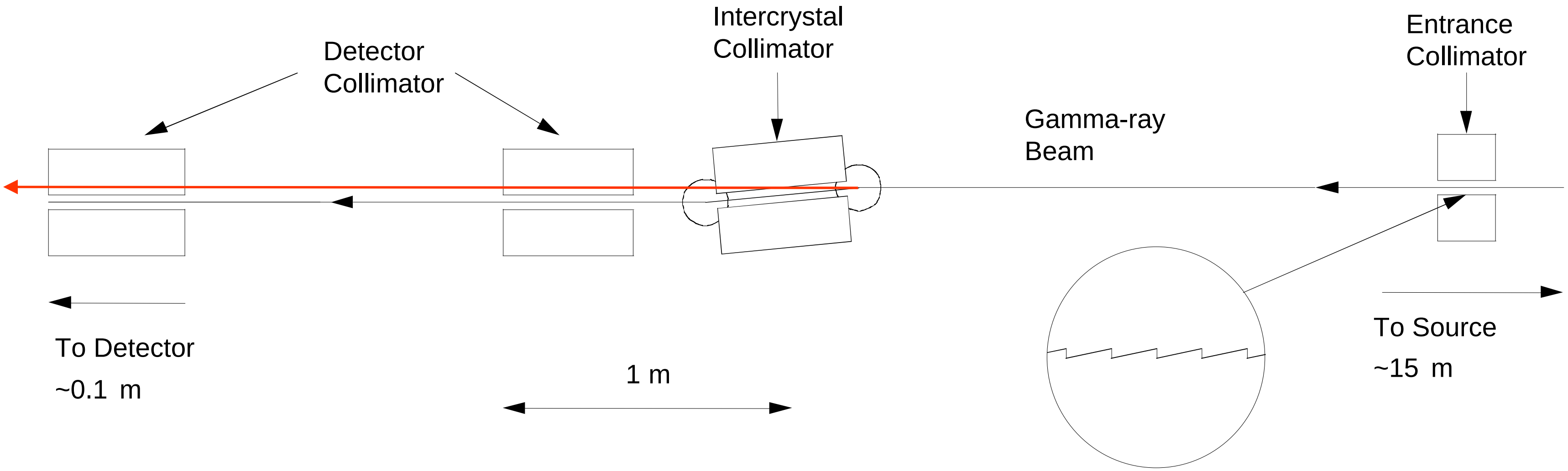
- Neutron flux
- Capture cross section
- Density of source material

Typical total activities:

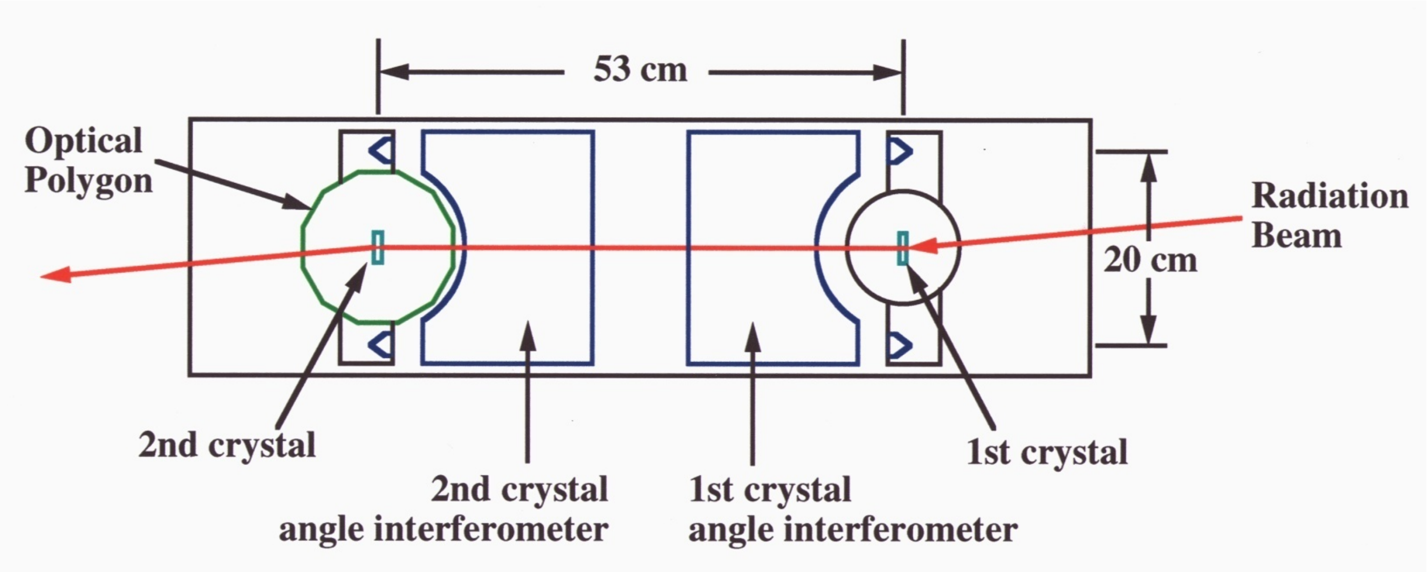
10^{13}-10^{15} Bq (s^{-1})

