SANE:
Spin Asymmetries on the Nucleon Experiment

Accessing the Nucleon Spin Structure

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Lepton Scattering

How Scattering Provides Insight into Systems

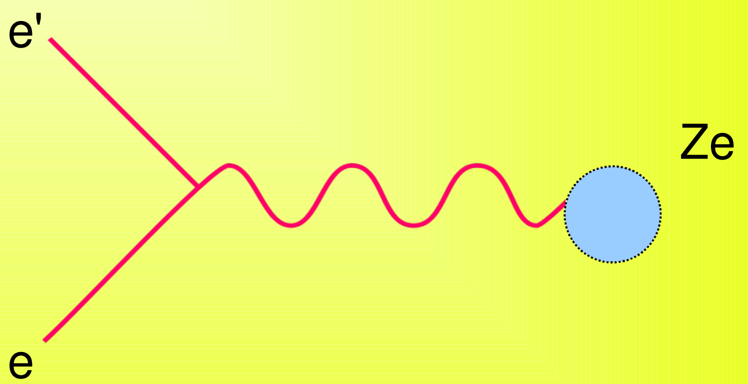
$\frac{d\sigma}{d\Omega}$ Differential Cross-section—essentially probability of interaction for different energies, angles, etc. of scattering

Example: Rutherford Scattering: scattering point-like (non-Dirac) from an infinitely massive charged point like particle

$$\frac{d\sigma}{d\Omega}_{Rutherford} = \frac{Z^2 e^4}{4E_0^2 \sin^4(\theta/2)}$$

Example: Mott scattering is as above, but for Dirac particle—good approximation for an electron scattering off a nucleus.

$$\frac{d\sigma}{d\Omega}_{Mott} = \frac{Z^2 e^4}{4E_0^2 \sin^4(\theta/2)} \cos^2(\theta/2)$$

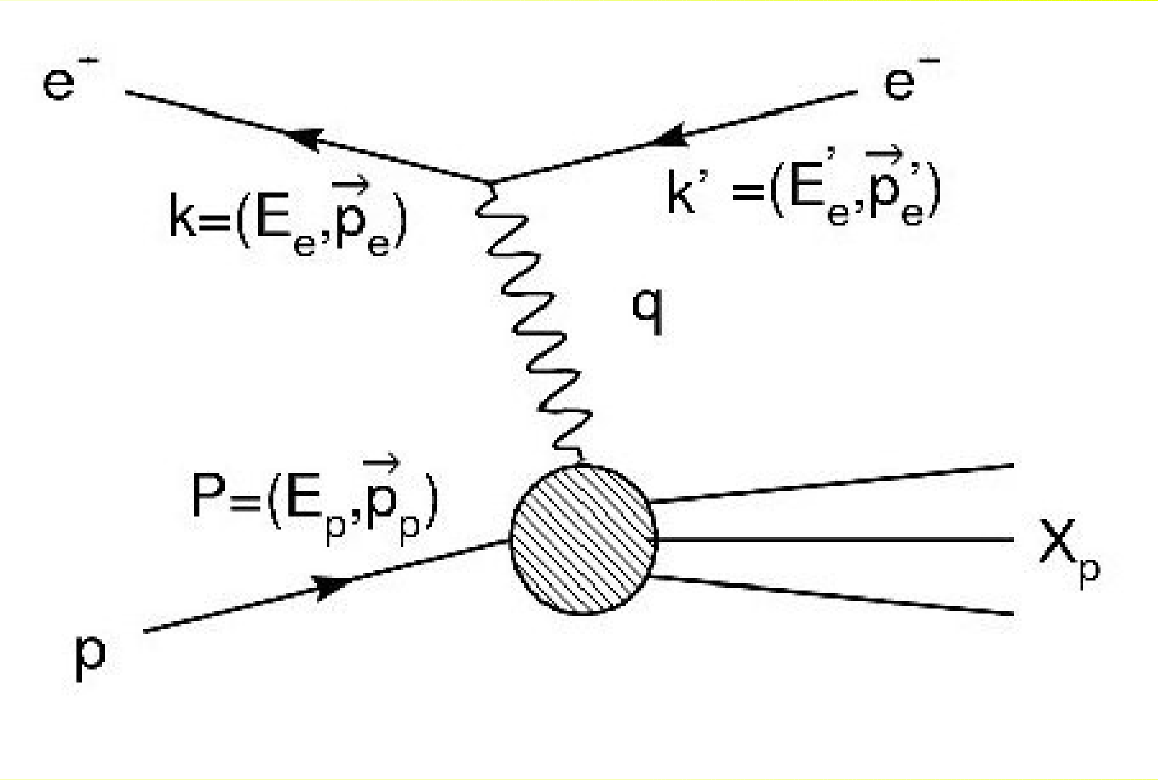


Scattering of an Electron From a Hadron

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{2MQ^4}\frac{E'}{E}L_{\mu\nu}W^{\mu\nu}$$

Some variables

- k, the incoming electron 4 momentum
- k', the outgoing electron 4 momentum
- q, the virtual photon momentum transferred to the nucleus
- P, the hadron's initial 4 momentum



Also... $Q^2 = -q^2$ and $\nu = E_e - E_e'$

The Leptonic Current Tensor

$$L_{\mu\nu} = 2\left(L^{(S)}_{\mu\nu} + i L^{(A)}_{\mu\nu}\right)$$

no spin

$$L^{(S)}_{\mu\nu} = k_\mu k'_\nu + k'_\mu k_\nu - g_{\mu\nu}\left(k\cdot k' - m^2\right)$$

$$L^{(A)}_{\mu\nu} = m\,\epsilon_{\mu\nu\alpha\beta}\, s^\alpha (k - k')^\beta$$

spin!

no mystery here...just kinematic variables (we'll detect the scattered electron)

Hadronic Tensor...all the mystery's here

$$W^{\mu\nu} = W^{(S)\mu\nu} + i W^{(A)\mu\nu}$$

$$\frac{1}{2\mathrm{M}} W^{(S)\mu\nu} = \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) W_1(\nu, Q^2)$$

$$+\left(P_\mu - \frac{P\cdot q}{q^2} q_\mu\right)\left(P_\nu - \frac{P\cdot q}{q^2} q_\nu\right) \frac{W_2(\nu, Q^2)}{M^2}$$

$$\frac{1}{2\mathrm{M}} W^{(A)\mu\nu} = \epsilon_{\mu\nu\alpha\beta} q^\alpha \left\{ M S^\beta G_1(\nu, Q^2) + [P\cdot q\, S^\beta - S\cdot q\, P^\beta] \frac{G_2(\nu, Q^2)}{M} \right\}$$

spin!

Although complicated, all we are saying is that we are stuffing all the unknown interactions into the W's and G's.

The Symmetric Terms

If one averages over the initial spins and sum over the final spin states, one obtains a cross section that depends only on the symmetric terms...

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{2MQ^4}\frac{E'}{E}L_{\mu\nu}^{(S)}W^{\mu\nu(S)}$$

$$= \sigma_{Mott}\left[2W_1(\nu, Q^2)\tan^2(\theta/2) + W_2(\nu, Q^2)\right]$$

W_1 and W_2 show us how the scattering process differs from Mott scattering.

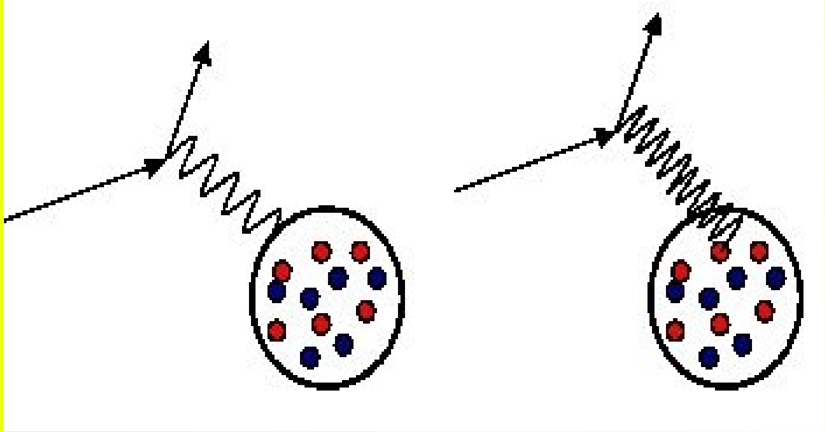
The Anti-Symmetric Terms
or
Enter the Spin Structure Functions

The cross sections for scattering with the target hadron's spin parallel to the electron and with the target hadron's spin in the scattering plane and perpendicular to the electron spin involve only the anti-symmetric terms.

$$\frac{d^2\sigma_{\parallel}}{d\Omega dE'} = 4\sigma_{Mott}\tan^2(\theta/2)\left[(E+E'\cos(\theta))MG_1 - Q^2G_2\right]$$

$$\frac{d^2\sigma_{\perp}}{d\Omega dE'} = 4\sigma_{Mott}\tan^2(\theta/2)E'\sin(\theta)(MG_1 + 2\mathrm{E}\mathrm{G}_2)$$

Bjorken Scaling and The Structure Functions' Limit



Higher Q^2 means a smaller wavelength, which means better resolution. At a high enough energy loss in DIS, one is scattering elastically off of <u>free</u> quarks.

