Searching for Dark Matter in a Bubble Chamber

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Seminar at University of California, Davis
April 15, 2013
There is pretty strong consensus regarding how much stuff there is in the universe.

By that same consensus, we only understand 5% of it.
Dark matter - evidence?

- Galaxy rotation curves
Dark matter - evidence?

- Galaxy rotation curves
- Galaxy clusters

Fritz Zwicky, 1930
Dark matter - evidence?

- Galaxy rotation curves
- Galaxy clusters
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- Galaxy rotation curves
- Galaxy clusters
- Gravitational lensing
Dark matter - evidence?

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- Cosmic microwave background
Dark matter - evidence?

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- Galaxy clusters
- Gravitational lensing
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Fig. 25. Measured angular power spectra of Planck + WMAP + HighL. The model plotted is Planck's best fit model including Planck's temperature + WMAP polarization + SPT. The model is labelled [Planck + WP + HighL] in Planck collaboration XVI. Error bars include cosmic variance. The horizontal axis is $\ell$.

The measured angular power spectra are in agreement with those determined by other experiments, though in agreement with the recent WMAP analysis where Hinshaw et al. find $H_0 = 70.8 \pm 3.5$ km s$^{-1}$ Mpc$^{-1}$, consistent with the Planck value to within $\sim 2\sigma$. Freedman et al. as part of the Carnegie Hubble Program use Spitzer Space Telescope mid-infrared observations to recalibrate secondary distance methods used in the HST Key Program. These authors find $H_0 = 85.4 \pm 2.6 \pm 3.2$ km s$^{-1}$ Mpc$^{-1}$ where the first error is statistical and the second systematic. Parallel effort by Riess et al. used the Hubble Space Telescope observations of Cepheid variables in the host galaxies of eight SNe Ia to calibrate the supernova magnitude-redshift relation. Their 'best estimate' of the Hubble constant from fitting the calibrated SNe magnitude-redshift relation is $H_0 = 84.9 \pm 3.5$ km s$^{-1}$ Mpc$^{-1}$ where the error is 2σ and includes known sources of systematic errors. These measurements are discrepant with the current Planck estimate at about the 3.6σ level. This discrepancy is discussed further in Planck collaboration XVI.

Extending the Hubble diagram to higher redshifts we note that the best-fit ΛCDM model provides strong predictions for the distance scale. This prediction can be compared to the measurements provided by studies of Type Ia SNe and baryon acoustic oscillations driven in large part by our preference for a higher matter density. We find mild tension with the relative distance scale inferred from compilations of SNe by Tonley et al. Suzuki et al. In contrast our results are in excellent agreement with the ΛCDM distance scale compiled in Anderson et al.

The Planck data in combination with polarization measured by WMAP and high-frequency anisotropies from τ and SPT and other lower redshift data sets provides strong constraints on deviations from the minimal model. The low redshift measurements provided by the ΛCDM allow us to break some degeneracies still present in the Planck data and significantly tighten constraints on cosmological parameters in these model extensions. The τ and SPT data help to fix our foreground model at high $\theta$. The combination of these experiments provides our best constraints on the standard 7-parameter model: values of some key parameters in this model are summarized in Table 0.

From an analysis of an extensive grid of models, we find no strong evidence to favour any extension to the base ΛCDM cosmology either from the ΛCDM temperature power spectrum alone or in combination with Planck lensing power spectrum and other astrophysical datasets. For the wide range of extensions which we have considered, the posteriors for extra parameters generally overlap the fiducial model within 2σ. The measured values of the ΛCDM parameters are relatively robust to the inclusion of different parameters, though a few do broaden significantly if additional degeneracies are introduced. When the Planck likelihood does provide marginal evidence for extensions to the base ΛCDM model, this comes predominantly from a deficit of power compared to the base model in the data at $\ell < 41$.

The primordial power spectrum is well described by a power-law over three decades in wave number, with no evidence for an increase in power at high wave numbers.
Dark matter - evidence?

- Galaxy rotation curves
- Galaxy clusters
- Gravitational lensing
- Cosmic microwave background
- Galactic collisions
So what is it?

