Precision Measurement of *a* and *b* in Neutron β Decay

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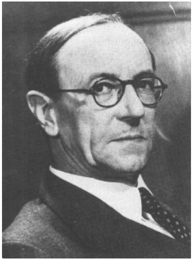
Outline

Background

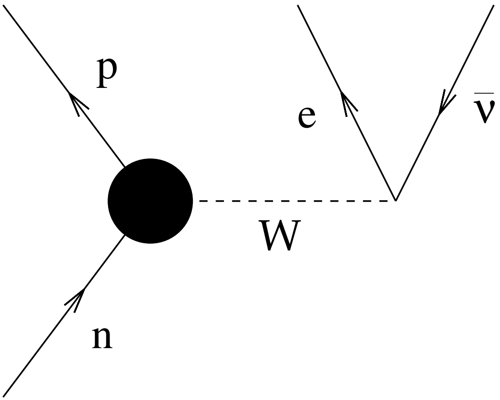
- Discovered 1932
- $\alpha + {}^{9}Be \rightarrow {}^{12}C + n$
- Unstable: $n \rightarrow pe\bar{\nu}_e$



Sir James Chadwick

β Decay

- $M_n = 939.565\, MeV/c^2$
- $M_p = 938.272\, MeV/c^2$
- $M_e = 0.511\, MeV/c^2$
- $M_\nu << M_e$
- Free Energy $= 0.782\, MeV$



β Decay

- Hadronic Terms
  - $\langle p|V_\mu|n\rangle = \left\langle \bar{u}_p|g_V\gamma_\mu - i\frac{g_M-g_V}{2m}\sigma_{\mu\nu}q_\nu + \frac{g_S}{2m}q_\mu|u_n\right\rangle$
  - $\langle p|A_\mu|n\rangle = \left\langle \bar{u}_p|g_A\gamma_\mu\gamma_5 - i\frac{g_T}{2m}\sigma_{\mu\nu}q_\nu\gamma_5 + \frac{g_P}{2m}q_\mu|u_n\right\rangle$
- Leptonic Term
  - $\langle \bar{u}_e|\gamma_\mu(1+\gamma_5)|u_{\nu_e}\rangle$
- Differential Decay Rate
  - $\partial\Gamma_n \propto \left(1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\frac{m_e}{E_e} + \vec{\sigma}_n\cdot\vec{f}[\vec{p}_e,\vec{p}_\nu]\right)$
  - $a = \frac{1-|\lambda|^2}{(1+3|\lambda|)^2}$ with $\lambda = \frac{g_A(0)}{g_V(0)}$

Significance

- Very sensitive way to measure λ
- Dependent on V-A nature of the weak force $\rightarrow$ sensitive to deviations
- When combined with neutron lifetime measurements determines V_{ud}
  - CKM Unitarity $\rightarrow$ constraints on new physics
  - Inconsistencies between measurements from neutron decay
- A star's neutrino production is proportional to λ^2
- Something new