Bjorken Limit

$$Q^2 \rightarrow \infty \qquad \nu^2 \rightarrow \infty$$

$$M W_1(\nu, Q^2) \rightarrow F_1(x) \qquad \nu M^2 G_1(\nu, Q^2) \rightarrow g_1(x)$$

$$\nu W_2(\nu, Q^2) \rightarrow F_2(x) \qquad \nu^2 M G_2(\nu, Q^2) \rightarrow g_2(x)$$

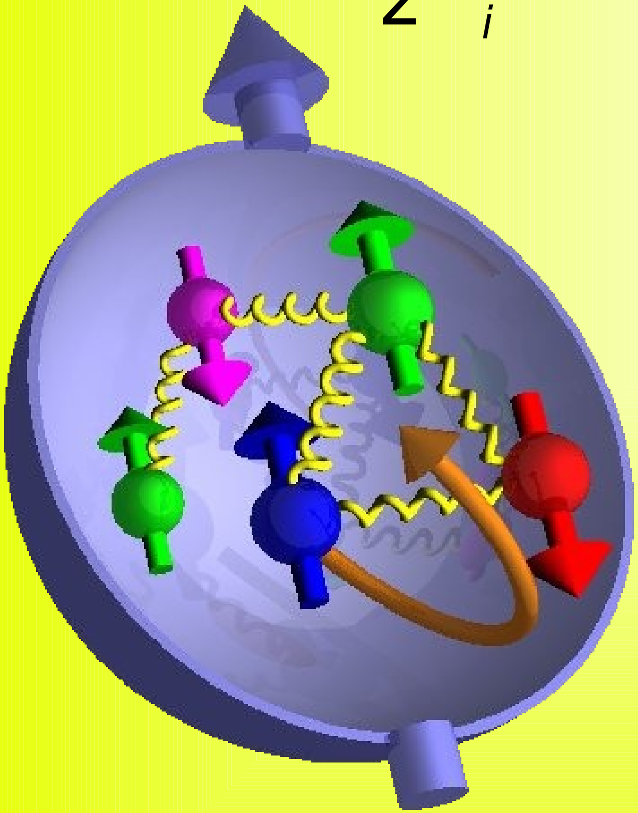
where $x = \dfrac{Q^2}{2M\nu}$ is the fraction of the nucleon's momentum carried by the struck quark in the Breit Frame.

Finding Meaning in the Bjorken Limit

probability of finding a quark with flavor *i* and momentum fraction *x*

$$F_1(x) = \frac{1}{2}\sum_i e_i^2 [q_i^{\uparrow}(x) + q_i^{\downarrow}(x)] = \frac{1}{2}\sum_i e_i^2 q_i(x)$$

$$g_1(x) = \frac{1}{2}\sum_i e_i^2 [q_i^{\uparrow}(x) - q_i^{\downarrow}(x)] = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x)$$



Where's the Spin?

$$S_z^p = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_z \rangle$$

Ellis Jaffe Sum Rule
or
What Happened to All the Spin?

Ellis-Jaffe Sum Rule: $\Gamma_1^p = \int_0^1 g_1^p(x)\,dx = \frac{1}{2}\left(\frac{4}{9}\Delta u + \frac{1}{9}[\Delta d + \Delta s]\right)$

Quark Constituent Model Predicts: $\Gamma_1^p = .278$

or $\Delta G = \langle L_z \rangle = 0$ and $S_z^{proton} = \frac{1}{2}\Delta\Sigma = \frac{1}{2}$

EMC measurement result: $\Gamma_1^p = .143$ *ALERT!*

Conclusion: The valence quark spins contribute only a fraction of the total proton spin. Studying $g_1(x)$ is quite important!

g_1's more obscure but equally important sibling

g_2 provides corrections to sum rules and

information about QCD interactions

$g_2(x)$ is made up of twist 2 and twist 3 terms

$$g_2(x) = -g_1(x) + \int_x^1 g_1(x')\frac{dx'}{x'} - \int_x^1 \frac{\partial}{\partial x'}\left[\frac{m}{M} h_T(x', Q^2) + \xi(x', Q^2)\right]\frac{dx'}{x'}$$

These terms are contributed by q-q and q-g interactions and can provide corrections to sum rules.

SANE's Access to g_1 and g_2

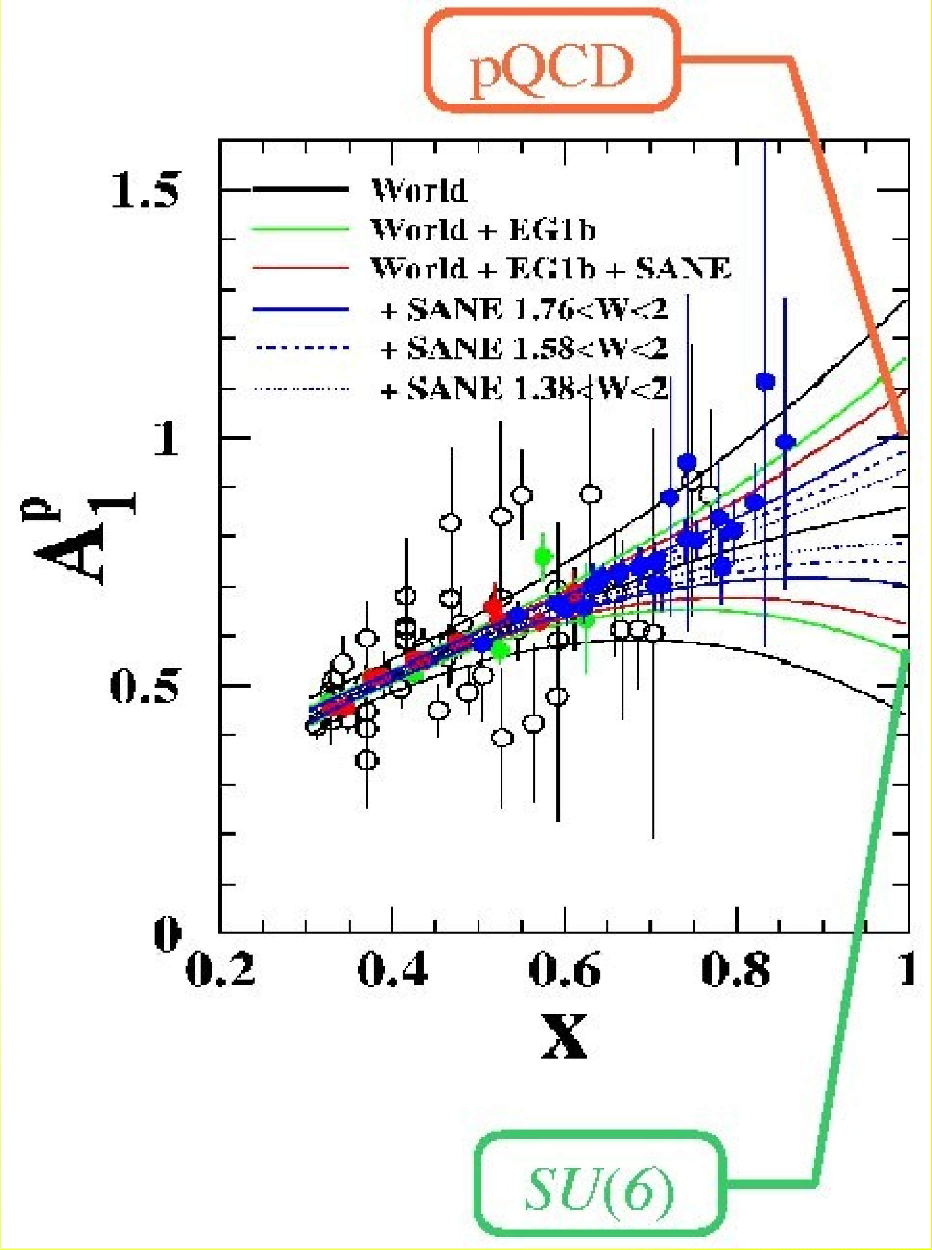
...through the asymmetries A_1 and A_2, which are themselves linear combinations of the experimental asymmetries $A_\parallel$ and $A_\perp$