kilo-curies

Collimation

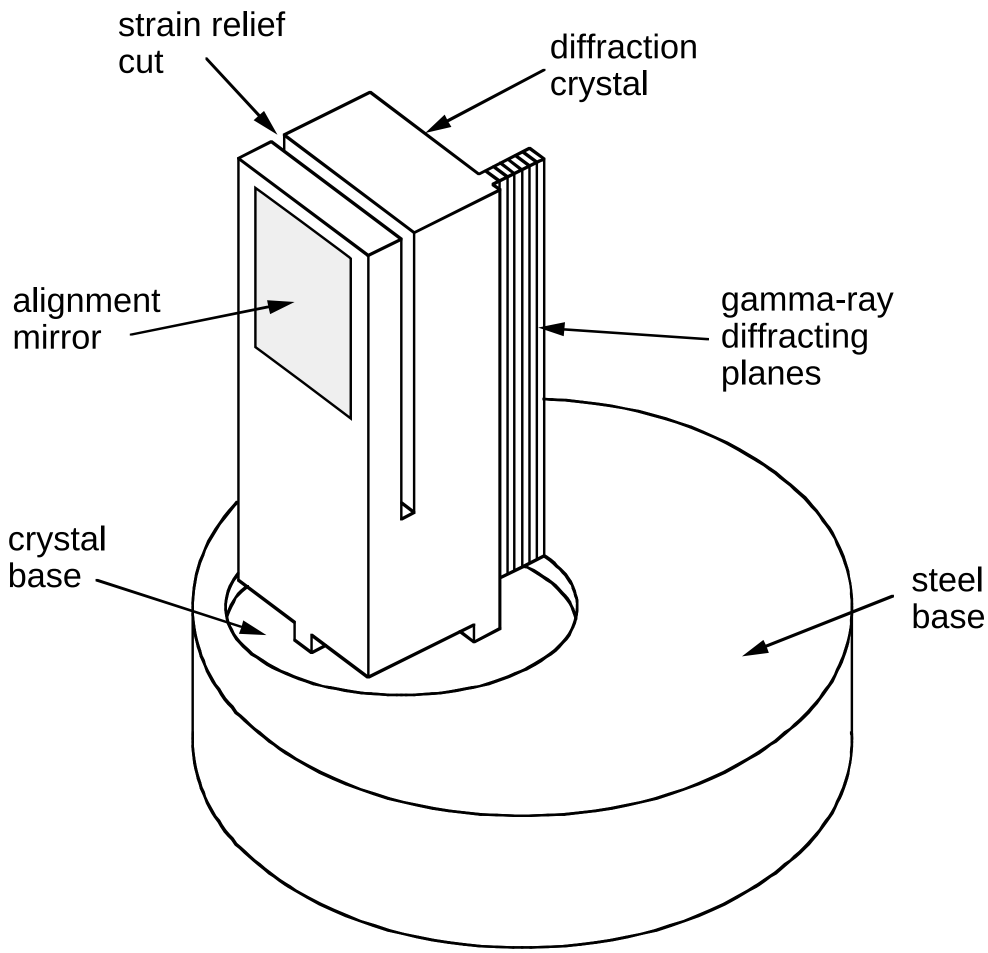


Two Crystal Spectrometer

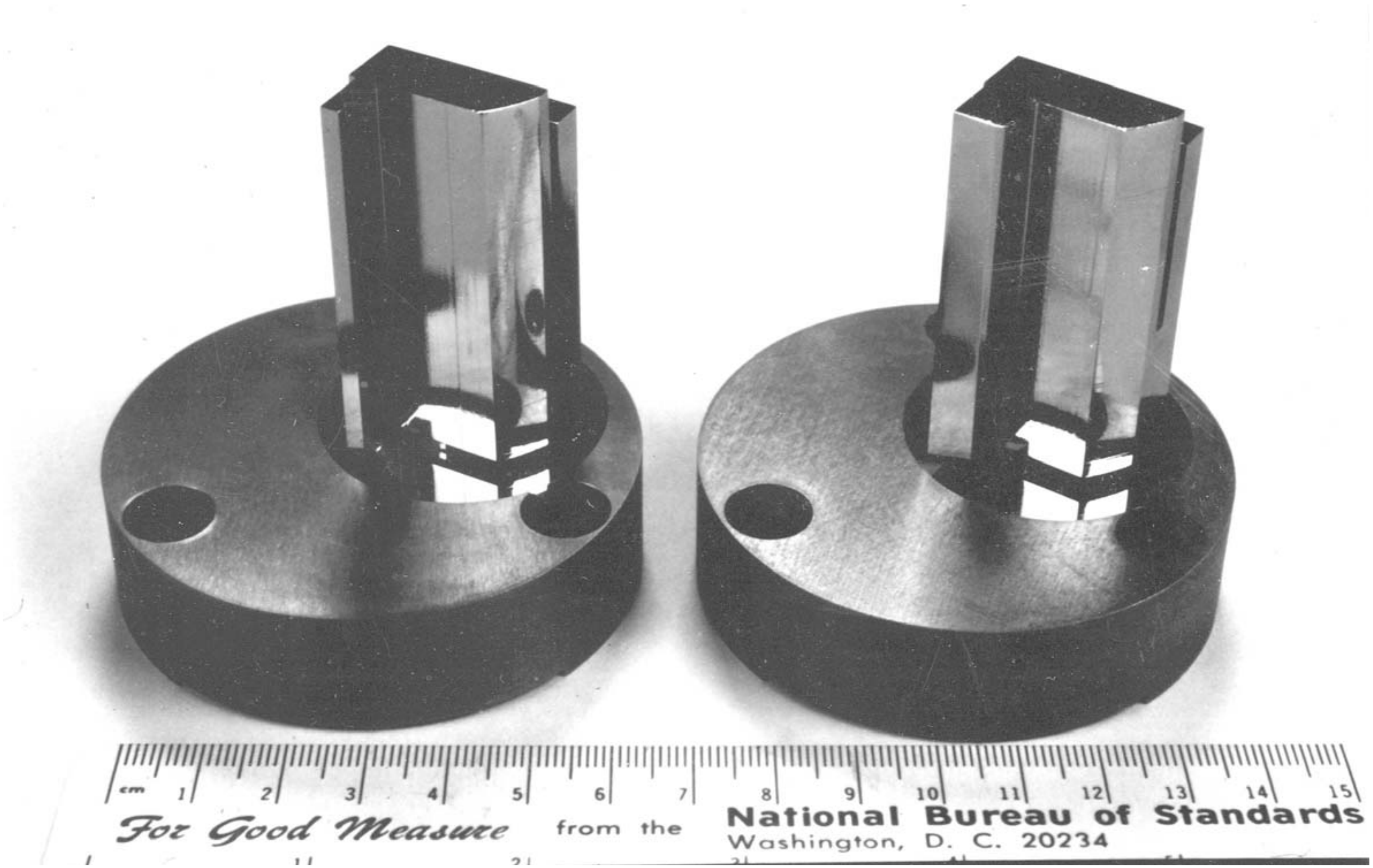


- Radiation beam
- Crystals
- Angle interferometers
- Optical polygon (angle calibration)