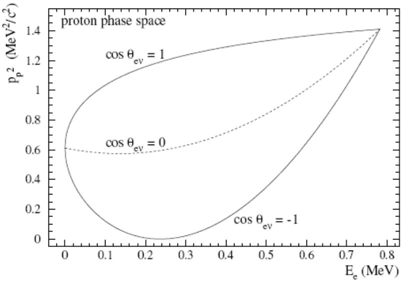
Outline

The Nab Experiment

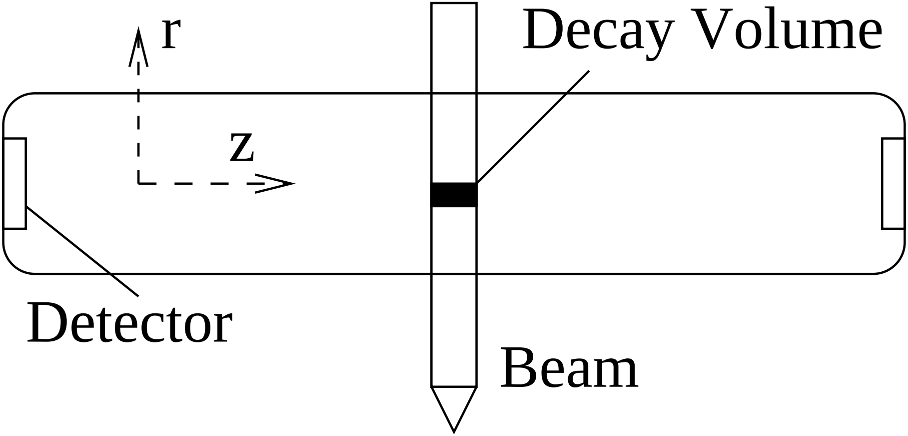
- $\partial\Gamma_n \propto \left(1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \vec{\sigma}_n \cdot \vec{f}[\vec{p}_e, \vec{p}_\nu]\right)$
  - Goal: $\frac{\Delta a}{a} \approx 10^{-3}$
  - Goal: $\Delta b \approx 10^{-3}$
- Method: Measure kinematics of the decay products and compare with the decay rate
- Neutrino detectors of high efficiency do not exist
  - Relate E_ν to E_e and measure E_e directly
  - Cannot measure $\vec{p}_e \cdot \vec{p}_\nu$ directly

Measuring $\vec{p}_e \cdot \vec{p}_\nu$

- Neutron rest frame: envoke momentum conservation
  - $\vec{p}_p + \vec{p}_e + \vec{p}_\nu = 0$
  - $2\vec{p}_e \cdot \vec{p}_\nu = 2p_e p_\nu cos\theta_{e\nu} = p_p^2 - p_e^2 - p_\nu^2$
- $\partial\Gamma_n \propto \left(1 + aX(E_e)p_p^2 + aY(E_e) + bZ(E_e)\right)$
- Measure $E_e \sim 100\,\text{keV}$
- Measure $E_p \sim 100\,\text{eV}$



The Nab Approach

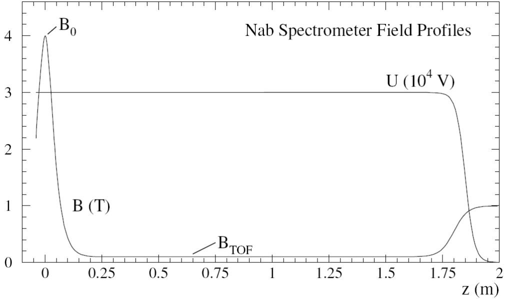


Properties of the Spectrometer

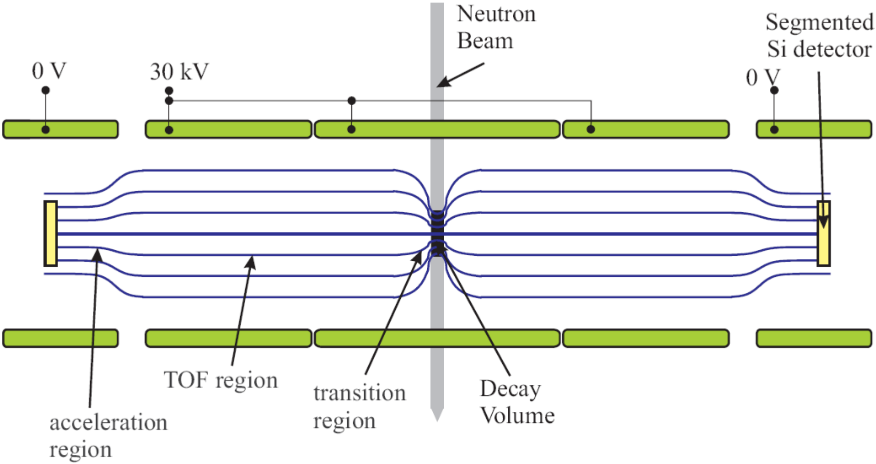
- Shepherd particles to the detectors
- Longitudinalize the decay product's momentum rapidly
- Accelerate protons to detectable range
- Azimuthal symmetry
- Large decay volume

