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Workshop on

Nuclear Data for Science & Technology: Accelerator Driven Waste Incineration

10 - 21 September 2001

Miramare - Trieste, Italy

Experimental activities at high energies

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Experimental activities at high energies

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Lecture given at the:

Workshop on Nuclear Data for Science & Technology:

Accelerator Driven Waste Incineration

Trieste, 10-21 September 2001

Why nuclear data for ADS?

This is possible in principle	Small amounts Large costs
Is industry-scale processing possible?	Acceptable costs Political acceptance Sound handling Small losses Good environment

Still open question

Balance between safety and cost

Unknown cross section → exaggerate for safety → extra costs

The role of nuclear data:

Improve the balance of safety versus economy

Why neutrons?

Characteristic energies	Atoms	1 eV
	Nuclei	10 MeV

Nuclei contain enormous energies!

Atoms	EM forces
Nuclei	Strong forces

Strong/EM forces = 100 – 1000
Atom/nuclear area = 10^{10} EM wins in a real material

We need a particle with

Strong interaction	Otherwise no nuclear reactions	
No charge	Otherwise EM wins	
Reasonable life time	n	15 min
	K^0_L	50 ns

Conclusion: neutrons

Which reactions are of interest for waste incineration?

1) Really low energies (thermal)

Capture	(n,γ)	Q = + 8 MeV
Elastic scattering	(n,n)	Q = 0 MeV
Fission	(n,f)	Q = + 200 MeV

Best transmutation reaction: Fission

Releases LOTS of energy	Can pay the bill…
Releases 2-4 neutrons	Can induce more reactions

Second alternative: Capture

Releases little energy	Wrong type too (photons)
But it changes the element	

Useless: Scattering

No change, just moderates

2) Low, but not really low, energies

Other channels open (n,p), (n,α), (n,whatever), …

Most are useless or even detrimental

A few are of interest:

^{3}He(n,p)t	APT = Accelerator-based Production of Tritium
^{6}Li(n,α)t	"Classic" tritium production (Savannah, Hanford)
^{7}Li(n,2n)^{6}Li	Castle Bravo goes berserk!

First H-bomb	D-D fusion ("wet")	Big dewar of LD_2 Not useful as a weapon
Second H-bomb	D-T fusion ("dry")	^{6}LiD
Chain reaction	^{6}Li(n,α)t	t(d,n)α + E
But 40 %	^{6}Li	(Nature: 7 % ^{6}Li, 93 % ^{7}Li)
60 %	^{7}Li	

^{7}Li(n,2n)^{6}Li has a significant cross section

1) Increases the number of neutrons
2) Increases the amount of ^{6}Li

Both increase
the yield…

5 Mt expected, 15 Mt obtained

Biggest US test ever

Why accelerator-driven systems?

Wrong answer: Safety
Critical power reactors EXTREMELY safe

Right answer: Difficulties to destroy some elements in critical reactors

Fission on ^{235}U → 2.43 neutrons 1.00 should make new fission
1.43 neutrons to waste (capture)

Mistake: 1.01 neutrons $1.01^{1000000}$ (!) after 1 s
Impossible to control

Natural solution: delayed neutrons 0.7 % delayed
(seconds – minutes)

Slow system: 0.993 prompt neutrons
0.007 delayed neutrons

^{235}U very favourable nucleus Many delayed neutrons
Some nuclei have almost no delayed neutrons

→ Replace delayed neutrons with externally produced!

Which data are of interest for ADS?

Direct measurements or data for theory?

High energies (>20 MeV) 1 element, 1 cross section, 1 energy
= 1 week = 1 MEUR

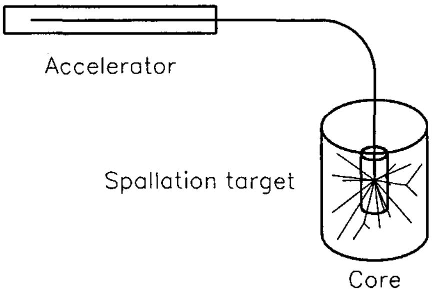
→ Requirements for good coverage: National budgets
Few centuries

Still not a complete solution! Short-lived elements in reactors
Example: 135Xe (Chernobyl!)
9 h halflife → impossible target

Conclusion: Measure data for theory guidance

Possible consequence: Measure processes not even
taking place (!)