- We know it interacts gravitationally
- It is “dark” - should not interact with light or electromagnetism
- Nearly collisionless
- Slow

Axions
Champs
Kaluza-Klein particles
WIMPs, WIMPzillas, Light WIMPS
MACHOs

Many more
So what is it?

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• It is “dark” - should not interact with light or electromagnetism

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Beyond the Standard Model!
WIMPs

- Most discussed candidate is Weakly Interacting Massive Particle
- Produced during big bang
- Decouples from ordinary matter as the universe expands and cools
- Still around today with densities of about a few per liter
- Supersymmetry produces a theoretical candidate (LSP), but others exist (e.g. Kaluza-Klein particles, ...)

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How do we find it?

- Indirect - detect annihilation products from regions of high density like the sun or the center of the galaxy

Fermi bubbles, courtesy of NASA
How do we find it?

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-Accelerators - create a WIMP at the LHC

- Missing ET and monojet searches
How do we find it?

- Indirect - detect annihilation products from regions of high density like the sun or the center of the galaxy

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- Missing ET and monojet searches

- Direct detection - WIMPs can scatter elastically with nuclei and the recoil can be detected

\[
\frac{dR}{dQ} = \frac{\rho_0}{m_\chi} \times \frac{\sigma_0 A^2}{2 \mu_p^2} \times F^2(Q) \times \int_{v_m} \frac{f(v)}{v} dv
\]

- Rate calculation

The differential cross section \(y\) for spin-independent interactions per kilogram of target mass per unit recoil energy is

- Dark matter density component, from local and galactic observations with historically a factor of 2 uncertainty
- The unknown particle physics component, hopefully determined by experiment
- Proportional to \(A^2\) for most models
- The nuclear part, approximately given by \(F^2(Q) \propto e^{-Q/Q_0}\) where \(Q_0 \sim 80 A^{5/3} \text{MeV}\)
- The velocity distribution of dark matter in the galaxy - of order 30\% uncertainty, and \(v_m = \frac{Q}{2 m^2 r^{3/2}}\)
Rate calculation

- The differential cross section (for spin-independent interactions) per kilogram of target mass per unit recoil energy is

\[
\frac{dR}{dQ} = \frac{\rho_0}{m_\chi} \times \frac{\sigma_0 A^2}{2\mu_p^2} \times F^2(Q) \times \int_{v_m} f(v) \frac{dv}{v}
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Rate calculation

- The differential cross section (for spin-independent interactions) per kilogram of target mass per unit recoil energy is

\[
\frac{dR}{dQ} = \frac{\rho_0}{m_X} \times \frac{\sigma_0 A^2}{2\mu_p^2} \times F^2(Q) \times \int_{v_m} \frac{f(v)}{v} dv
\]

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- The velocity distribution of dark matter in the galaxy - of order 30% uncertainty, and $v_m = \sqrt{Q/2m_f}$
The energy scale

- Energy of recoils is tens of keV
- Entirely driven by kinematics, elastic scattering of things with approximately similar masses (100 GeV) and \( v \sim 0.001c \)

\[
\frac{1}{2} m_N v^2 = \frac{1}{2} \times 100 \text{ GeV} \times 10^{-6} = 50 \text{ keV}
\]
Rate calculation

- Integrated rate above threshold, 100 GeV WIMP, $\sigma_0 = 10^{-45} \text{ cm}^2$

\[ I = \int_{Q_{\text{thresh}}} \frac{dQ}{dR} = \int_{Q_{\text{thresh}}} dQ \frac{\rho_0 \sigma_0 A^2}{m_\chi 2\mu_p^2} F^2(Q) \int_{v_m} \frac{f(v)}{v} dv \]

- Looking for a handful of events
The canonical plot

- Limited at low mass by detector threshold
- Limited at high mass by density
The canonical plot

- What happened to “weakly” interacting?

- Mediation via Z was excluded long ago ($\sim 10^{-39}$ cm$^2$), but only now are we probing Higgs exchange.
So we look for WIMPs

• A few hundred just passed through us, and we might expect a handful of counts in a detector per year
So we look for WIMPs

• A few hundred just passed through us, and we might expect a handful of counts in a detector per year

• The problem is that background radioactivity is everywhere!