Realization

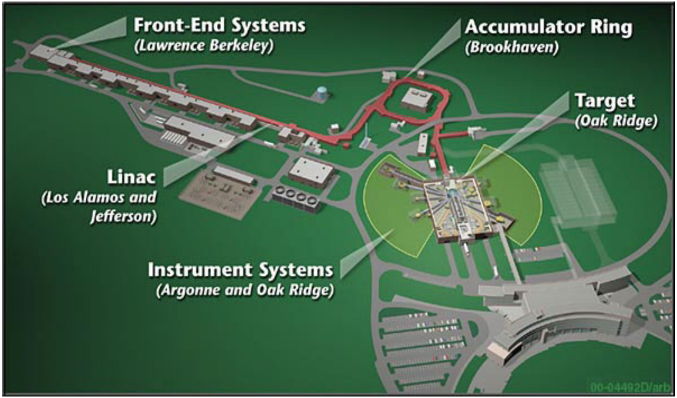
- Shepherd decay particles $\longrightarrow$ magnetic confinement
  - $\vec{F} = q\vec{v} \times \vec{B} \longrightarrow$ uniform field along spectrometer axis
- Longitudinalize decay products $\longrightarrow$ magnetic tipping
  - Adiabatic Invariant $\frac{p_\perp^2}{B} \longrightarrow$ decrease field along $\hat{z}$ axis [Jackson 12.69]
- Accelerate protons $\longrightarrow$ electric potential



The Nab Apparatus

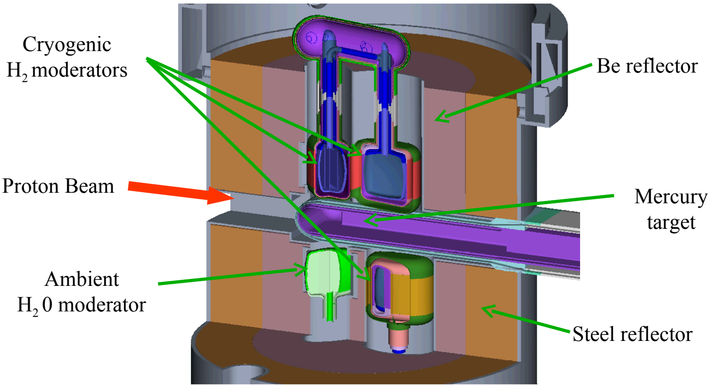


The Spallation Neutron Source

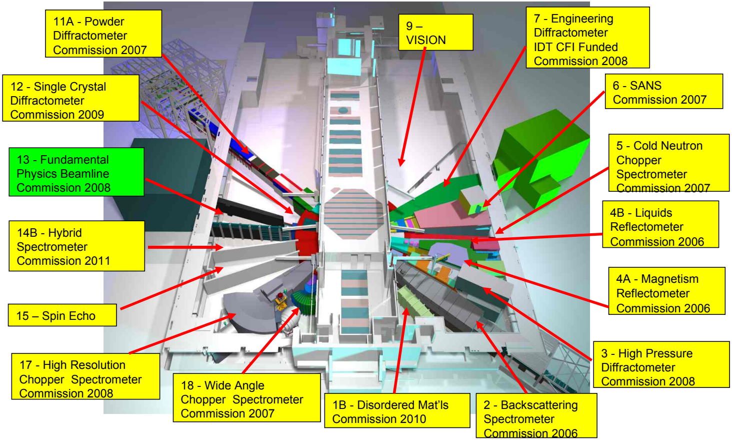


- 1.4 GeV protons, 60Hz
- LHg Spallation target
- H_2 moderator
- 17m guide, curved