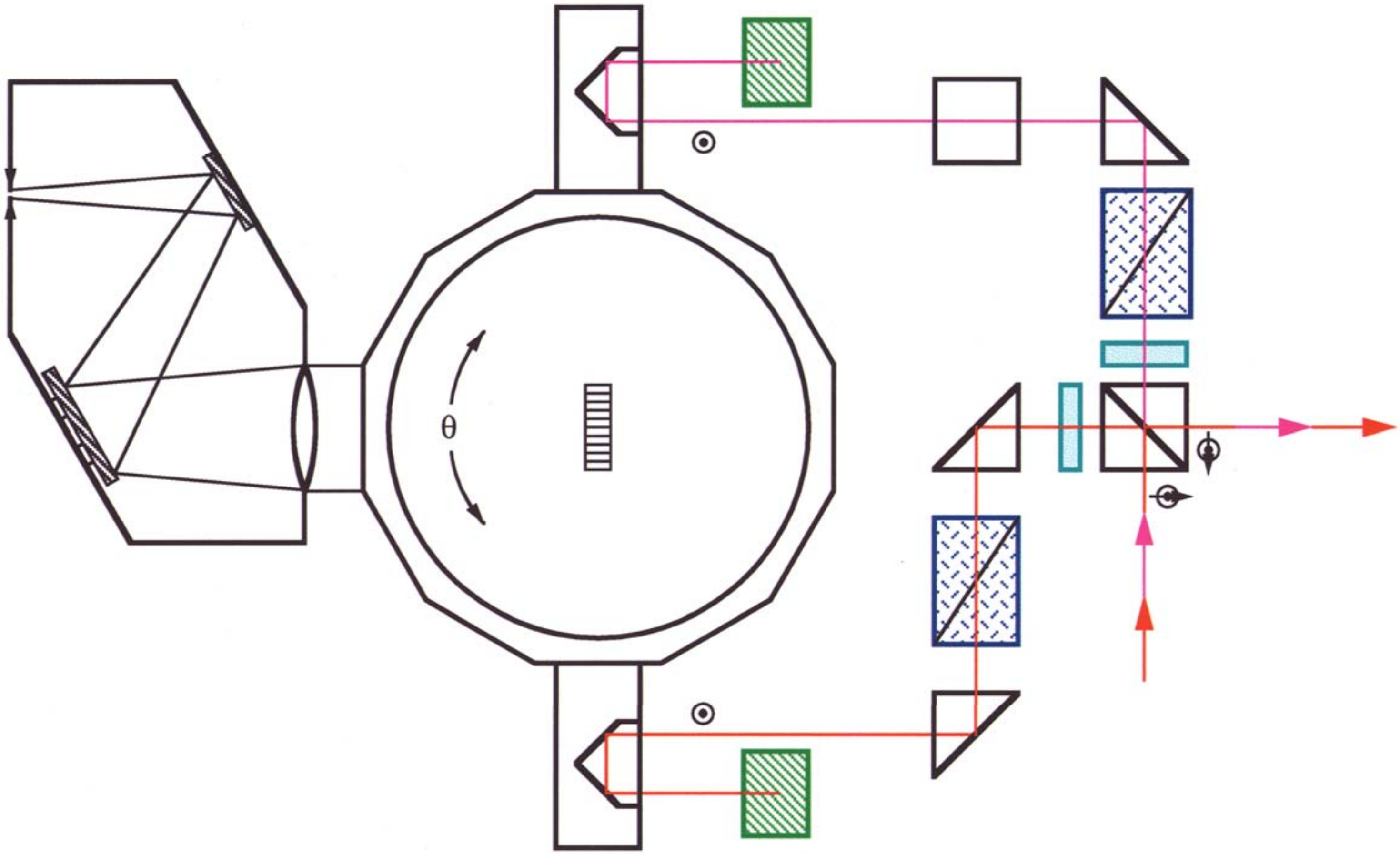
GAMS4 Diffraction Crystal



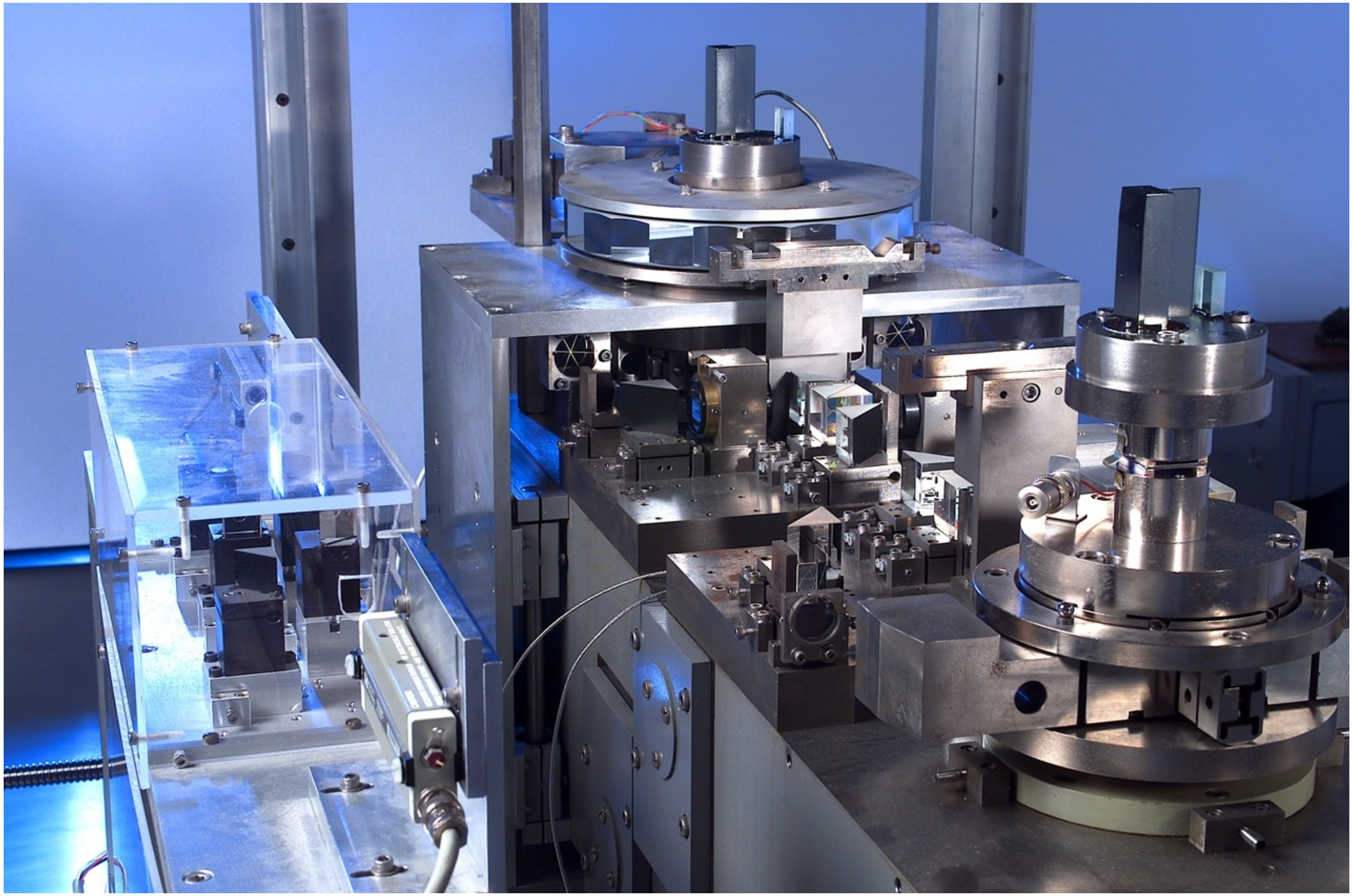
GAMS4 Diffraction Crystals



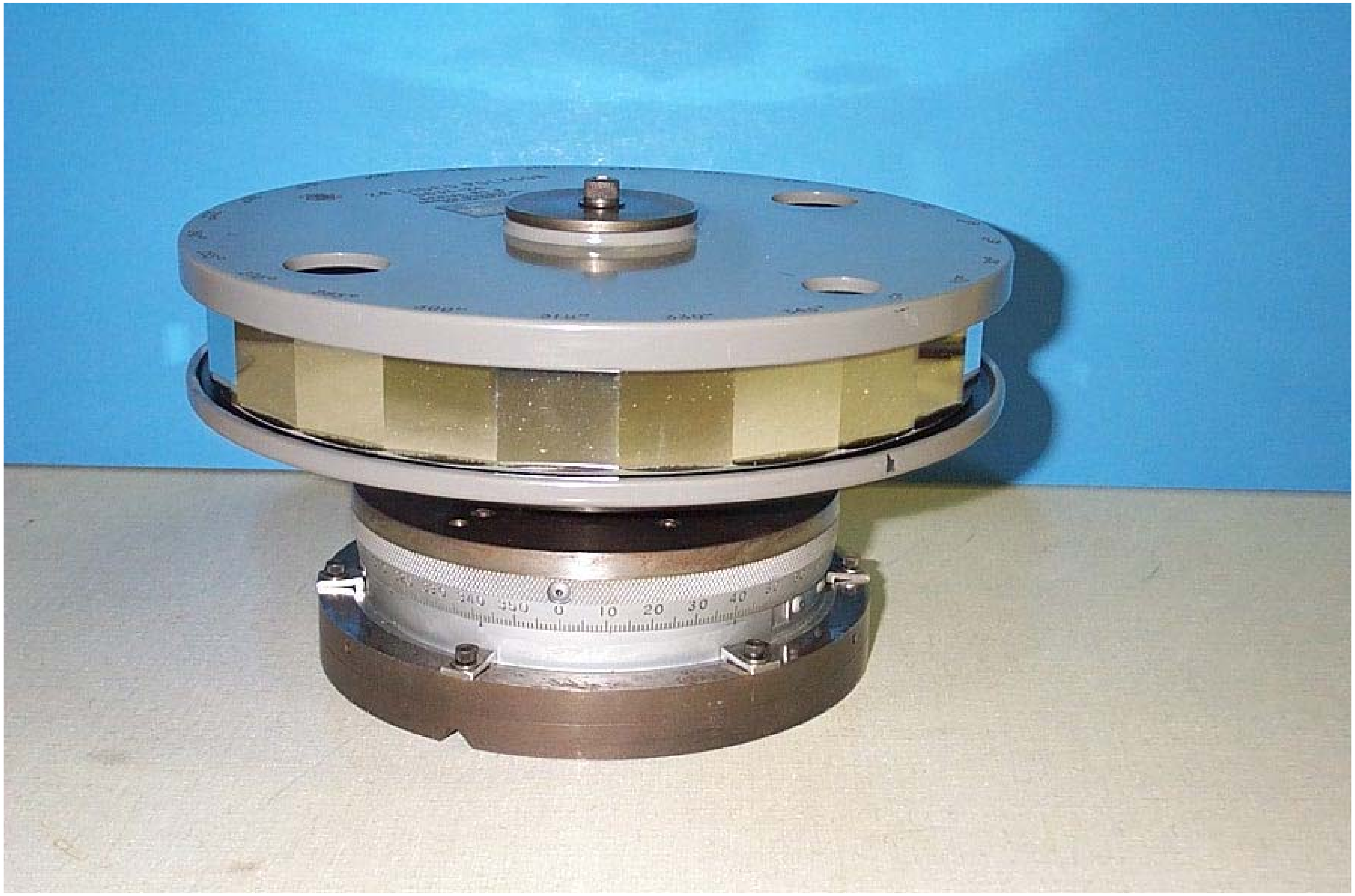