100 events/second/kg = 3,000,000,000,000 events/year in a ton-scale experiment
Backgrounds!
Background sources

- Cosmic rays are constantly streaming through

- All experiments have to go underground to get away from cosmic rays
Background sources

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- Radioactive contaminants - rock, radon in air, impurities
- Emphasis on purification and shielding
Background sources

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• Radioactive contaminants - rock, radon in air, impurities

• Emphasis on purification and shielding

• The detector itself - steel, glass, detector components

• Self-shielding to leave a clean inner region

• Discrimination - can you tell signal from background (gamma rays, alphas, neutrons, etc)?
CDMS - Charge to heat

Xenon TPCs - Charge to light

Electronic recoils (gammas) vs. nuclear recoils (WIMPs)

Argon - Pulse shape discrimination

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Background sources

- Cosmic rays are constantly streaming through
  - All experiments have to go underground to get away from cosmic rays
- Radioactive contaminants - rock, radon in air, impurities
  - Emphasis on purification and shielding
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Chicagoland Observatory for Underground Particle Physics (COUPP)

[Some debate over the pronunciation (should the Ps be silent?)]

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COUPP bubble chamber

- Pressure expansion creates superheated fluid, CF$_3$I
  - F for spin-dependent
  - I for spin-independent
- Alternatives - e.g. C$_3$F$_8$
- Particle interactions nucleate bubbles
- Cameras see bubbles
- Recompress chamber to reset

Propylene glycol (hydraulic fluid)
Why bubble chambers?

• To form a bubble requires two things

• Enough energy

• Enough energy density - length scale must be comparable to the critical bubble size

• By choosing superheat parameters appropriately (temperature and pressure), bubble chambers are blind to electronic recoils
Why bubble chambers?
Why bubble chambers

- Easy to identify multiple scattering events backgrounds
- Easy DAQ and analysis chain
- Cameras
- Piezos
- No PMTs, no cryogenics
Why not bubble chambers?

- Threshold detectors - no energy resolution
- Harder to distinguish some backgrounds, less information about any potential signal
  - Alphas (several MeV) were a big concern
- Energy threshold calibrations are hard and important
- Bubble chambers are slow - about 30 s of deadtime for every event
- Overall rate must be low
About those alphas

- Alphas deposit energy over tens of microns
- Nuclear recoils deposit theirs in tens of nanometers
- In COUPP bubble chambers, alphas are several times louder
The COUPP program

- COUPP4: A 2-liter chamber operating at SNOLAB since 2010
- COUPP60: Up to 40 liters, commissioning at SNOLAB now
- COUPP500: Ton scale detector, funded by NSF and DOE, at SNOLAB in 2015?
COUPP-4
COUPP4: First run 2010-2011

- 17.4 live days at 8 keV threshold
- 21.9 live days at 11 keV threshold
- 97.3 live days at 16 keV threshold
- 79% acceptance for nuclear recoils after all cuts (including fiducial)
Better than 99.3% rejection against alphas at 16 keV threshold

Limited by statistics, and backgrounds
This is what dark matter would sound like
This is what dark matter would sound like
This is what an alpha sounds like
This is what an alpha sounds like
Both together, just to hear the difference
COUPP4: Results and sensitivity

- 20 WIMP candidates (8 at 8 keV, 6 at 11 keV, 8 at 16 keV)
- 3 multiple bubble events imply neutrons
COUPP4: Results and sensitivity

- 20 WIMP candidates (8 at 8 keV, 6 at 11 keV, 8 at 16 keV)

- 3 multiple bubble events imply neutrons

- U, Th in the piezo-acoustic sensors and the viewports
20 WIMP candidates (8 at 8 keV, 6 at 11 keV, 8 at 16 keV)

3 multiple bubble events imply neutrons

U, Th in the piezo-acoustic sensors and the viewports

Remaining excess of singles at low threshold

Time clustering

Correlated with activity at water-CF$_3$I interface
COUPP4: Results and sensitivity

