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The E143 Collaboration
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We report on a high-statistics measurement of the deuteron spin structure function g_1^d at a beam energy of 29 GeV in the kinematic range $0.029 < x < 0.8$ and $1 < Q^2 < 10$ (GeV/c)^2. The integral $\Gamma_1^d = \int_0^1 g_1^d dx$ evaluated at fixed $Q^2 = 3$ $(GeV/c)^2$ gives 0.042 ± 0.003(stat.) ± 0.004(syst.). Combining this result with our earlier measurement of g_1^p, we find $\Gamma_1^p - \Gamma_1^n = 0.163 \pm 0.010$(stat.) ± 0.016(syst.), which agrees with the prediction of the Bjorken sum rule with O(α_s^3) corrections, $\Gamma_1^p - \Gamma_1^n = 0.171 \pm 0.008$. We find the quark contribution to the proton helicity to be $\Delta q = 0.30 \pm 0.06$.

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The longitudinal and transverse spin-dependent structure functions $g_1(x, Q^2)$ and $g_2(x, Q^2)$ for polarized deep-inelastic lepton–nucleon scattering provide information on the spin structure of the proton and neutron. A fundamental quantum chromodynamics (QCD) sum rule, originally derived from current algebra by Bjorken [1], predicts the difference $\Gamma_1^p - \Gamma_1^n = \frac{1}{6}(g_A/g_V)$ at infinite Q^2 where $\Gamma_1^{p(n)} = \int_0^1 g_1^{p(n)}(x, Q^2)dx$ for the proton (neutron), and g_A and g_V are the axial–vector and vector coupling constants in neutron β-decay. QCD corrections up to third order in α_s have been computed [2], thus making a test of the Bjorken sum rule possible at finite Q^2. Measurements of Γ_1^p [3] [4], Γ_1^n from ^{3}He [5], as well as results from deuterium [6] targets, are in agreement with this prediction within experimental uncertainties. Separate sum rules for Γ_1^p and Γ_1^n were derived by Ellis and Jaffe [7] under the assumptions of SU(3) flavor symmetry and an unpolarized strange sea. Higher order QCD corrections have been calculated [8] [9].

The polarized spin structure function g_1 is related to the virtual photon asymmetries A_1 and A_2:

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

where F_1 is the unpolarized structure function, $\gamma^2 = Q^2/\nu^2$, $\nu = E - E'$, E and E' are incident and scattered electron energies respectively, and A_1 and A_2 are virtual photon cross section asymmetries. [10] These asymmetries are related by kinematic factors to the experimentally measured electron asymmetries $A_\parallel$ and $A_\perp$. The longitudinal asymmetry $A_\parallel$ is the cross section asymmetry between negative- and positive-helicity electron beams when the target nucleon is polarized parallel to the beam direction. The transverse asymmetry $A_\perp$ is the asymmetry when the target nucleon is polarized transverse to the beam direction. We use the relationships $A_1 = (A_\parallel/D - \eta A_\perp/d)/(1 + \eta\zeta)$, and $A_2 = (\zeta A_\parallel/D + A_\perp/d)/(1 + \eta\zeta)$, where $\eta = \epsilon\sqrt{Q^2/E^2}/(1 - \epsilon E'/E)$, $\zeta = \eta(1+\epsilon)/2\epsilon$, $D = (1 - \epsilon E'/E)/(1 + \epsilon R)$ is the depolarization factor, $d = D\sqrt{2\epsilon/(1+\epsilon)}$, $\epsilon^{-1} = 1 + 2[1 + (\nu^2/Q^2)]\tan^2(\theta/2)$, $R = \sigma_L/\sigma_T$, and θ is the electron scattering angle. Thus, the quantity g_1 can be written as $g_1 = (F_1/D')(A_\parallel + \tan(\theta/2)A_\perp)$, where $D' = (1-\epsilon)(2-y)/[y(1+\epsilon R)]$ and $y = \nu/E$.

Experiment E143 used the SLAC polarized electron beam with energies of 9.7, 16.2, and 29.1 GeV incident on polarized proton and deuteron targets in End Station A to measure g_1^p, g_2^p, g_1^d, and g_2^d in the range $1 < Q^2 < 10$ (GeV/c)^2 and $0.029 < x < 0.8$. This Letter reports on our analysis of the 29.1 GeV data, which yielded g_1^d results with considerably smaller statistical uncertainties than previous measurements [6]. We adopt the convention that g_1^d refers to the average structure function of the nucleon in the deuteron: $g_1^d \approx \frac{1}{2}(g_1^p + g_1^n)$.