Angle Interferometer And Polygon



GAMS4 Spectrometer



Interferometer Calibration

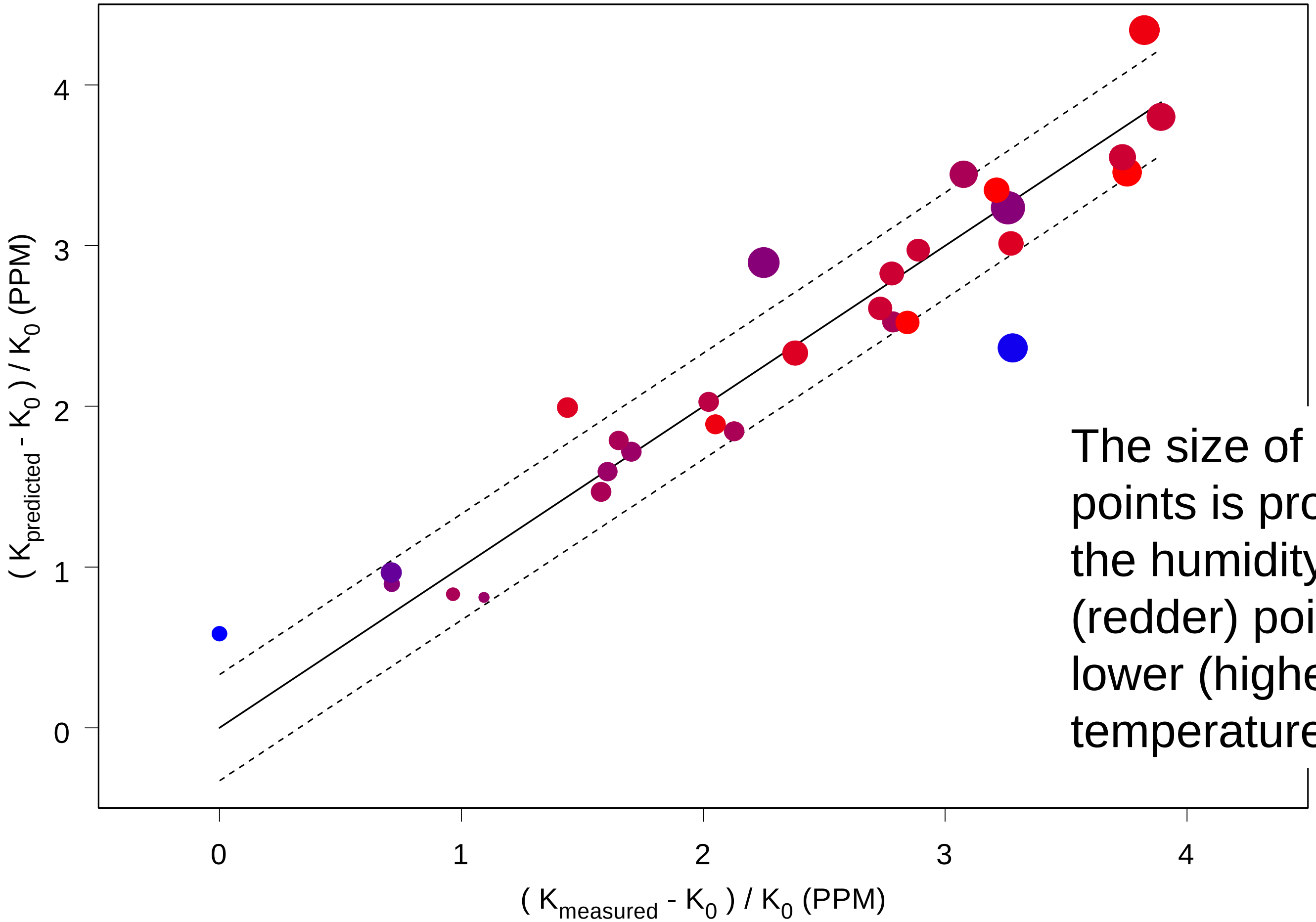


Interferometer Calibration

$$f = K \sin\theta + f_0$$