- Given uncertainties on backgrounds, no background subtraction: PRD 86:052001 (2012)
COUPP4: Results and sensitivity

- Given uncertainties on backgrounds, no background subtraction: PRD 86:052001 (2012)
COUPP4: Results and sensitivity

- Removed known neutron sources and improved fluid purification
- Second run ended last November
Detour: Threshold and efficiency

- Threshold determined from Seitz, Phys. of Fluids 1, 2 (1958)

\[ p_v - p_l = \frac{2\sigma}{r_c} \]

\[ E_{th} = 4\pi r_c^2 \left( \sigma - T \frac{\partial \sigma}{\partial T} \right) + \frac{4}{3} \pi r_c^3 \rho_v h \]

- Energy deposition \( E_{th} \) within length \( R_c \) will nucleate a bubble (Hot Spike model)

- Theory assumes a step function above threshold
Rate = \int \text{WIMP recoil spectrum} \times \text{Bubble nucleation efficiency}

- Effect of threshold shape depends on target, WIMP mass
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- Energy deposition \( E_{th} \) within length \( r_c \) will nucleate a bubble (Hot Spike model)

- Theory assumes a step function above threshold

- Needs calibration
Detour: Threshold and efficiency

- Complicated by molecule, CF$_3$I
- Recall that the recoil track length L must be comparable to the bubble radius R$_c$
Carbon and fluorine

- Use neutron calibration sources at SNOLAB

- Compare MCNP-predicted rates of single, double, triple and quadruple bubble events with observation

- Data show a shortfall of events compared to simulation of the Seitz Model - i.e. the threshold is not a step function
What about iodine?

- Main sensitivity to spin independent dark matter from iodine
- 85% of neutron source interactions are with C and F
- Heavy radon daughter nuclei are a proxy and are step-like

- We really need a direct calibration

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COUPP Iodine Recoil Threshold Experiment

- Bubble chambers are insensitive to MIPs
- Elastic scattering of charged particles can be tracked with very high precision

\[
T = E_{\text{recoil}} = \frac{(p\theta)^2}{2m_r}
\]
COUPP Iodine Recoil Threshold Experiment

- Provides event by event energy information bubble chambers normally can’t provide

- 75% of elastic scattering events with 12 GeV pions at energies relevant to dark matter involve iodine
COUPP Iodine Recoil Threshold Experiment

- Test beam at Fermilab with a silicon pixel telescope
- Designed a new test tube sized bubble chamber
COUPP Iodine Recoil Threshold Experiment

- Beam run at Fermilab in March, 2012

---

**Telescope trigger**

**Acoustic signal**

![Graph showing voltage (au) vs time (ms)]

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>-22.5</td>
</tr>
<tr>
<td>200</td>
<td>-22</td>
</tr>
<tr>
<td>0</td>
<td>-21.5</td>
</tr>
<tr>
<td>200</td>
<td>-21</td>
</tr>
</tbody>
</table>

![Graph showing Z position (mm) vs Y position (mm)]

- **Upstream hits**
- **Downstream hits**

![Graph showing track vertex in y (mm) vs track vertex in y (mm)]

---

Tuesday, April 16, 2013
COUPP Iodine Recoil Threshold Experiment

- Analysis shows that iodine threshold is very close to a step function at the predicted energy
- Limited by resolution (MCS) and statistics
COUPP60

- Engineering run at shallow site in 2010
- Low backgrounds and acoustic discrimination
COUPP60

- Engineering run at shallow site in 2010
- Low backgrounds and acoustic discrimination
- Fluid darkening due to photodissociation of iodine
- Excessive surface rate
COUPP60

- Engineering run at shallow site in 2010
- Low backgrounds and acoustic discrimination
- Fluid darkening due to photodissociation of iodine
- Excessive surface rate
- Solutions tested in second run November, 2011
- Moving to SNOLAB since last summer
Running by end of month?
COUPP500 (or EREBOS-500)

- New merger with Canadian PICASSO collaboration (recent vote chose EREBOS as the new name)
- Funded by NSF and DOE as part of G2 (big showdown in October?)
- Engineering well underway
- Construction 2014-2015?
COUPP4 redux