The longitudinally polarized electron beam [11] was produced by a circularly polarized laser beam illuminating a strained gallium arsenide photocathode. Beam pulses of typically 2 μsec duration were delivered at 120 Hz, and the helicity was selected randomly on a pulse-to-pulse basis to minimize instrumental asymmetries, which were found to be negligible. The beam polarization P_b was measured daily with a Møller polarimeter, and was found to vary with the cathode quantum efficiency from 0.83 to 0.86. An overall uncertainty on P_b of ± 0.02 was achieved. [4]

The target [12] was a 3-cm-long 2.5-cm-diameter cylinder filled with granules of deuterated ammonia, $^{15}ND_3$, of greater than 98% isotopic purity. It was polarized by the technique of dynamic nuclear polarization in a 4.8-T magnetic field. An average in-beam polarization P_t of 25% was measured with a nuclear magnetic resonance (NMR) technique, and a maximum of greater than 40% was achieved. The NMR signal was calibrated by measuring the thermal–equilibrium polarization near 1.6 K. An overall relative uncertainty of 4% on P_t was achieved.

Scattered electrons were detected in two independent spectrometers [13] at angles of 4.5° and 7° with respect to the incident beam. Electrons were identified in each spectrometer by use of two threshold gas Čerenkov counters and a 200–element shower–counter array of lead glass blocks 24 radiation lengths thick. Particle momenta and scattering angles were measured with seven planes of scintillator hodoscopes.

The experimental longitudinal and transverse asymmetries $A_\parallel$ and $A_\perp$ were determined from

$$A_\parallel \text{ (or } A_\perp) = C_1\left(\frac{N_L - N_R}{N_L + N_R}\frac{1}{fP_bP_t} - C_2\right) + A_{rc}, \tag{2}$$

where N_L and N_R are the corrected numbers of scattered electrons per incident charge for negative and positive beam helicity, respectively. Charge–symmetric background processes were measured by reversing the spectrometer polarity and have no measurable asymmetry. These processes led to rate corrections of 10% at the lowest x bin, decreasing rapidly at higher x. The rates were also corrected for deadtime effects.

The correction factors C_1 and C_2 account for the polarizations of ^{15}N, unsubstituted ^{14}N, and residual protons in the target. The factor C_2 ranges from 3 to 5% of the measured proton asymmetry, and C_1 is typically 1.016. These factors were determined from measured nitrogen polarizations and a shell-model calculation to determine the contribution of the unpaired p-shell proton.

The dilution factor f represents the fraction of measured events expected to originate from polarizable deuterons in the target. It was calculated from the composition of the target, which contained about 23% deuterons, 56% ^{15}N, 10% ^{4}He, 6% Al, 4% Cu, and 1% Ti by weight. The dilution factor was x dependent and varied from 0.22 at low x to 0.25 at high x. The relative systematic error in f was determined from uncertainties in the target composition and cross section ratios, and ranged from 2.2 to 2.6%.

The radiative correction A_{rc} includes both internal [14] and external [15] contributions, and typically changed $A_\parallel$ by 10% of its value. Systematic errors on A_{rc} were estimated based on uncertainties in the input models and correspond to relative errors on $A_\parallel$ of typically 7% for $x > 0.1$, increasing to 100% at $x = 0.03$.

Data from the two spectrometers, which differ by about a factor of two in average Q^2, are consistent with A_1^d, A_2^d, and g_1^d/F_1^d being independent of Q^2 in the overlap region $0.07 < x < 0.55$, and therefore have been averaged together. The values of A_1^d from this experiment at $E = 29.1$ GeV shown in Fig. 1 and listed in Table I are consistent with the higher Q^2 results from the Spin Muon Collaboration (SMC) [6].

Values of g_1^d at the average $Q^2 = 3$ (GeV/c)^2 of this experiment are shown in Fig. 2a. The evaluation of g_1^d at constant Q^2 is model–dependent. We made the assumption that g_1^d/F_1^d is independent of Q^2. For $F_1^d/(1+\gamma^2) = F_2^d/[2x(1+R)]$ we used the New Muon Collaboration fit [16] to F_2^d and the SLAC fit to R [17]. Using the SLAC fit to F_2^d [18] gives similar results. The systematic error on F_1^d is typically 2.5%, increasing to 5% at the lowest x bin and 15% at the highest x bin. The integral of g_1^d at $Q^2 = 3$ (GeV/c)^2 and over the measured range $0.029 < x < 0.8$ is $\int_{0.029}^{0.8} g_1^d(x)dx = 0.040 \pm 0.003 \pm 0.004$, where the errors are statistical and systematic respectively. The integral is decreased by 0.002 if we make the alternate assumption that both A_1^d and A_2^d are independent of Q^2.