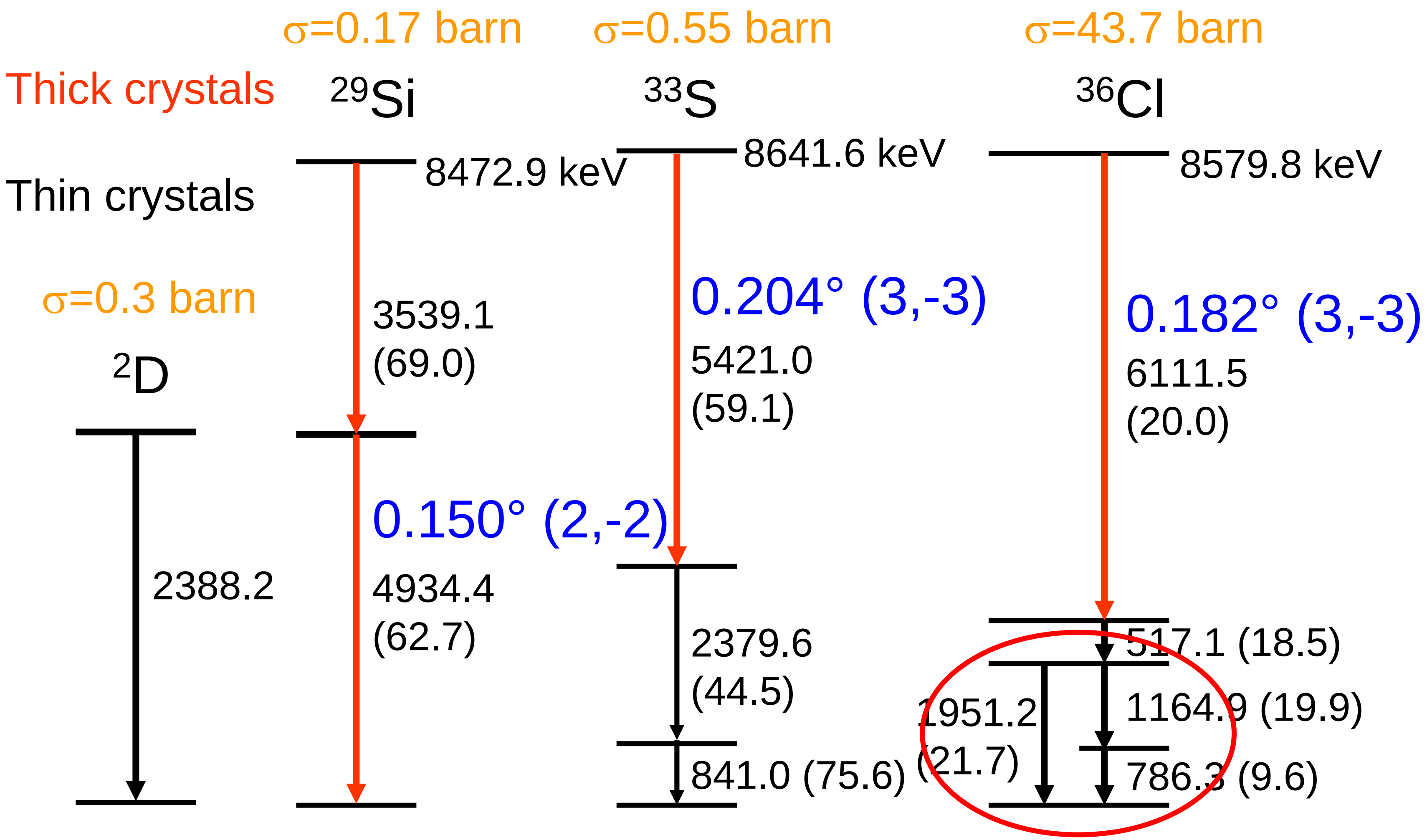
$$360^\circ = \sum_{i=1}^{24} \arcsin\left\{\frac{f_{i+1} - f_0}{K}\right\} - \arcsin\left\{\frac{f_i - f_0}{K}\right\}$$