- Alternate fluid - remove the iodine - $\text{C}_3\text{F}_8$
- Lower threshold (down to 3 keV in test stand)
- Improved sensitivity at low WIMP mass
- Improved SD sensitivity
- First effort in concert with the PICASSO collaboration
- Possible use in COUPP500 chamber
Projections

Spin-dependent proton cross-section (cm$^2$)

- SIMPLE (2011)
- IceCube
- Super-K (hard)
- cMSSM

WIMP Mass (GeV)

-UCK (soft)
- IceCube
- CMS (A-V)
- PICASSO (2012)
- SIMPLE (2010)
- COUPP (Apr. 2012)
- PICASSO (2012)

- COUPP-2L, C3F8, 4 months
- COUPP500, 3 yrs

- $\chi \chi \rightarrow b\bar{b}$
- $\chi \chi \rightarrow W^+W^-$

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Projections

Spin-independent cross-section (cm$^2$) vs. WIMP Mass (GeV)

- DAMA
- CoGent
- CRESST
- COUPP-2L, C3F8, 4 months
- COUPP4 (Apr. 2012)
- COUPP60, 1000 kg·d
- XENON100
- COUPP60, 10000 kg·d
- COUPP500, 3 yrs

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Projections

Spin-independent cross-section (cm$^2$)

- DAMA
- CoGent
- CRESST

CDMS

- COUPP-2L, C3F8, 4 months
- COUPP4 (Apr. 2012)
- COUPP60, 1000 kg–d
- COUPP60, 10000 kg–d
- XENON100
- COUPP500, 3 yrs

SuperCDMS (Soudan, 3 yrs, running)

WIMP Mass (GeV)

10$^{-39}$ to 10$^{3}$
Projections

Spin-independent cross-section (cm$^2$)

- DAMA
- CoGent
- CRESST
- CDMS
- SuperCDMS (Soudan, 3 yrs, running)
- DarkSide 50 (3 yrs, not running)
- COUPP-2L, C3F8, 4 months
- COUPP4 (Apr. 2012)
- COUPP60, 1000 kg–d
- XENON100
- COUPP60, 10000 kg–d
- COUPP500, 3 yrs

Tuesday, April 16, 2013
Projections

- CDMS
- XENON100
- COUPP4 (Apr. 2012)
- COUPP60, 1000 kg
- COUPP60, 10000 kg
- COUPP500, 3 yrs
- CoGent
- CRESST
- DAMA
- SuperCDMS (Soudan, 3 yrs, running)
- DarkSide 50 (3 yrs, not running)
- LUX (1 yr, running?, "conservative")

Spin–independent cross-section (cm$^2$)

- $10^{-47}$
- $10^{-46}$
- $10^{-45}$
- $10^{-44}$
- $10^{-43}$
- $10^{-42}$
- $10^{-41}$
- $10^{-40}$
- $10^{-39}$

WIMP Mass (GeV)

- $10^1$
- $10^2$
- $10^3$
~1 event kg\(^{-1}\) day\(^{-1}\)

(Gross Masses kg)

~1 event 100 kg\(^{-1}\) yr\(^{-1}\)

~1 event 1 tonne\(^{-1}\) yr\(^{-1}\)

Many of current projections omitted from this plot
Conclusion

- Dark matter searches are making fast progress (indirect, accelerator and direct)

- COUPP is producing the best direct detection limits on spin-dependent dark matter

- COUPP bubble chambers are also competitive for spin-independent searches
Dark matter controversies

DAMA - positive claim for 10 years!
Dark matter controversies

DAMA - positive claim for 10 years!
Dark matter controversies

DAMA - positive claim for 10 years!

A few years ago, CoGeNT saw an excess and then a possible annual modulation
Dark matter controversies

DAMA - positive claim for 10 years!

CoGeNT reanalyzed their own data and found a new background, decreasing the sensitivity.
Dark matter controversies

Recently, CoGeNT (run by my boss) saw an excess and now a possible annual modulation.