Contraints imposed by ADS



1) Proton-induced neutron production (spallation)
2) Whatever the neutrons will do

Spallation neutrons ≈ 5 % of the neutrons (rest from fission)
Half of spallation neutrons below 20 MeV even before moderation

Three energy ranges:

<20 MeV	LOTS of data (3 M)	Reactors/fission weapons (<8 MeV)
		Fusion/thermonuclear (14 MeV)
	Some work left	"New" isotopes
		Inconsistencies
		→Tassan-Got talk
>200 MeV	Very few neutrons	(but powerful!)
	Theory rather good	Single interaction
		→ Leray talk
20-200 MeV	Bad theory	
	No data	
	Lots of work required…	

Data classification

Data for theory development	Example: elastic scattering Basis for optical potentials Total/reaction cross section
Strong channels	Elastic scattering (>50 %) (n,xp), (n,xn), $(n,x\alpha)$
Special, important data	Spallation neutrons (p,xn) Fission → residual activity (n,xp) hydrogen production embrittlement $(n,x\alpha)$ helium production swelling
Overall quantities	Residue production → Total radioactivity

The black magic of neutron experiments

How many neutrons are there in the beam?

Charged particles	Interact with electrons Every particle gives a signal → just count
Neutrons	Interact with nuclei only No way to get a signal for each neutron
Vicious circle:	Example: measure neutrons by np scattering Detecting protons rather easy Cross sections needed to know the number of incident neutrons = beam intensity Beam intensity needed to know to measure the cross section…

Tricks to get out:

1) Tagging

Example: d(d,n)^{3}He Only one final state
Detect ^{3}He → "tag" on neutron
Low (but known!) intensity beam

2) Hydrogen combinations

Total cross section well known (1%)
Measured by attenuation
Absolute intensity not needed

Measure angular np distribution
Normalize to total cross section

3) Total/reaction/elastic combinations

Also reaction cross section well known (2%)
Also attenuation experiments
Integrated elastic = total – reaction
Measure elastic angular distribution
Normalize to integrated elastic

4) Theoretically "known" relations

Example: $np \to d\pi^0$ half of $pp \to d\pi^+$
Measure relative to $np \to d\pi^0$
Trouble: large corrections

Methodology:

Determine a reference cross section
Measure relative to it

How large is a neutron detector?

Need to know solid angle = active detector area

Charged particles:	Collimators
Low energies:	B/Cd huge capture cross sections
Slightly higher energies:	Moderator (paraffin) + B/Cd
High energies:	Collimators useless (harmful) No strong capture Only reactions and scattering Produce as much as they remove In-scattering of junk
Conclusion:	“Naked” detectors
Recent test:	Tagged efficiency measurement Events from outside the detector (!) In-scattering from front plastic shield

How are high-energy neutron experiments carried out?

Case study: elastic scattering (all the trouble…)

Neutron production

Mono-energetic beams possible only up to a few MeV
Break-up energies typically 8 MeV → low-E tail above 8 MeV

Up to 20-30 MeV:	T(d,n)	few 100 keV d → 14 MeV n
Above 50 MeV:	D(p,n)	large cross section 3 MeV wide
	^{6}Li(p,n)	1 MeV wide
	^{7}Li(p,n)	Equally good
	^{6}Li	Bomb material = hard to get
	^{7}Li	For free = standard choice

50 % of the neutrons in a high-E peak
Remaining equally distributed in energy
This is as good as it gets…

Different approach:
All energies (white source)
Large total number of neutrons
Most at low energy
Few per energy bin
Event-by-event necessary
Good for Large cross sections
Excitation functions

Neutron detection

Low energies:	Time-Of-Flight (TOF) standard technique Initial (d) beam stopped in a thin metal foil No neutrons from beam stop Scattering target close to production Movable detector (large hall) Beam swinger (fixed flight path)
High energies:	TOF increasingly difficult
Example:	1 ns time resolution 0.5 MeV energy resolution wanted 5 m flight path at 20 MeV 60 m (!) at 100 MeV → Beam swinger needed
Next problem:	Above all neutron thresholds → Most neutrons from the beam stop → Move beam stop → second magnet
Different approach:	Skip TOF Convert neutrons to protons Measure proton energy
Plus:	Large distance n production to target OK Short distance target to detector
Minus:	Poor conversion efficiency