GAMS4 Calibration Fit

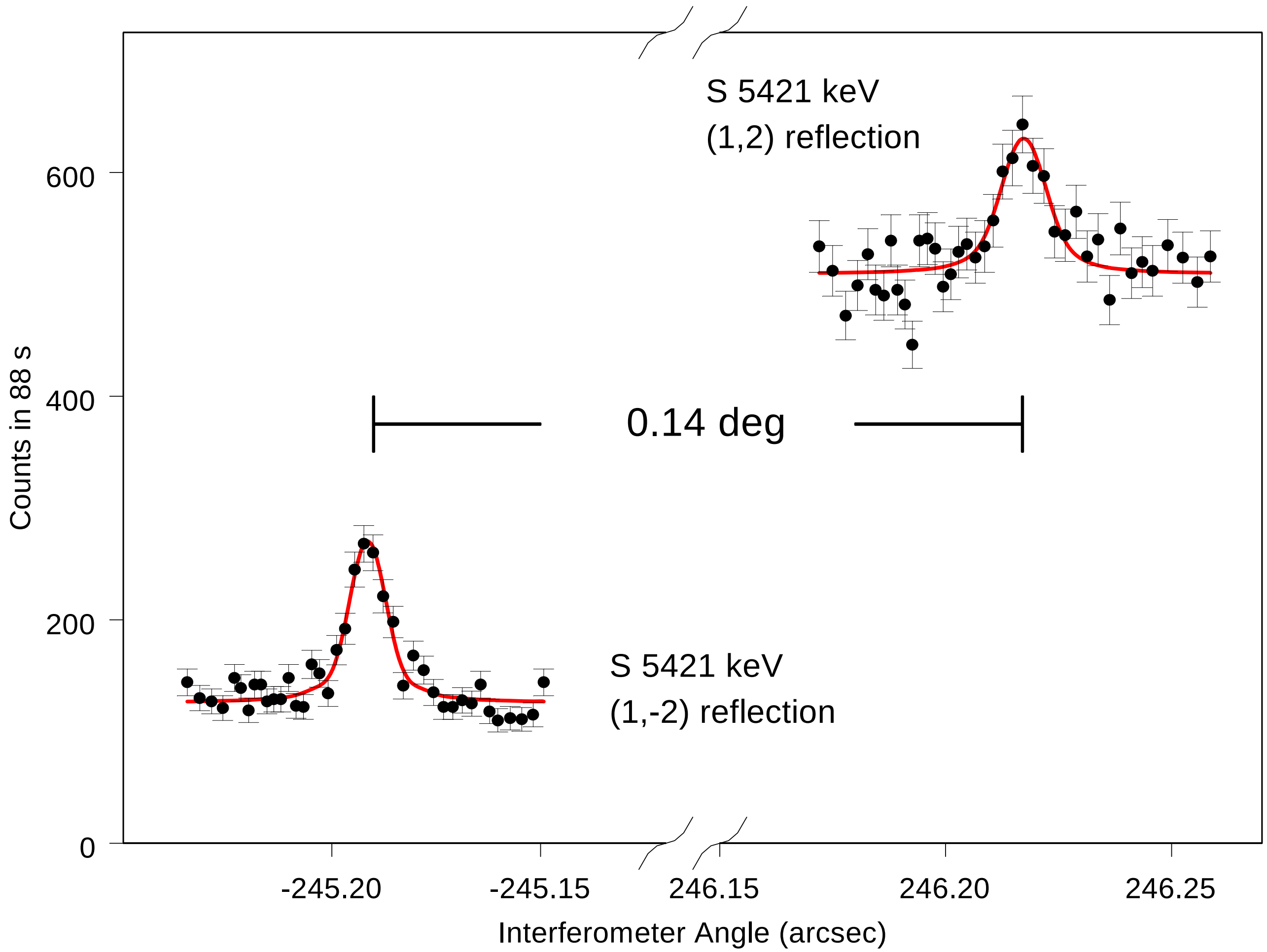


The size of the plotted points is proportional to the humidity; bluer (redder) points represent lower (higher) temperatures.