Assuming g_1^d varies as $(1-x)^3$ at high x [19], the extrapolation for $x > 0.8$ yields $\int_{0.8}^{1} g_1^d(x)dx = 0.000 \pm 0.001$. To make the extrapolation to $x = 0$, we make a model-dependent assumption that the data is described by the Regge-motivated form [20] $g_1^d(x) = Cx^{-\alpha}$, where α is allowed to be in the range –0.5 to 0. [21] A fit to the data of this experiment in the range $x < x_{max} = 0.1$ gives $\int_0^{0.029} g_1^d(x)dx = 0.001 \pm 0.001$. The uncertainty includes a statistical component, the uncertainty in α, and the effect of varying the fitting range from $x_{max} = 0.05$ to $x_{max} = 0.12$. Including the data of the SMC [6] in the fit does not change the results. An alternate form [22], $g_1^d(x) = C' \log(x)$, which provides good fits to low x data on F_2 from HERA, gives similar results. Thus, we obtain the total integral $\Gamma_1^d(E143) = 0.042 \pm 0.003(\text{stat.}) \pm 0.004(\text{sys.})$, to be compared with the results of SMC at $Q^2 = 4.7(GeV/c)^2$: $\Gamma_1^d(SMC) = 0.023 \pm 0.020(\text{stat.}) \pm 0.015(\text{sys.})$. The contributions to systematic uncertainties are given in Table II.

The Ellis-Jaffe sum rule for the deuteron is related to the sum rules for the proton and the neutron by: $\Gamma_1^d = \frac{1}{2}(\Gamma_1^p + \Gamma_1^n)(1 - 1.5\omega_D)$, where ω_D is the probability that the deuteron will be in a D-state. We use $\omega_D = 0.05 \pm 0.01$ [23] given by $N-N$ potential calculations. No other nuclear contributions to ω_D are included. The sum rule predicts $\Gamma_1^d(EJ) = 0.069 \pm .004$ where we have used $F + D = g_A/g_V = 1.2573 \pm 0.0028$ and $F/D = 0.575 \pm 0.016$ [24], and $\alpha_s = 0.35 \pm 0.05$ [25] for QCD corrections to $Q^2 = 3(GeV/c)^2$. [8] Our measurement of Γ_1^d provides a precise test of the Ellis Jaffe sum rule, and shows a disagreement of more than 3–σ.

The spin structure function integral can be used in the quark parton model to extract the helicity contributions to the proton of each type of quark and antiquark. Measurements using the deuteron are expected to be more sensitive than those using either the proton or the neutron [26]. We find the total contribution from all quarks to be $\Delta q = 0.30 \pm 0.06$, and the contribution from strange quarks and antiquarks to be $\Delta s = -0.09 \pm 0.02$. They are the most precise determinations to date and are consistent with earlier results [27].

The neutron spin structure function can be extracted using the relation $g_1^n(x) = 2g_1^d(x)/(1 - 1.5\omega_D) - g_1^p(x)$. The results obtained using our earlier measurements [4] of $g_1^p(x)$ are compared in Fig. 2b with the results obtained by E142 [5] at $Q^2 = 2(GeV/c)^2$ using a ^{3}He target. We use the same extrapolation procedure as in the case of the deuteron and find $\Gamma_1^n(E143) = -0.037 \pm 0.008(\text{stat.}) \pm 0.011(\text{sys.})$, compared with $\Gamma_1^n(E142) = -0.022 \pm 0.007(\text{stat.}) \pm 0.009(\text{sys.})$. The correlations between proton and deuteron measurements were accounted for when determining the systematic uncertainty contributions in Table II.

The Bjorken sum rule prediction of $\Gamma_1^p - \Gamma_1^n = 0.171 \pm 0.008$ at 3 $(GeV/c)^2$ can be tested by combining proton and deuteron results: $g_1^p(x) - g_1^n(x) = 2g_1^p(x) - 2g_1^d(x)/(1 - 1.5\omega_D)$. The extrapolation to $x = 0$ and $x = 1$ follows the same procedure as in the case of the deuteron. Our result at $Q^2 = 3$ $(GeV/c)^2$, $\Gamma_1^p(E143) - \Gamma_1^n(E143) = 0.163 \pm 0.010(\text{stat.}) \pm 0.016(\text{sys.})$, is consistent with the prediction. Contributions to systematic uncertainties are given in Table II. This result is also consistent with that obtained by combining the Γ_1^p result from this experiment [4] and the Γ_1^n result from E142 [5]: $\Gamma_1^p(E143) - \Gamma_1^n(E142) = 0.149 \pm 0.014$.