The HINDAS project

High and Intermediate energy Nuclear Data for Accelerator driven Systems

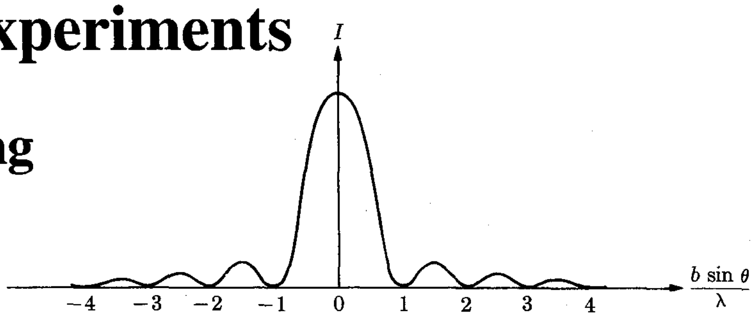
EU project 16 universities/laboratories
6 of these are experimental facilities

Essentially all competence in Europe above 20 MeV gathered

8 work packages:	1-3	20-200 MeV, n- or p-induced data
	4-6	200-2000 MeV, p(d)-induced data
	7	20-200 MeV theory
	8	200-2000 MeV theory

Survey of ongoing experiments

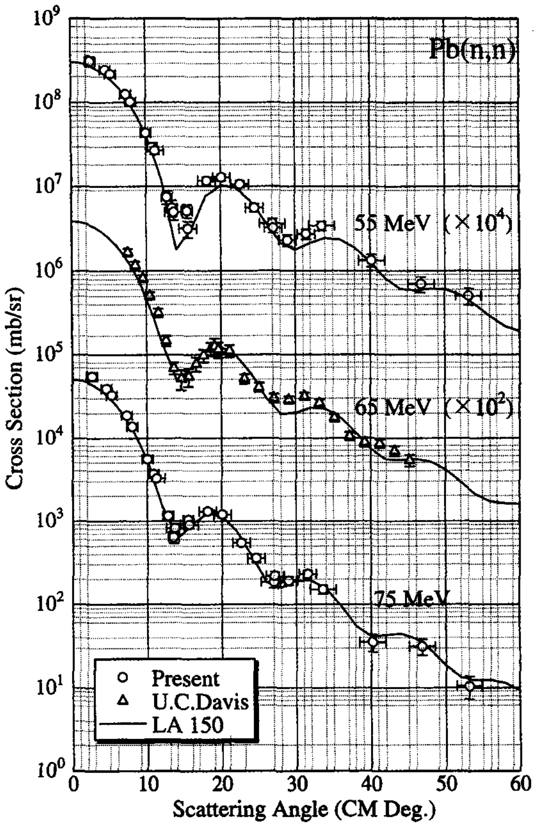
Elastic neutron scattering



Why bother?

Optics:

Slit scattering
Interference between two slits
Max-min distance related to
slit separation