$$g_1 = \frac{F_1}{1+\gamma^2}(A_1 + \gamma A_2)$$

$$g_2 = \frac{F_1}{1+\gamma^2}\left(\frac{A_2}{\gamma} - A_1\right) \quad \text{with} \quad \gamma = \frac{2xM}{\sqrt{Q^2}}$$

$$A_1 = \frac{1}{(E+E')D}\left((E - E'\cos\theta)A_\parallel - \frac{E'\sin\theta}{\cos\phi}A_\perp\right)$$

$$A_2 = \frac{\sqrt{Q^2}}{2E'D}\left(A_\parallel + \frac{E - E'\cos\theta}{E'\sin\theta\cos\phi}A_\perp\right)$$



The Necessity of Polarization

$$A_{\parallel,\perp} = \frac{\epsilon}{f P_b P_t C_1} + C_2$$

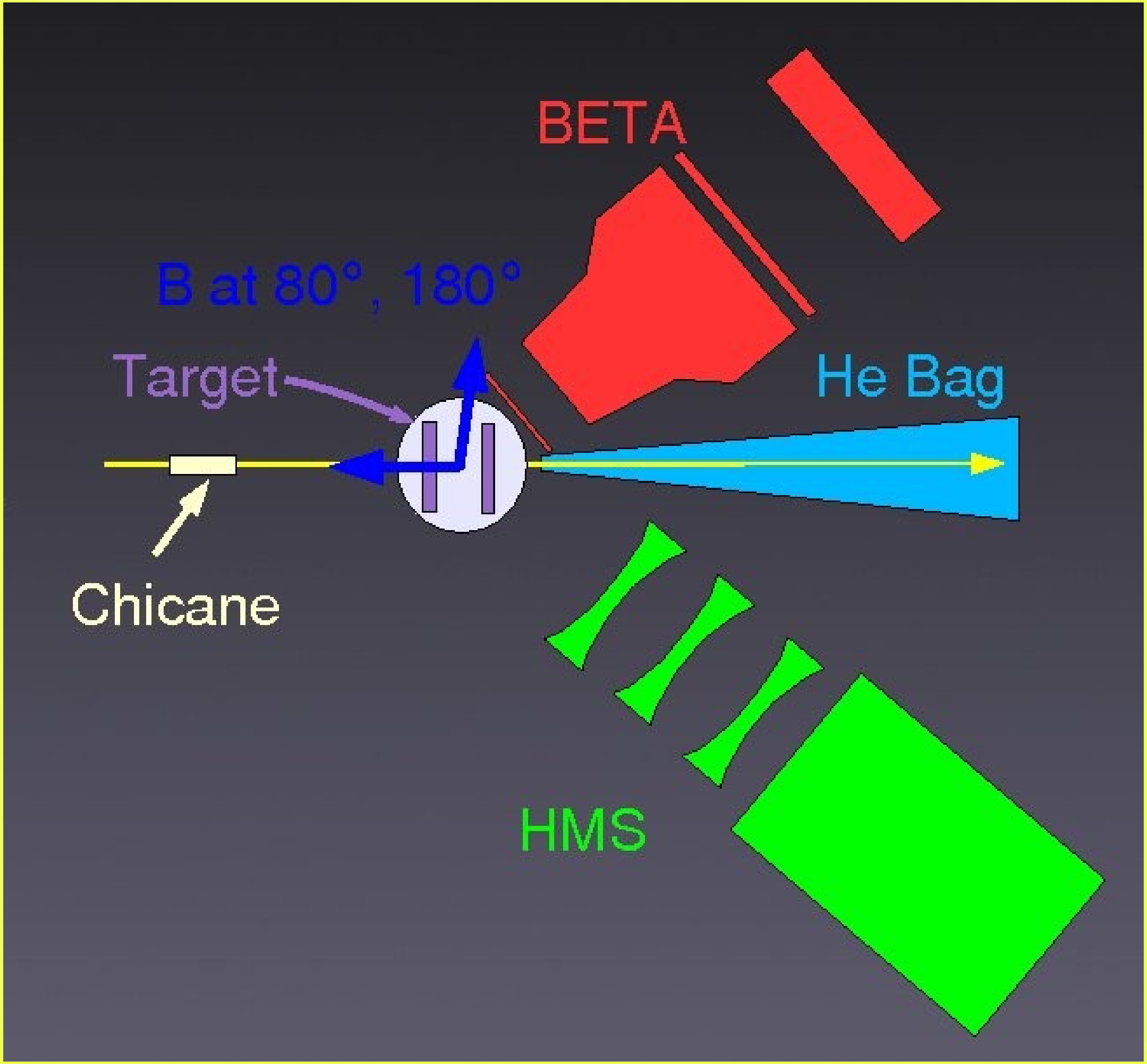
$$\epsilon = \frac{(N^- - N^+)}{(N^- + N^+)}$$

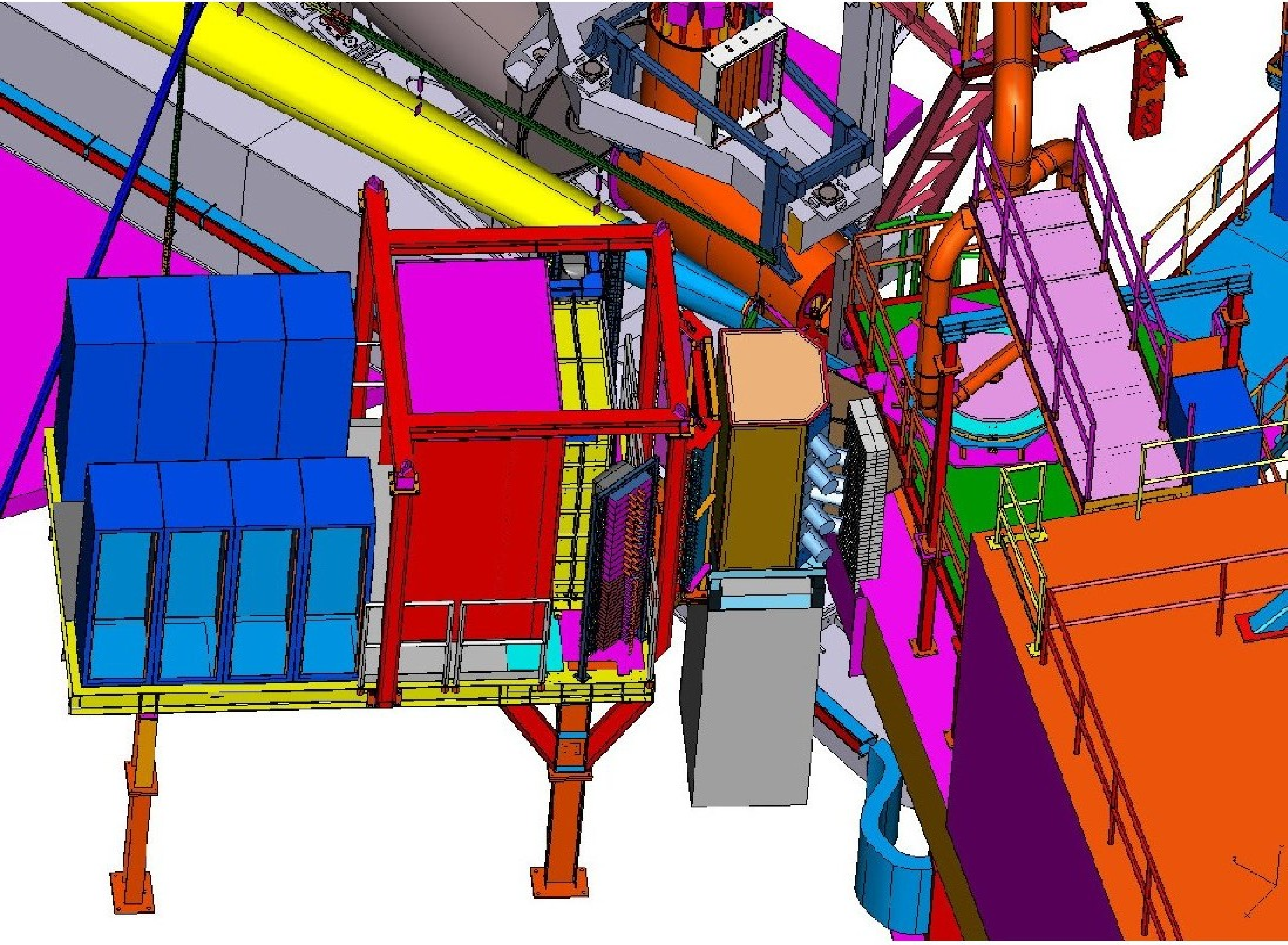
- $N^{-(+)}$: adjusted yields for -(+) beam helicity
- $P_{b(t)}$: beam (target) polarization
- f: dilution factor
- C_1 and C_2: correction factors