Binding Energy Measurements



Representative ^{33}S Profiles



Binding Energy Results

Nuclide	λ_{be}£10^{12} *(m)*	S_n £ 10^3 *(u)*	u_r £ 10^6 *total*
^{29}Si	0.146318275(86)	9.0967793(53)	0.59
^{33}S	0.143472991(54)	9.2771820(35)	0.38
^{36}Cl	0.144507180(80)	9.2107883(51)	0.55
^{2}H	0.557341007(98)	2.38816996(42)	0.18

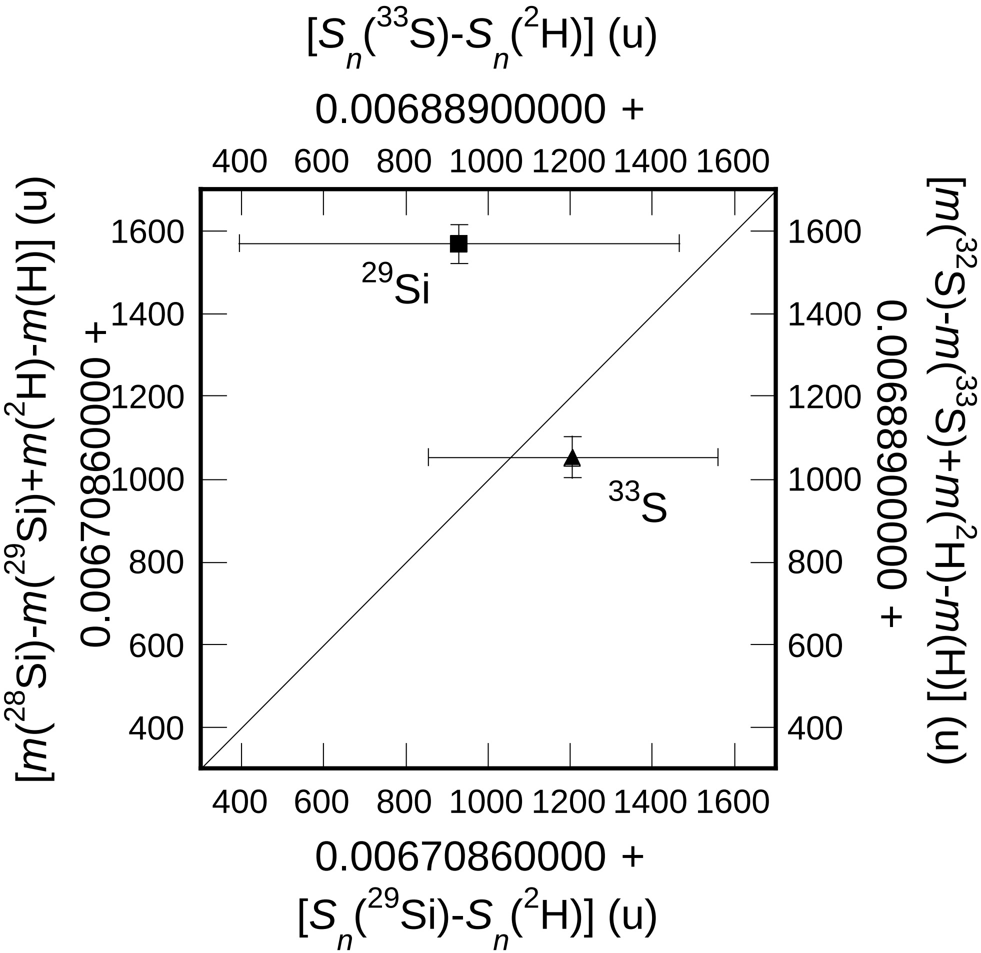
Uncertainty Sources

Source	*Relative* σ *£* 10^{6}	*Comments*
statistics	~0.4	two weeks measuring time
calibration	0.4	interferometer instability
crystal temperature	0.1	$\Delta T_{crystal}$ = 0.05° K
vertical divergence	0.06	§5 mm over 15 m; γ-beam vs. plane of dispersion
crystal lattice spacing	0.05	conservative figure

Mass-Energy Comparison

^{A+1}X	*Δm from Penning trap (u)*	*Δm from GAMS4 (u)*	*Rel. Diff. £ 10^7*
^{29}Si	0.00670861569(47)	0.00670860929(536)	-9.5(8.0)
^{33}S	0.00688901053(50)	0.00688901206(351)	2.2(5.1)
weighted average relative difference			-1.2(4.3)

Mass Difference Comparison



Special Relativity Test

$$\frac{E - \Delta mc^2}{E} = (-1.2 \pm 4.3) \times 10^{-7}$$

- The most precise direct test of $E = mc^2$
- This result is 55 times more accurate than the previous best direct test performed by comparing the electron and positron masses to the energy released in their annihilation
- Doesn't require the assumption of the existence of a preferred frame of reference in order to place constraints on proposed Lorentz-violating parameters

Towards 10^{-8} precision

- **Statistics:** longer measuring times, greater source density, reduce spectrometer drift, concentrate on sulfur and chlorine and radioactive isotopes
- **Calibration:** redesign interferometer, remove non-linearities, reduce sensitivity to environment
- **Crystal temperature:** more sensors on crystal, 3-4 mK absolute accuracy required
- **Vertical divergence:** need to rethink the way the beam and spectrometer are aligned with respect to each other
- **Crystal lattice spacing:** 10^{-8} precision possible