In conclusion, we have performed a high-statistics measurement of the deuteron spin structure function g_1^d, and find the Ellis-Jaffe sum rule violated by more than 3–σ. When combined with our earlier results on g_1^p, we find the difference $\Gamma_1^p - \Gamma_1^n$ is in agreement with the fundamental Bjorken sum rule.

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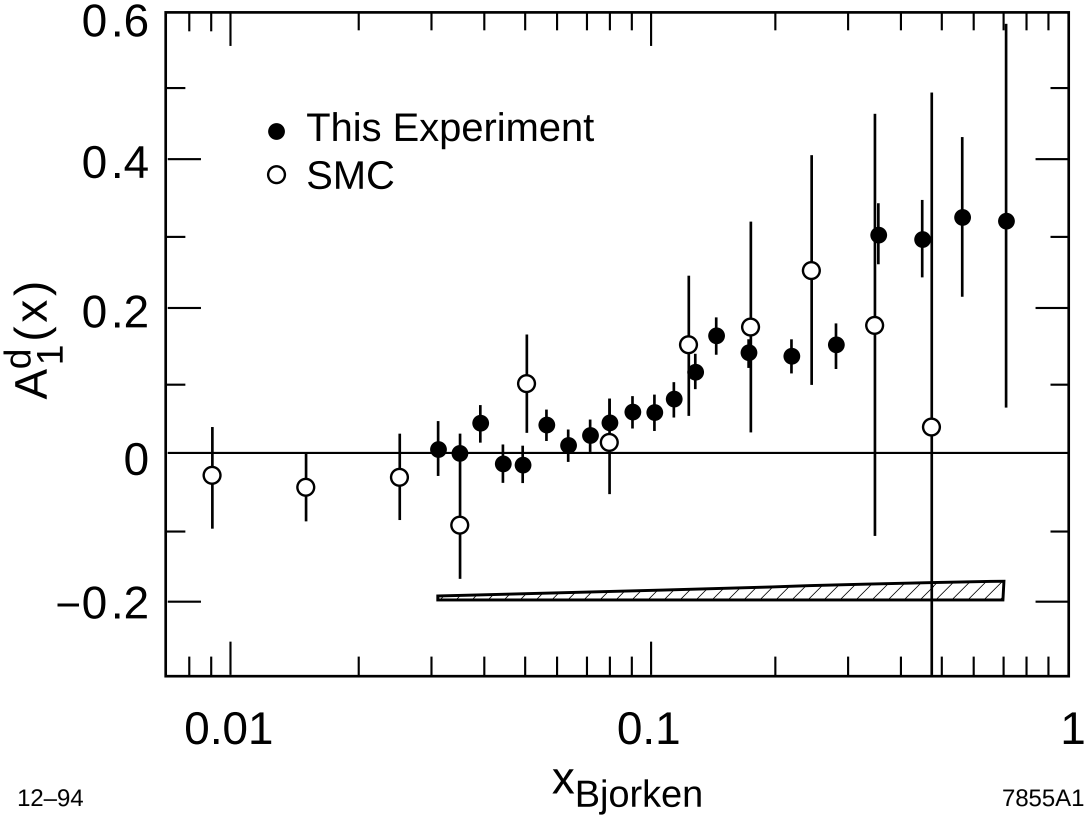

FIG. 1. The virtual photon asymmetry A_1^d from this experiment. The systematic errors are indicated by the shaded band. The average Q^2 varies from 1.3 $(\mathrm{GeV/c})^2$ at low x to 9 $(\mathrm{GeV/c})^2$ at high x. Data from the SMC collaboration [6] are also shown.