$$\left(\frac{\delta A}{A}\right)^2 = \frac{1}{(A P_b P_t)^2 N} + \left(\frac{\delta P_b}{P_b}\right)^2 + \left(\frac{\delta P_t}{P_t}\right)^2 + \left(\frac{\delta f}{f}\right)^2$$

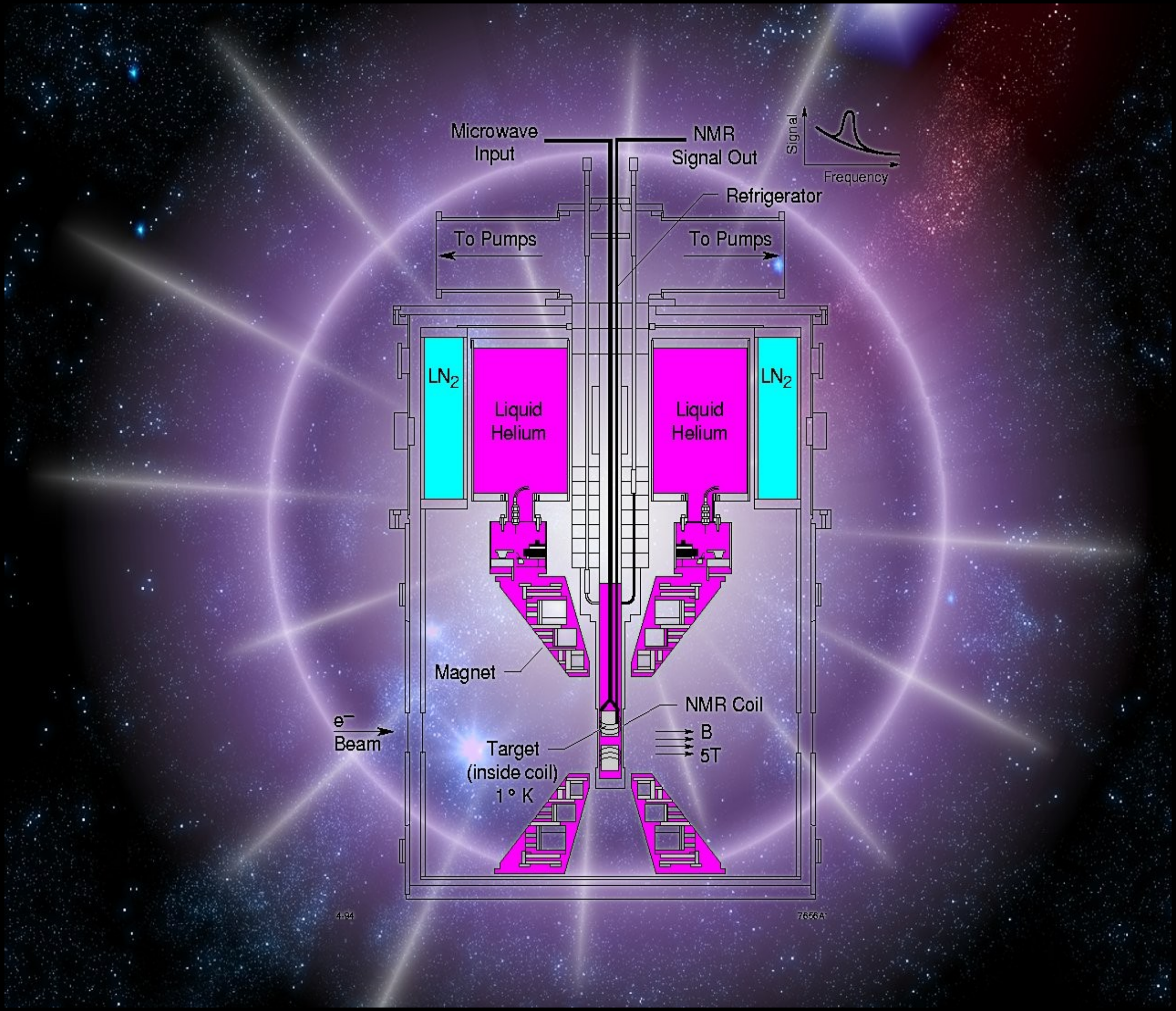
$$N_{goal} = \frac{1}{(f P_b P_t A \,\delta\epsilon/\epsilon)^2}$$