Progress on the GAMS-6 Double Crystal γ-Spectrometer

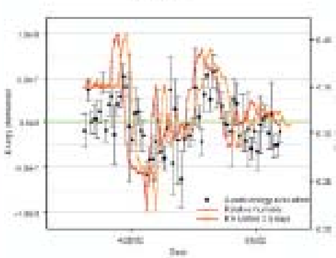
J. Krempel[1,2], M. Jentschel[1], P. Mutti[1], G. Mana[3], B. Lauss[4], P. Becker[2]

[1]Institut Laue-Langevin, Grenoble (F), [2]Physikalisch-Technische Bundesanstalt, Braunschweig (D), [3]Istituto Nazionale di Ricerca Metrologica, Torino (I), [4]Paul Scherrer Institut, 5232 Villingen (CH)

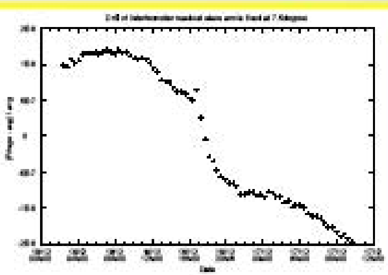
Performance

		Radian	Degree	ArcSec	Fringes
Interferometer properties	1 Fringe	633×10^{-9}	36×10^{-6}	0.13	1
	360°	6.3	360	1.3×10^{6}	9.9×10^{6}
	1"	4.8×10^{-6}	$0.3\ 10^{-3}$	1	7.7
Smallest Angle (interesting energy)	0.2°	3.5×10^{-3}	0.2	720	5500
Accuracy	1/14000 F	45×10^{-12}	2.6×10^{-9}	9.3×10^{-6}	7.1×10^{-5}
Resolution limit (by electronics)	1/36000 F	$18\ 10^{-12}$	$1\ 10^{-9}$	$3.6\ 10^{-6}$	$2.8\ 10^{-5}$

Drift



Drift of the old GAMS 4 interferometer at ILL due to a humidity sensitive glue

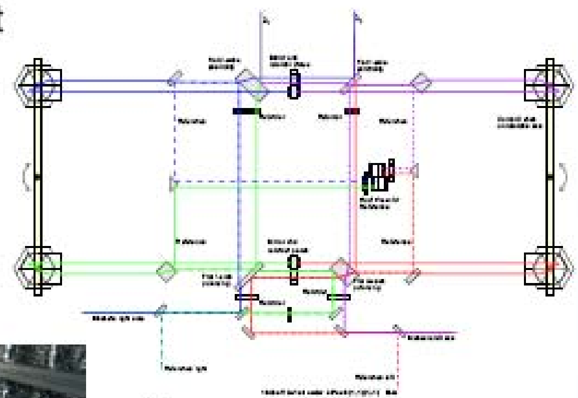


Drift of the old GAMS 4 interferometer.
Here the interferometer arm was fixed to 7.5° by the calibration unit. Despite the large drift of 10^{-4}° it is possible to obtain a calibration constant with an uncertainty of 10^{-7} as only the drift over 30 minutes (one calibration step) is important.
Thus, reducing the interferometer instability, as well as reducing the calibration/acquisition time will improve the result.

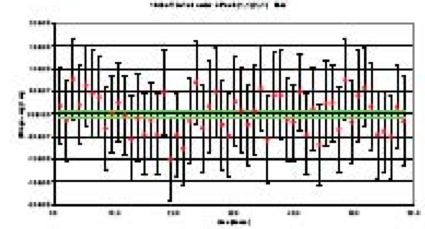
New Interferometer Layout

Main features:

- 2 axes in 1 interferometer: no longer drifts between two interferometers
- Compensating effects: elements are used twice. If they drift, the overall result stays constant.
- Spatial separation of beams, no frequency mixing – avoids non-linearity



The working prototype of the interferometer on GAMS5 at ILL



Stability test of the new interferometer:
A 182keV was measured in (1,1) and (1,-1) Crystal order the angle difference varies not much over time, although there is no correction for temperature, pressure or humidity at all. The fit error for each point is about 4.6×10^{-7}. The standard deviation of all points is 4.2×10^{-7}. Thus the 54 points yield a total relative uncertainty of 6×10^{-8}.

Historical Highlights

- **1969** the first combined x-ray and optical interferometer (XROI) is realized at the NBS by Deslattes and collaborators
- **1973** "*X-Ray to Visible Wavelength Ratios*" links the optical "standard" to x-ray transition wavelengths for the first time
- **1978** a double crystal spectrometer is used at NBS to measure reactor-produced, non-prompt Au and Ir gamma-ray reference lines (675 keV maximum energy)

Historical Highlights

- **1982** spectrometer moves to ILL in search of prompt lines having higher energies
- **1984** instrument "aiming" difficulties lead to a major upgrade that includes a new platform, position and vibration stabilization, and new collimators
- **1986-present** GAMS4 becomes a scheduled ILL instrument used to measure binding energies, reference lines, lifetimes of nuclear excited states in the sub-picosecond range, and interatomic potentials in the 10 eV to 100 eV range
- **1998** GAMS5 becomes operational

Useful References

- The deuteron binding energy and the neutron mass
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- Precision measurement of fundamental constants using GAMS4
  - Dewey, M. S. *et al. J. Res. Natl. Inst. Stand. Technol.* **105,** 11-23 (2000).
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- Precision measurement of the ^{29}Si, ^{33}S, and ^{36}Cl binding energies
  - Dewey, M. S. *et al. Phys. Rev. C* **73**, 044303-1 - 044303-11 (2006).
- A direct test of $E=mc^2$
  - Thompson, J. K. *et al. Nature* **430**, 58-61 (2005).