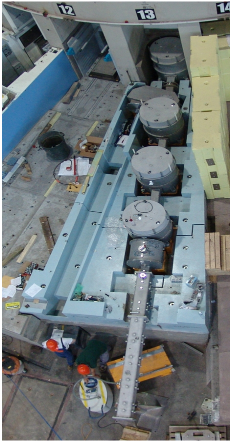
Target Assembly



Beamlines

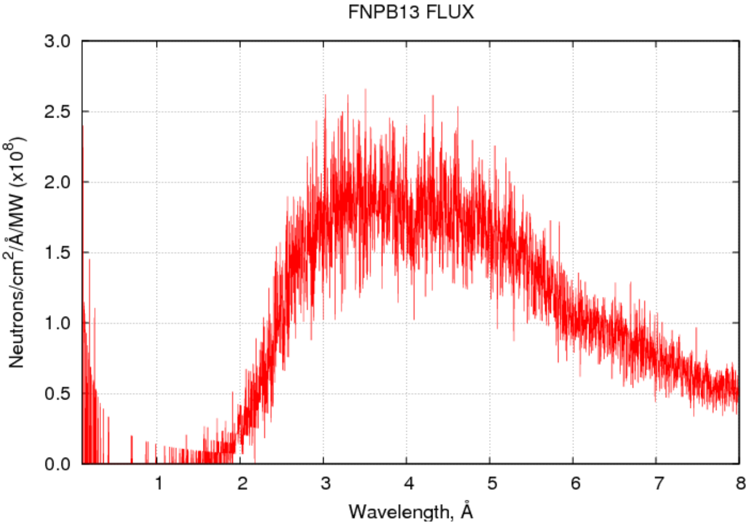

11A - Powder Diffractometer Commission 2007
9 – VISION
7 - Engineering Diffractometer IDT CFI Funded Commission 2008
12 - Single Crystal Diffractometer Commission 2009
6 - SANS Commission 2007
13 - Fundamental Physics Beamline Commission 2008
5 - Cold Neutron Chopper Spectrometer Commission 2007
4B - Liquids Reflectometer Commission 2006
14B - Hybrid Spectrometer Commission 2011
4A - Magnetism Reflectometer Commission 2006
15 – Spin Echo
3 - High Pressure Diffractometer Commission 2008
17 - High Resolution Chopper Spectrometer Commission 2008
18 - Wide Angle Chopper Spectrometer Commission 2007
1B - Disordered Mat'ls Commission 2010
2 - Backscattering Spectrometer Commission 2006

The Fundamental Neutron Physics Beamline



The Fundamental Neutron Physics Beamline

Flux Measurement September 12, 2008

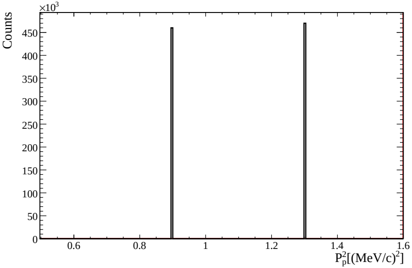


Outline

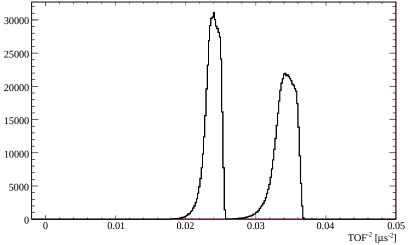
Simulation

- Geant4
  - Track particles through the EM spectrometer
  - Simulate Collisions with silicon detectors
- Galileo
  - 36 dual core hyperthreaded nodes (6 login, 30 batch)
  - Nominally: 120 processors at 3 Ghz with 1 Gb of RAM
- Process
  - Analytic formula for B_z (more control)
  - Real coils for B_z (more realistic)

Figure of Merit for the Spectrometer Response



Ideal Spectrometer

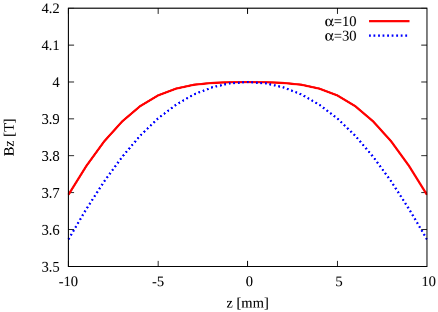


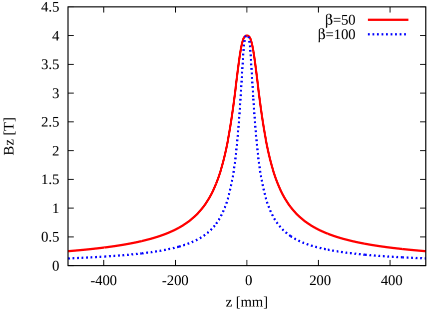
Practicable Spectrometer

- $\frac{RMS}{mean}$: width of peak
- 10^{-4} Quantile: tail of peak

The Tangent Field

- $$B_z = N\frac{\arctan\left[\beta z\left(1+\left(\frac{\beta^2}{3}-\alpha^2\right)z^2\right)\right]}{\beta z}+\epsilon$$