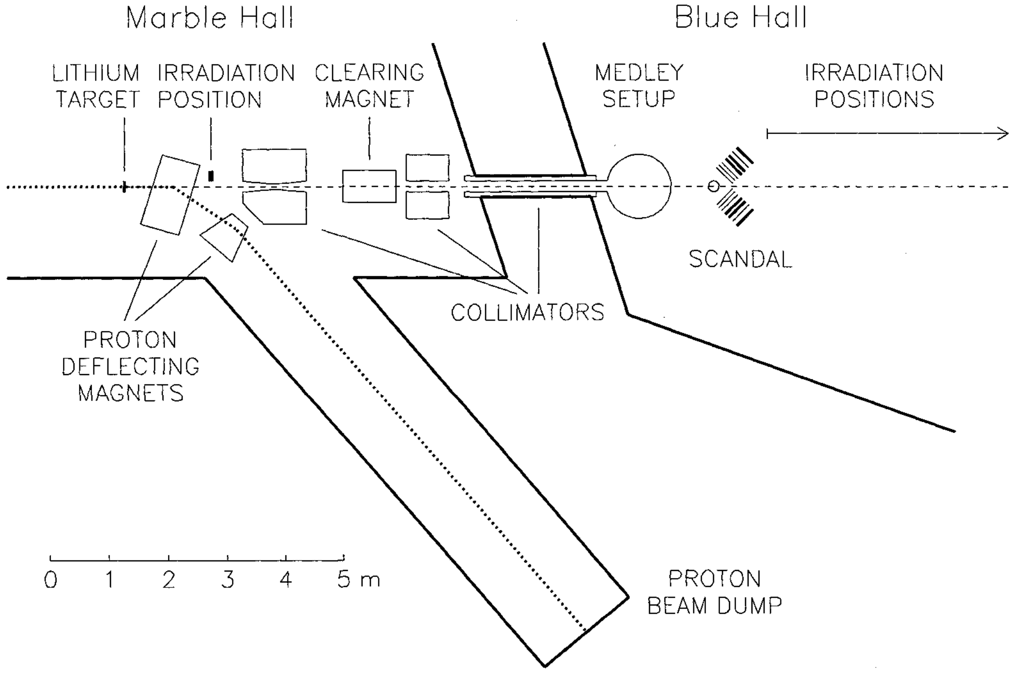


Neutrons:

Interference between two sides
of the nucleus ("black" nucleus)
Max-min distance related to
nuclear size

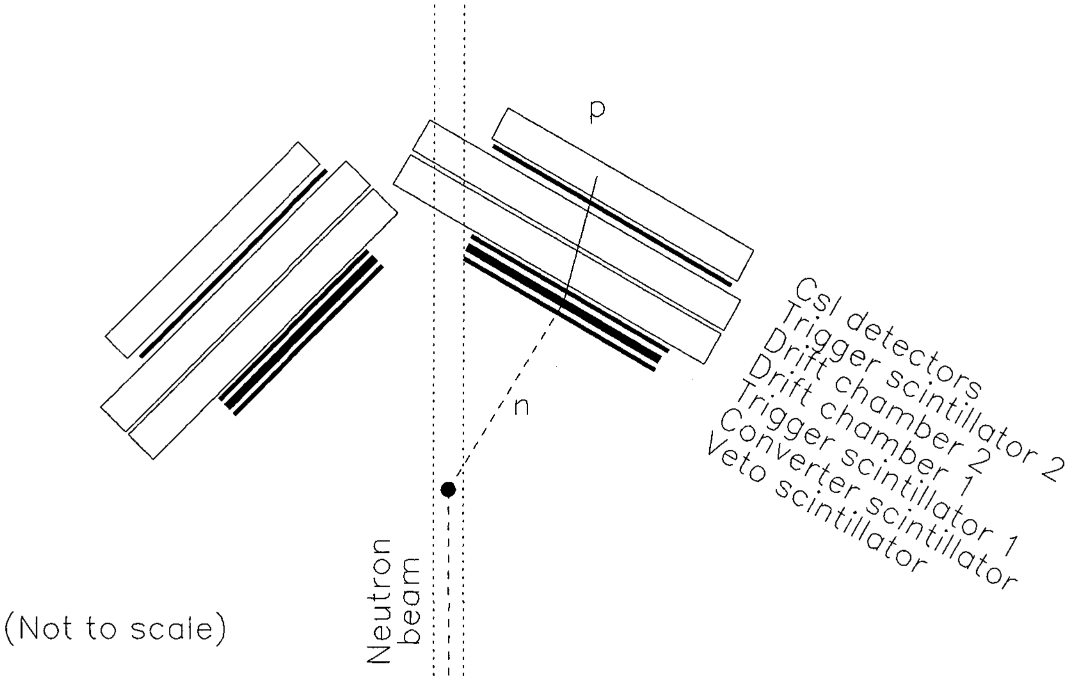
Optics/neutrons:	Quantum mechanics = Schrödinger equation Real potential = scattering only Losses = imaginary potential
Optical potential:	Work horse in nuclear physics Describes n-nucleus force Derived from elastic scattering
Also:	Elastic scattering largest (>50 %)

The TSL Neutron Beam Facility



SCANDAL

(SCAttered Nucleon Detection AssembLy)



Neutron/proton-induced charged-particle production

Why?

Low energy (<20 MeV)	Compound nucleus Statistical theory
High energy (>200 MeV)	Single interaction Direct reaction
Intermediate energy (20-200 MeV)	Few interactions Pre-compound reactions
Data for theory:	All emission energies, all angles
Also:	Protons = hydrogen = safety, embrittlement Alpha's = helium = steel swelling

Extra motivation for proton-induced experiments:

Coincidence measurements with low-E neutrons for spallation target modelling

Standard method:	Particle telescopes	$\Delta E - E$
Recent improvement:		$\Delta E - \Delta E - E$

Another improvement:	Add high-E proton detector with large solid angle

Residues

Why?