Fig. 13. The WIMP parameter space compatible with the CRESST results discussed here, using the background model described in the text, together with the exclusion limits from CDMS-II [12], XENON100 [13], and EDELWEISS-II [14], as well as the CRESST limit obtained in an earlier run [1]. Additionally, we show the 90% confidence regions favored by CoGeNT [15] and DAMA/LIBRA [16] (with the assumed signal at 2-6 keV).
• At APS on Saturday, CDMS (which has historically been the most conservative experiment, culturally speaking) announced a result that is consistent with a light WIMP hypothesis (best fit at 8.6 GeV, $1.9 \times 10^{-41}$ cm$^2$)

• 3 candidate events over an estimated background of $\sim$0.7. WIMP hypothesis fits with p-value of 68%, background only at 4.5%

• Nuclear recoil events (CDMS has discrimination, unlike DAMA or CoGeNT)
As of Saturday...

The figure shows a graph of WIMP-nucleon cross-section against WIMP mass, with various data sets and experimental limits represented by different colored regions.

- DAMA
- CoGeNT
- CRESST
- Xenon
- CDMS

The filled regions represent the best-fit regions from this analysis, while the dashed lines are the confidence levels. The figure illustrates the current status of WIMP dark matter searches.
We’ll see?
Possible signals

WIMP Mass (GeV)

Spin-independent cross-section (cm$^2$)

CDMS

COUPP4 (Apr. 2012)

COUPP60, 1000 kg·d

COUPP60, 10000 kg·d

COUPP500, 3 yrs

DAMA

CoGent

CRESST

XENON100

COUPP–2L, C3F8, 4 months

Tuesday, April 16, 2013
**$^{88}$YBe ($\gamma$,n) neutron source**

Mono-energetic 152 keV neutron source.

<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)</th>
<th>$\sigma(E_\gamma)$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1674.7</td>
<td>0.88 ± 0.16</td>
</tr>
<tr>
<td>1705.2</td>
<td>1.33 ± 0.24</td>
</tr>
<tr>
<td>1724.9</td>
<td>1.10 ± 0.20</td>
</tr>
<tr>
<td>1778.9</td>
<td>0.73 ± 0.13</td>
</tr>
<tr>
<td><strong>1836.0</strong></td>
<td><strong>0.47 ± 0.09</strong></td>
</tr>
<tr>
<td>2167.6</td>
<td>0.18 ± 0.04</td>
</tr>
</tbody>
</table>

WIMP-nucleon scattering

\[ \sigma_0 = \frac{4 \mu^2}{\pi} \left[ f_p N_p + f_n N_n \right]^2 + \frac{32 G_F^2 \mu^2}{\pi} \frac{J+1}{J} \left[ a_p \langle S_p \rangle + a_n \langle S_n \rangle \right]^2 \]

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Z</th>
<th>Odd Nucleon</th>
<th>J</th>
<th>\langle S_p \rangle</th>
<th>\langle S_n \rangle</th>
<th>C_A^P / C_p</th>
<th>C_A^n / C_n</th>
</tr>
</thead>
<tbody>
<tr>
<td>¹⁹F</td>
<td>9</td>
<td>p</td>
<td>1/2</td>
<td>0.477</td>
<td>-0.004</td>
<td>9.10 \times 10^{-1}</td>
<td>6.40 \times 10^{-5}</td>
</tr>
<tr>
<td>²³Na</td>
<td>11</td>
<td>p</td>
<td>3/2</td>
<td>0.248</td>
<td>0.020</td>
<td>1.37 \times 10^{-1}</td>
<td>8.89 \times 10^{-4}</td>
</tr>
<tr>
<td>²⁷Al</td>
<td>13</td>
<td>p</td>
<td>5/2</td>
<td>-0.343</td>
<td>0.030</td>
<td>2.20 \times 10^{-1}</td>
<td>1.68 \times 10^{-3}</td>
</tr>
<tr>
<td>²⁹Si</td>
<td>14</td>
<td>n</td>
<td>1/2</td>
<td>-0.002</td>
<td>0.130</td>
<td>1.60 \times 10^{-5}</td>
<td>6.76 \times 10^{-2}</td>
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