SANE'S Setup

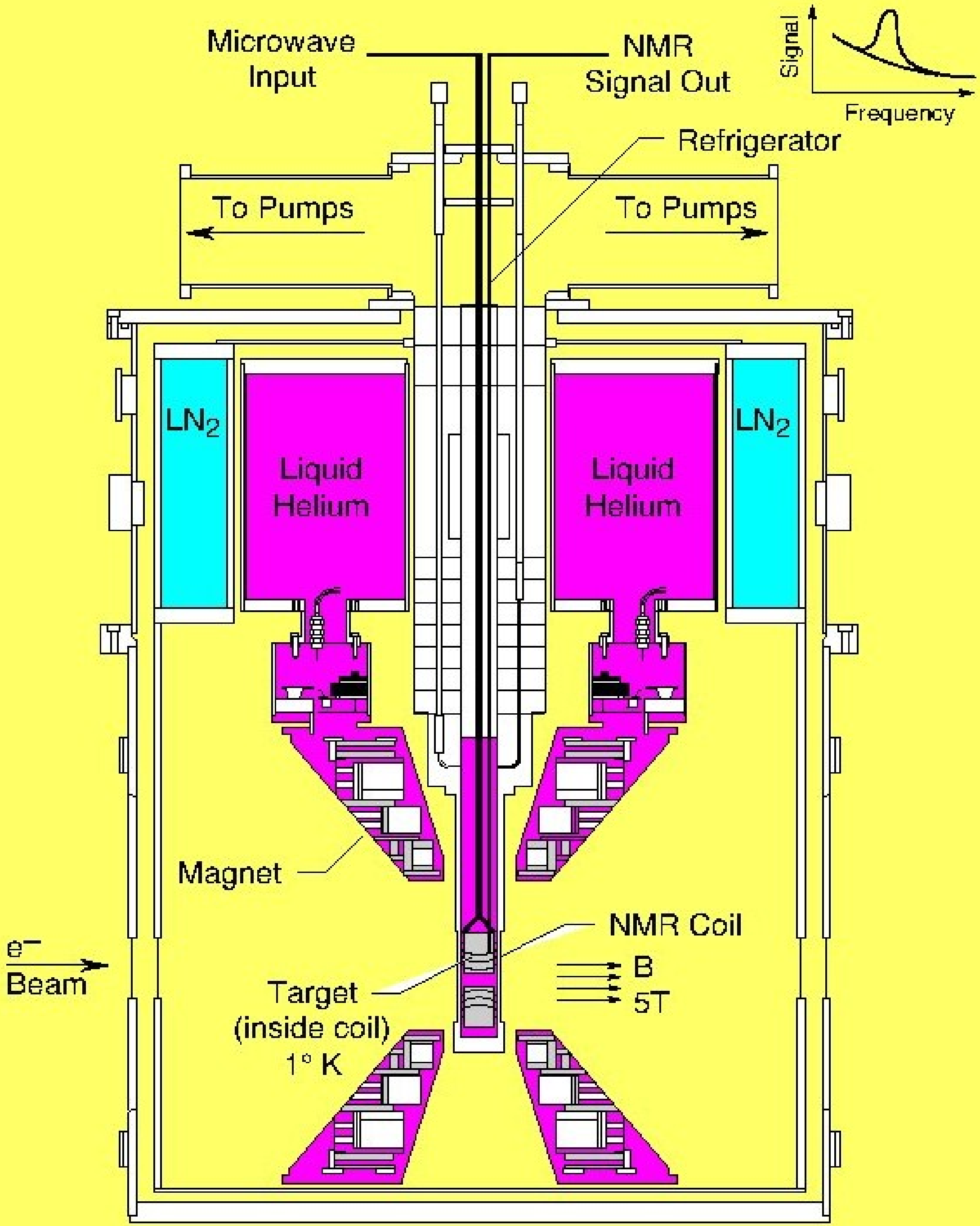


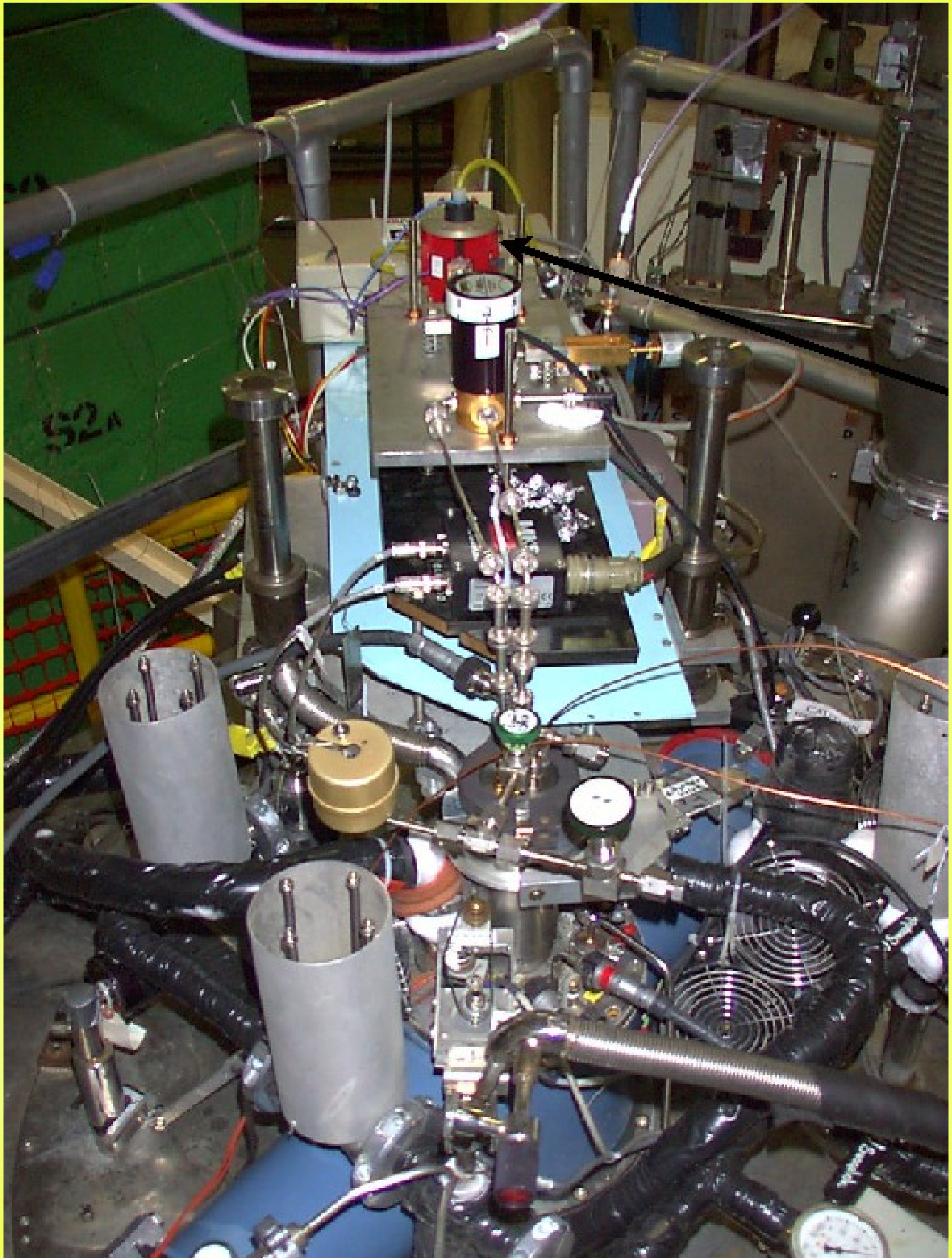


The polarized target for SANE is a solid target system developed here at UVA

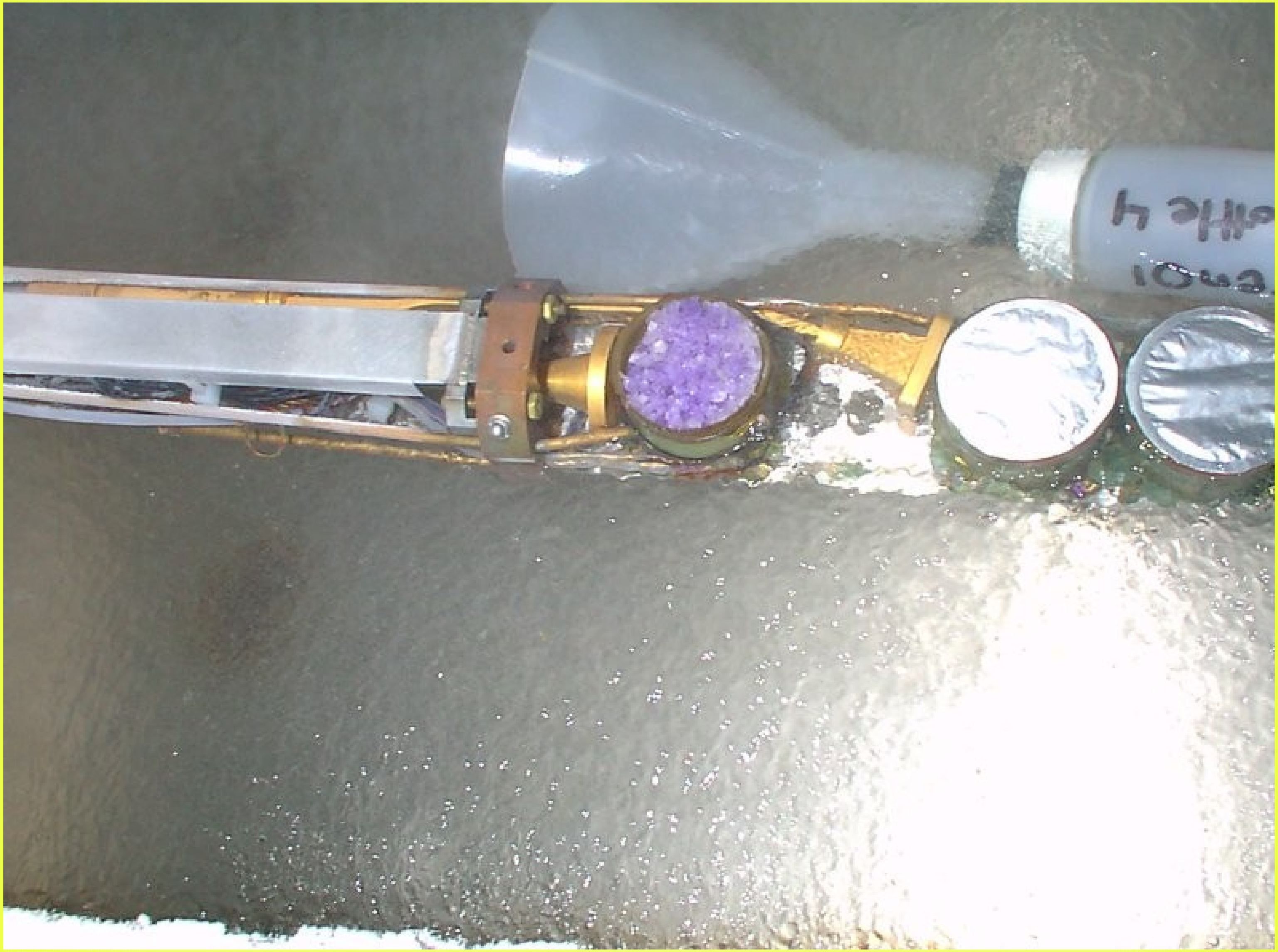


UVA/SLAC/JLAB Target



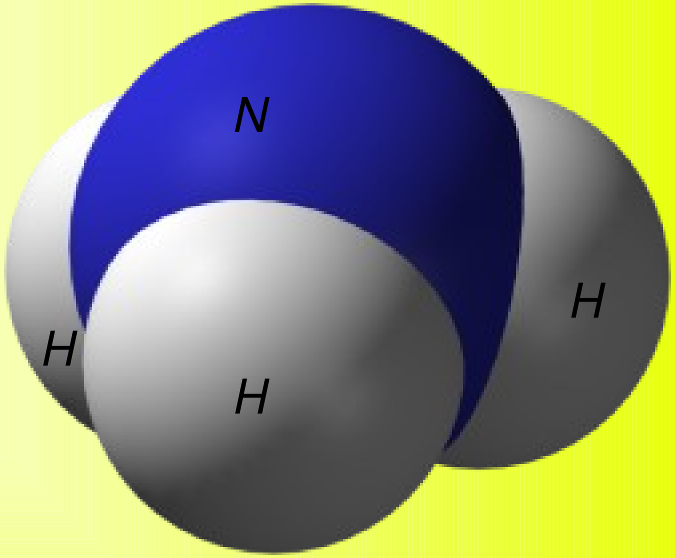



e⁻ IN



Dynamic Nuclear Polarization

It is necessary to have free paramagnetic centers in the material one is polarizing. These little magnets are polarized, and then their polarization is transferred to the protons. Several substances naturally have these, such as metals.

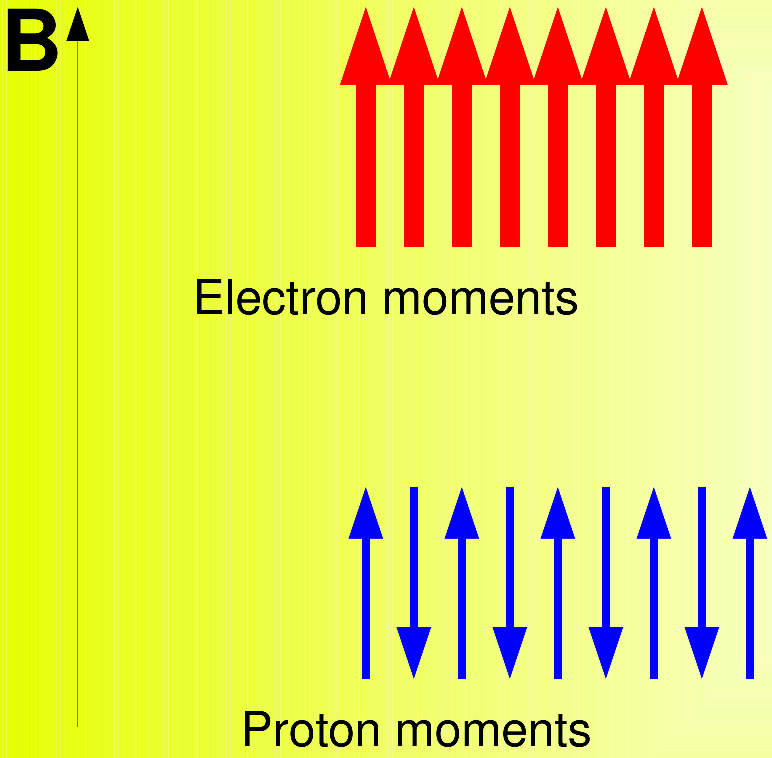


SANE will use Frozen 14NH3.