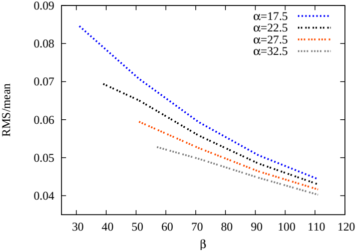


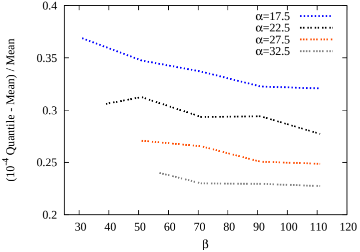
- $\alpha \sim$ curvature of field

- $\beta \sim$ adiabatic parameter
- $\frac{|p|}{B_z^2}\frac{\partial B_z}{\partial z}$

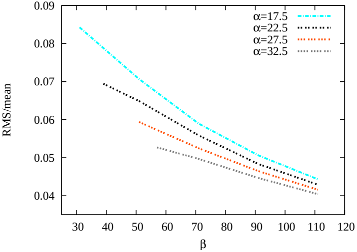
Results

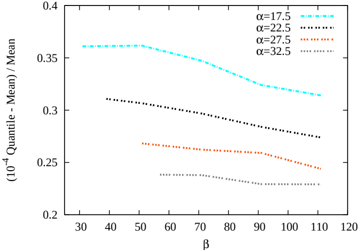
- $P_p = 0.949\, MeV/c$





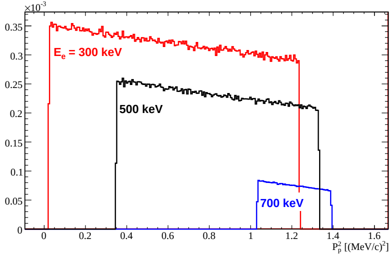
- $P_p = 1.14\, MeV/c$



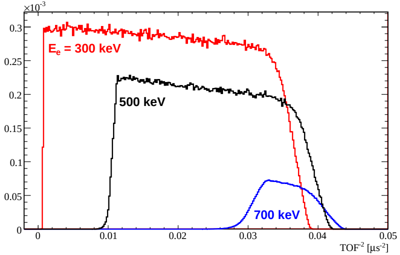


Results

Ideal Spectrometer

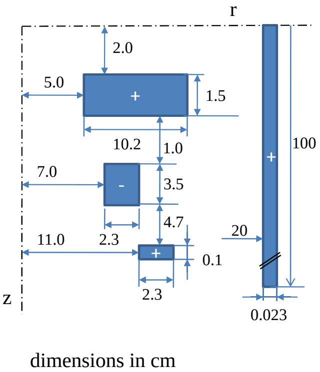


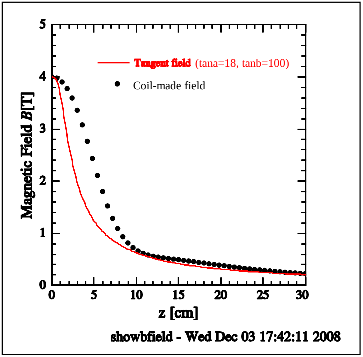
Practicable Spectrometer



E_e	Measured a
Seed	-0.10500
300 keV	-0.10526(10)
500 keV	-0.10509(10)
700 keV	-0.10529(10)

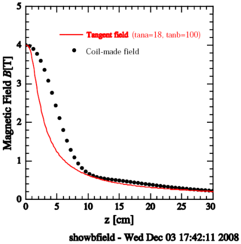
Optimization of Decay Volume Coils(_a130)

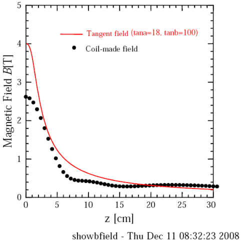


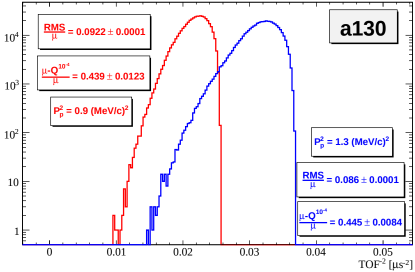


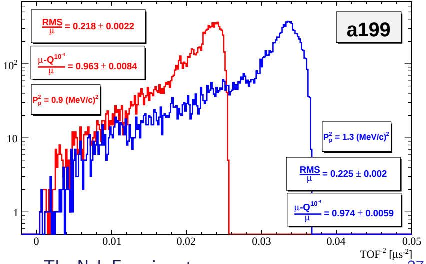
External (Big coil) field: 0.2T
Current density: 3500 A/cm^2