Ultimate goal: Know all elementary processes
Make a huge multistep calculation
Predict all what happens

Problem: We are not there (yet)

Large uncertaintites in predictions of final products
→ direct measurements needed

Special use: Total radioactivity of the system

Classic technique: Irradiation + γ detection afterwards
Gives all radioactive rest products

Improvement: AMS gives stable (and long-lived) nuclei

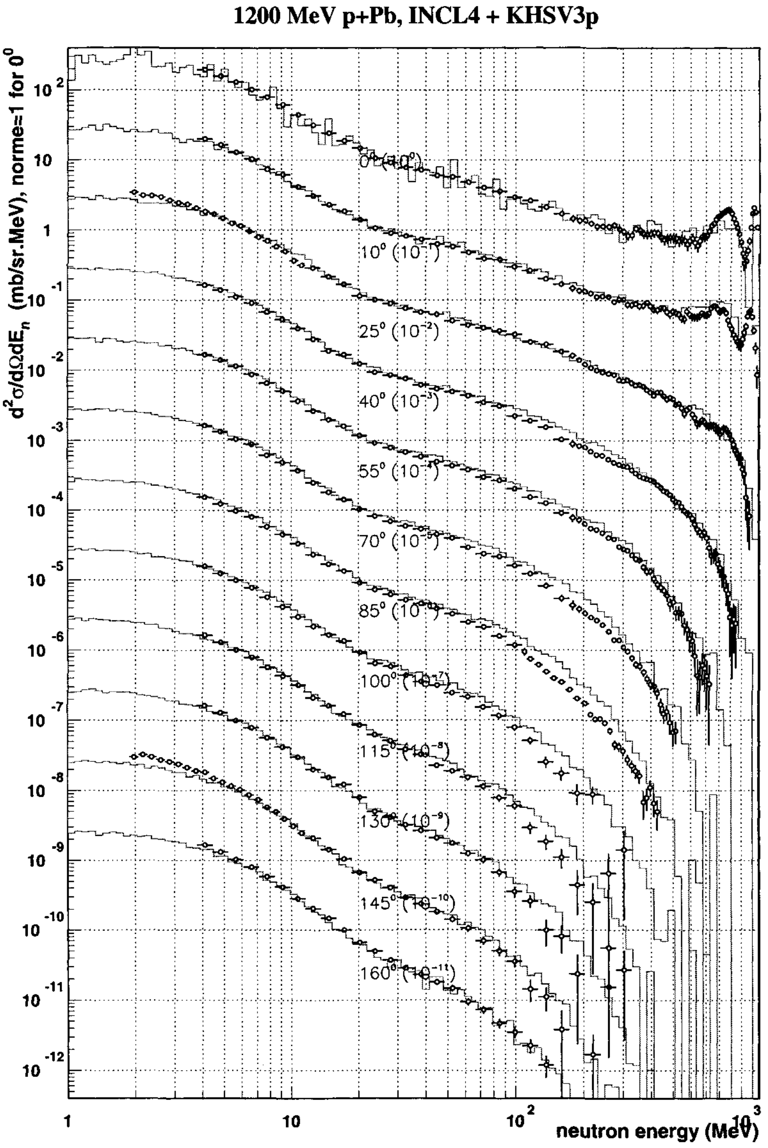
New technique: Inverse kinematics
Not proton on lead
Instead lead on proton
All fragments at high energy
→ "easy" detection
No waiting period → reaction mechanism

Minus: Just one element per experiment
Neutron interaction difficult
Low energies difficult

High-energy neutron production

(p,xn) at very high energies for spallation target modelling

Two techniques:
TOF at low E
Conversion to protons + magnetic spectrometer at high E
Overlap region for inter-comparison



Fission

Why?