Paramagnetic centers are artificially introduced by irradiating the material and knocking out H atoms from the material, creating free radicals.

Zeeman splitting and thermal polarization

The paramagnetic centers (free electrons) split into two populations, N_1 and N_2.



N_1 is # parallel with the field

N_2 is # anti-parallel with the field

Polarization $= \frac{N_1 - N_2}{N_1 + N_2} = \tanh\left(\frac{\mu H}{kT}\right)$

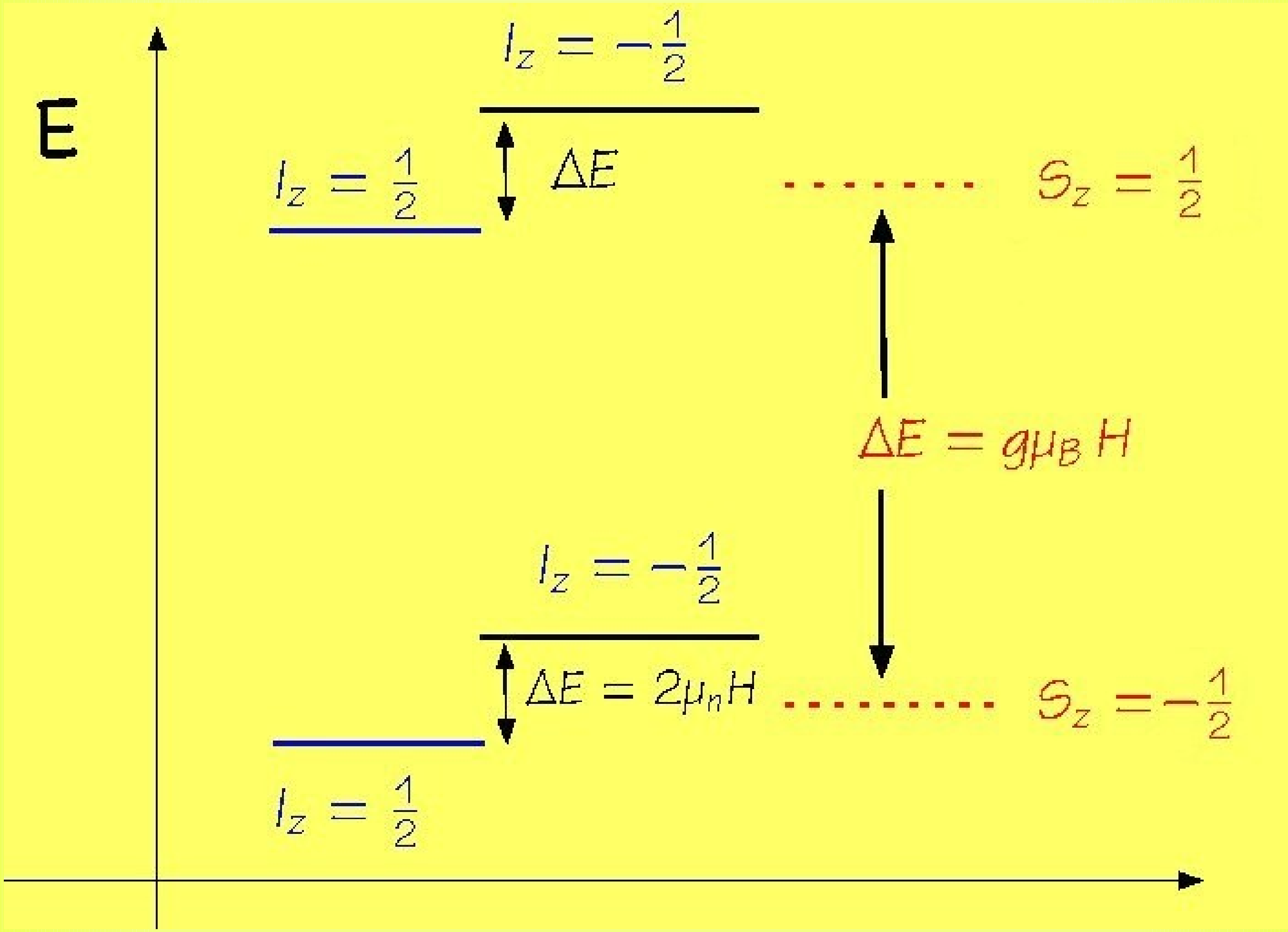
If H= 2.5 Tesla and T = 0.5 K

$P_{electron}$ = 99.8%

The Protons undergo a similar thermalization, but because their magnetic moment is so small $\mathbf{P_{proton}}$ **= 0.5%**