Results

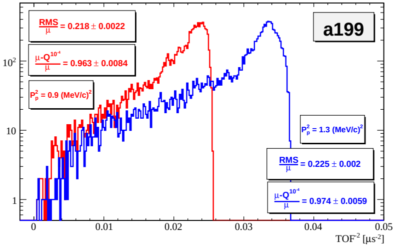

Tangent field (tana=18, tanb=100)
Coil-made field
Magnetic Field B[T]
z [cm]
showbfield - Wed Dec 03 17:42:11 2008

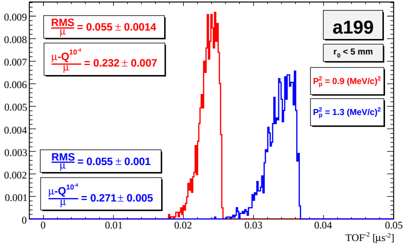

Tangent field (tana=18, tanb=100)
Coil-made field
Magnetic Field B[T]
z [cm]
showbfield - Thu Dec 11 08:32:23 2008


a130
RMS/μ = 0.0922 ± 0.0001
μ-Q^10-4/μ = 0.439 ± 0.0123
P²p = 0.9 (MeV/c)²
P²p = 1.3 (MeV/c)²
RMS/μ = 0.086 ± 0.0001
μ-Q^10-4/μ = 0.445 ± 0.0084
TOF⁻² [μs⁻²]

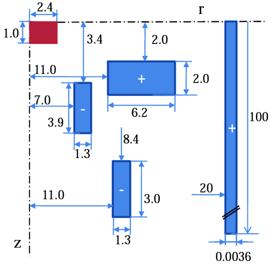

a199
RMS/μ = 0.218 ± 0.0022
μ-Q^10-4/μ = 0.963 ± 0.0084
P²p = 0.9 (MeV/c)²
P²p = 1.3 (MeV/c)²
RMS/μ = 0.225 ± 0.002
μ-Q^10-4/μ = 0.974 ± 0.0059
TOF⁻² [μs⁻²]

Large Radius Decays

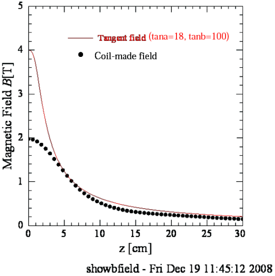


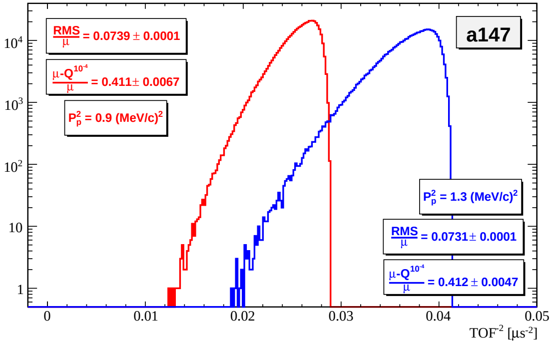


Results



dimensions in cm





Thank you for coming.

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Oxford English Dictionary

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practicable, *adj.* and *n.*

DRAFT REVISION June 2008 Earlier

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A. *adj.*

1. Able to be done or put into practice successfully; feasible; able to be used; useful, practical, effective.

2. a. Of a route, passage, entry, etc.: able to be used or traversed; that can be passed.

b. Functional, real; (*Theatre*) (of props or scenery) operable, able to be used, real as opposed to purely decorative or sham; = PRACTICAL *adj.* 1d.

†**3.** *slang.* Easily practised upon or manipulated, gullible; (also) open to collusion. *Obs.*

B. *n.*

†**1.** A course of action or an idea which is feasible, or is capable of being put into practice or realistically implemented. *Obs. rare.*

2. *Theatre.* A prop or item of usable scenery. Cf. sense A. 2b.

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