Low E: Fission only in some actinides

High E: Sizeable fission in many heavy elements

Example: 1.6 GeV lead spallation target
10-15 % of activity due to fission products

Standard fission data: Cross sections
Yields (element distributions)

Virtually absent above 50 MeV

Low-E: No other reactions look like fission

High-E: Fragmentation (spallation) imitates fission
Multiple light ions look like fission fragments

Solution: Detectors insensitive to light ions → TFBCs

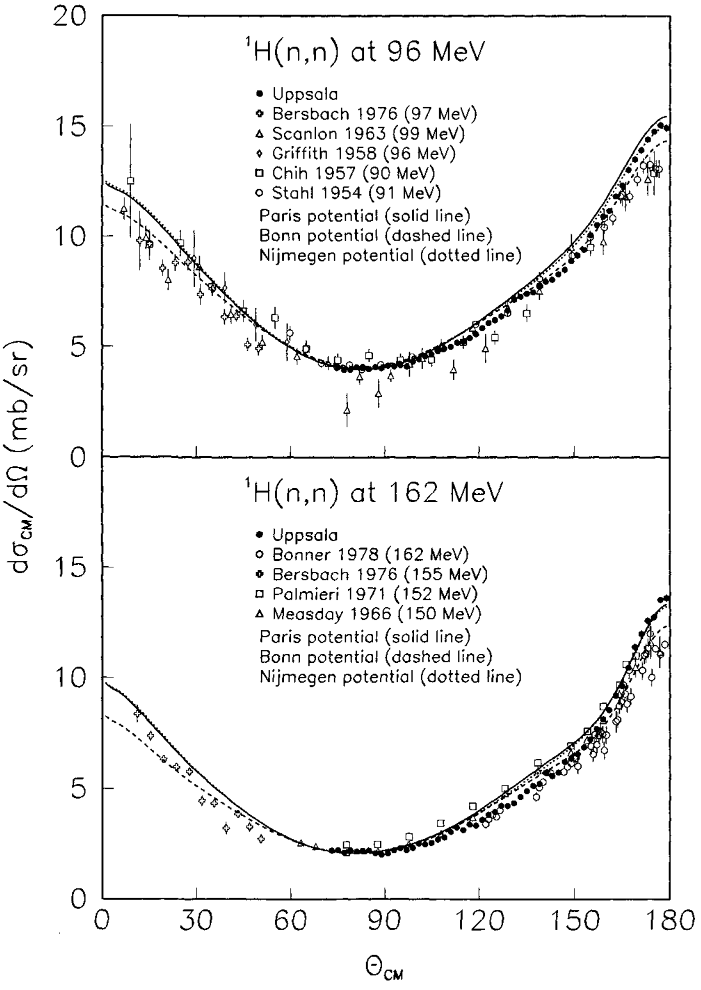
Now cross sections on uranium, lead and bismuth.

The length of the yardstick – np scattering

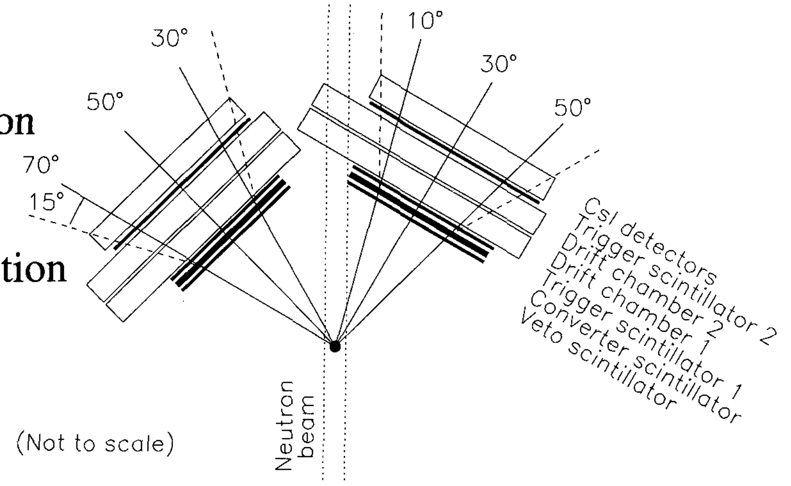
np scattering is used as primary standard
Almost all other data measured relative to np scattering

np 100-1000 MeV:	huge discrepancies (10-15%) → all other data equally uncertain…
Also:	np data determine absolute strength of the strong interaction

How strong is the strong interaction?



Ongoing work:



1) Complete np angular distribution
   70 – 180 degrees measured
   10 – 100 degrees underway
   normalization to total cross section
   Relatively simple experiment

2) Tagged measurement
   Storage ring experiment
   p(d,^{2}He)n production
   VERY complex experiment