Hyperfine Splitting

free radical interacts with nucleon



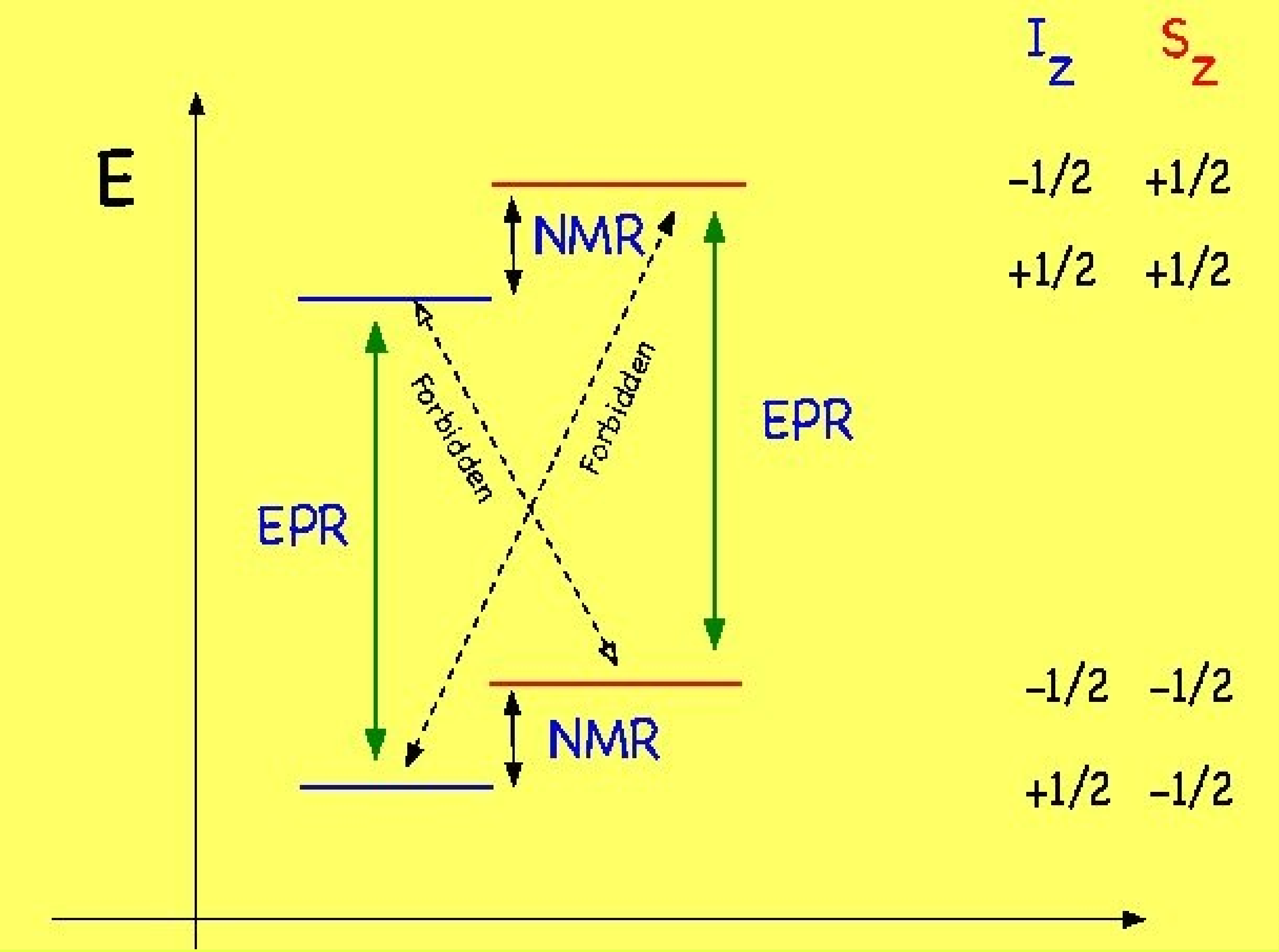
Want to collect all the nucleons into the same angular momentum state.

Microwaves drive “forbidden” transitions.

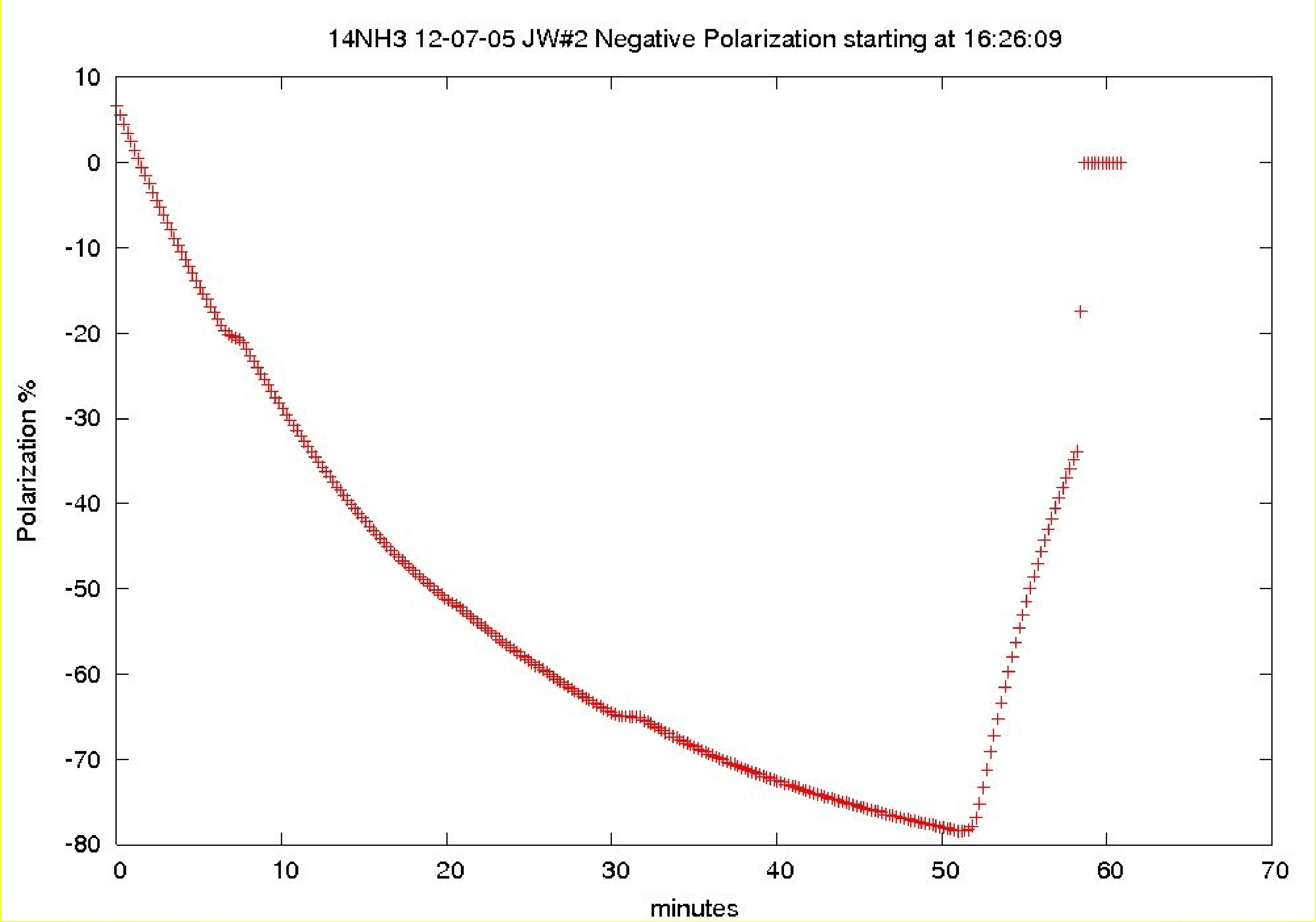
What makes everything work out nicely is the relaxation times.

Proton $\tau_p \sim$ 10s of minutes

Electron $\tau_e \sim$ miliseconds

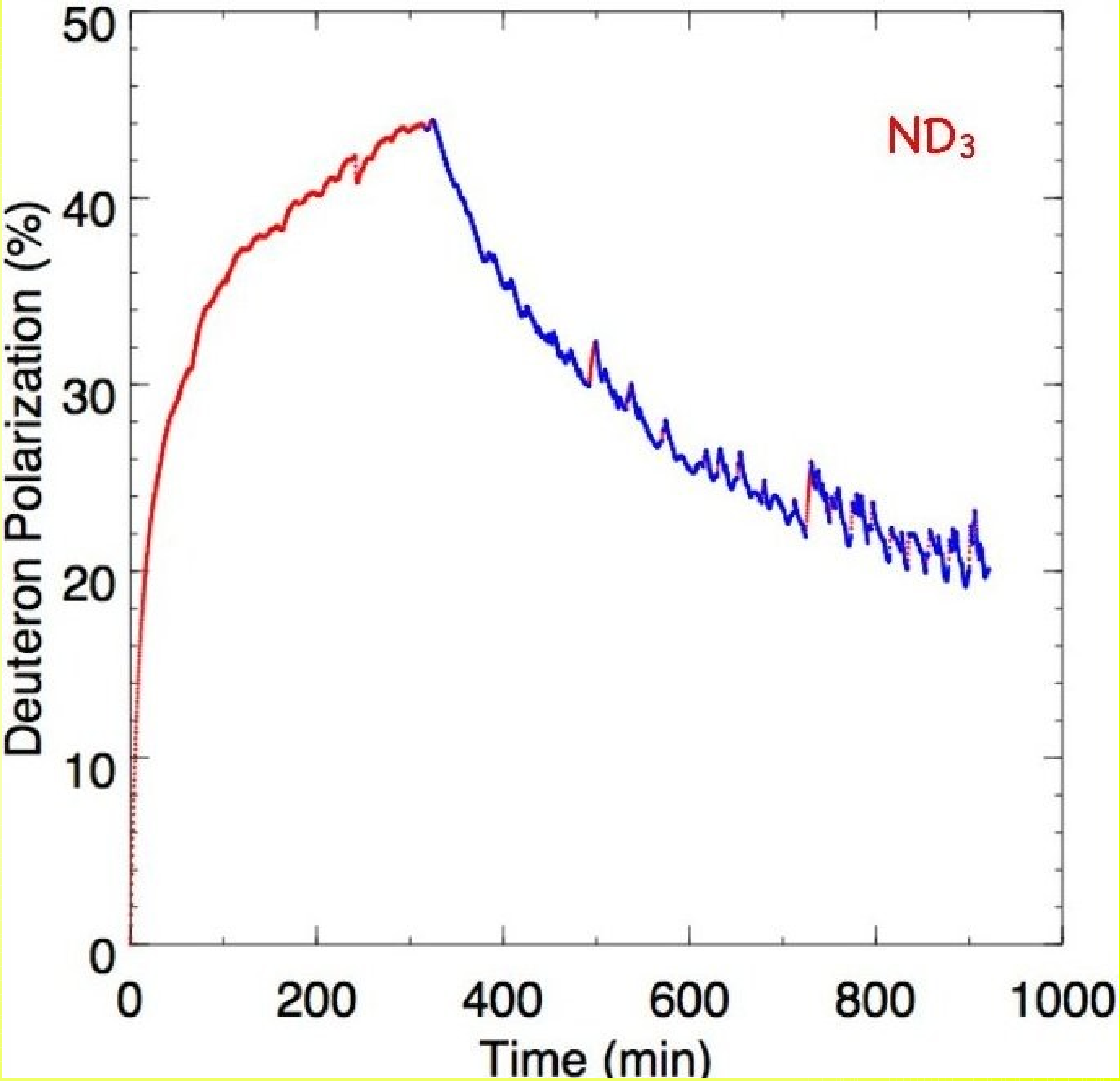


Using our DNP system at UVA we can achieve 95% or better polarization.



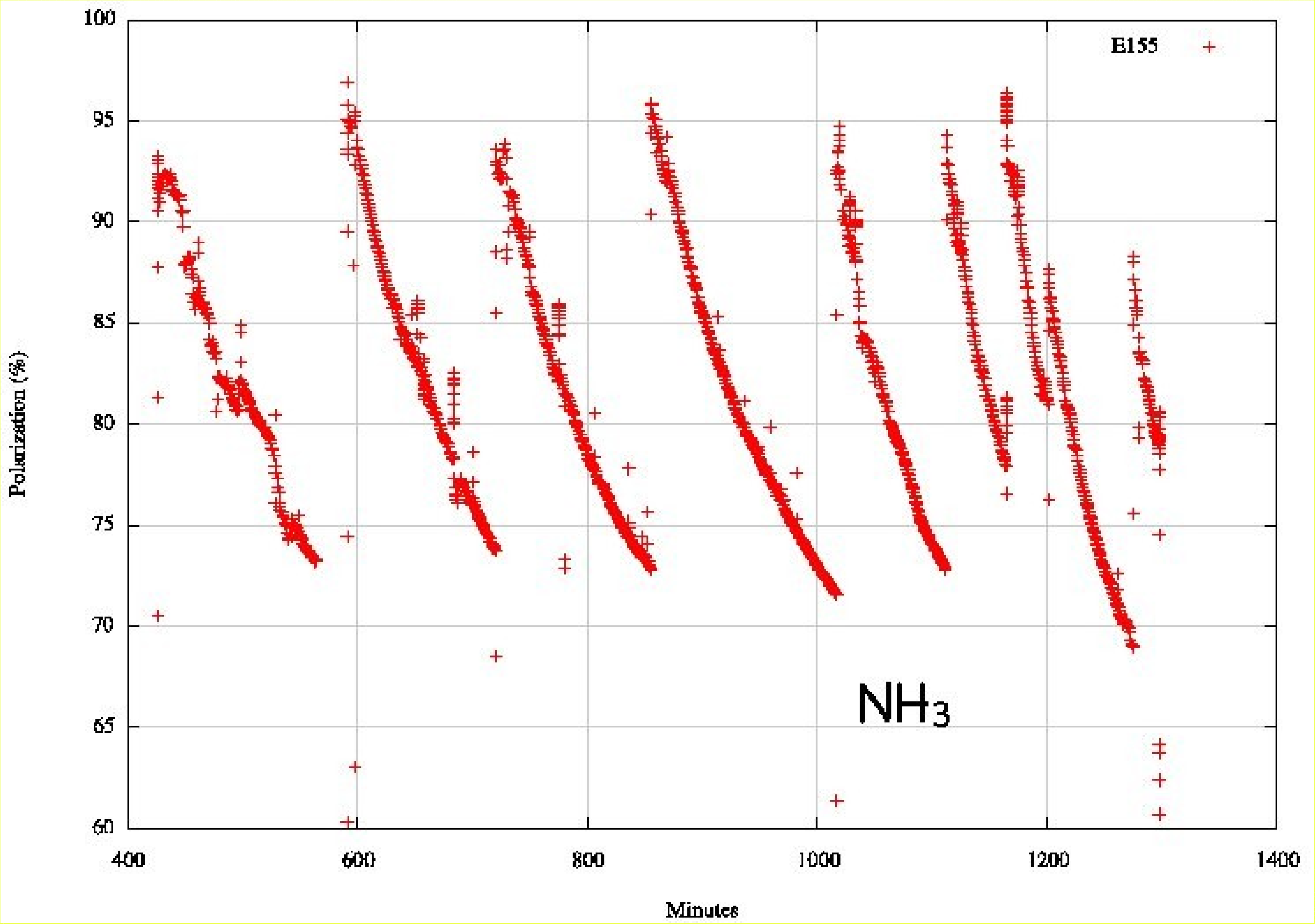
Material in the Beam

- Decay due to heat
- Decay due to radiation
- Beam trips
- Fast initial Polarization



Polarization Recovery

While in the beam, lots of different molecular species are being produced. Eventually the DNP mechanism is inhibited by these different species. An anneal can be performed to recover initial polarizabilty.



We are currently setting up the target system in the test lab, and a cooldown and test run is scheduled for early May.

SANE is scheduled to run at JLAB in October of this year.