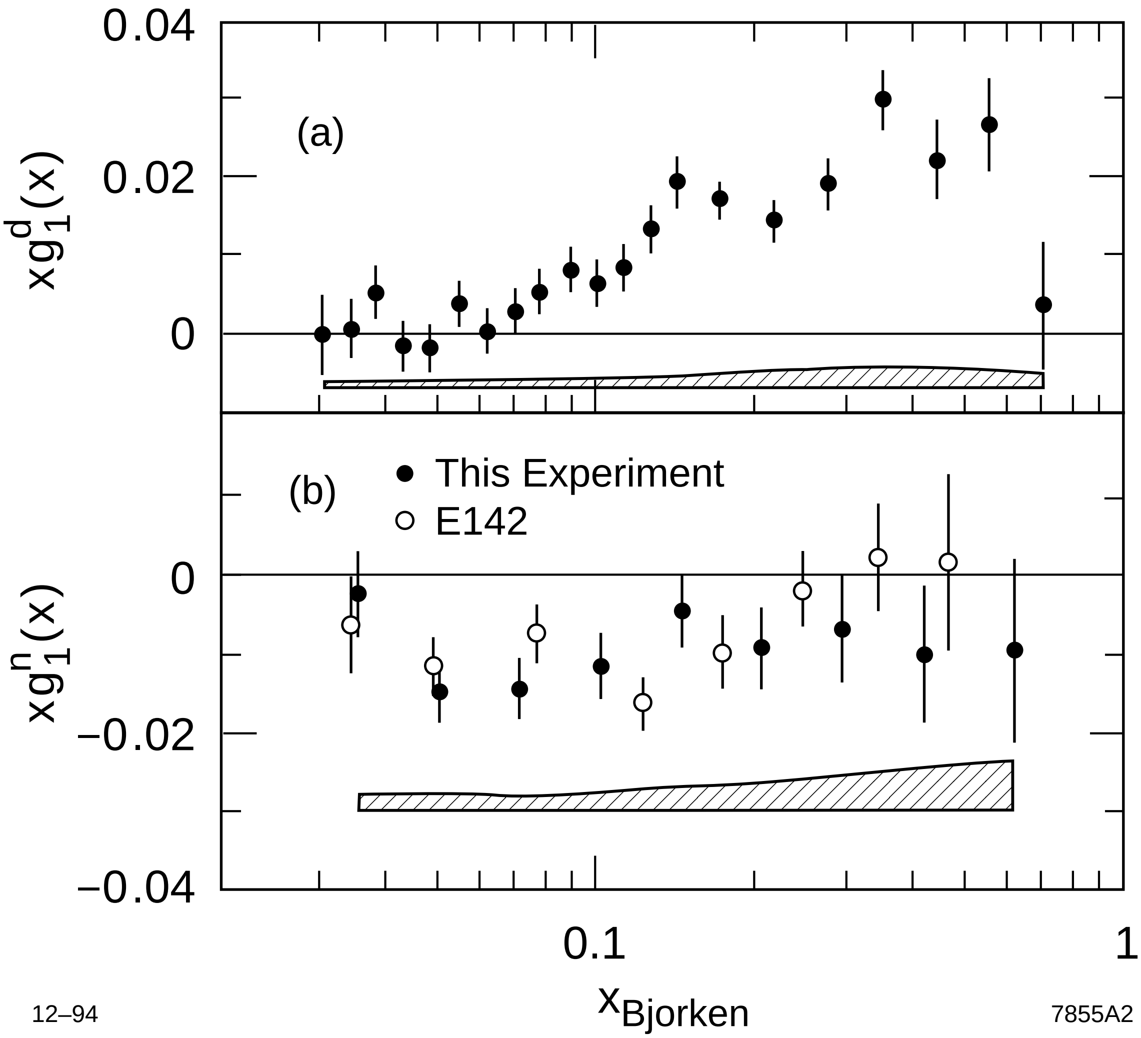

FIG. 2. Values of xg_1 from this experiment (E143) as a function of x for (a) the deuteron and (b) the neutron. The errors are statistical only. Systematic errors are indicated by the shaded bands. Also shown are the neutron results from SLAC E142. [5]

TABLE I. Average values A_1^d from the $E = 29.1$ GeV data of this experiment at the indicated average values of Q^2. Also shown are values of g_1^d at fixed $Q^2 = 3$ (GeV/c)^2, evaluated assuming g_1^d/F_1^d is independent of Q^2.

x	$<Q^2>$ (GeV/c)^2	A_1^d ±stat ±syst	g_1 at $Q^2 = 3$ $(GeV)^2$ ±stat ±syst
0.031	1.27	$0.007 \pm 0.037 \pm 0.007$	$0.009 \pm 0.166 \pm 0.030$
0.035	1.39	$-0.001 \pm 0.028 \pm 0.006$	$0.026 \pm 0.111 \pm 0.029$
0.039	1.52	$0.040 \pm 0.025 \pm 0.006$	$0.144 \pm 0.089 \pm 0.024$
0.044	1.65	$-0.015 \pm 0.024 \pm 0.006$	$-0.032 \pm 0.073 \pm 0.017$
0.049	1.78	$-0.016 \pm 0.023 \pm 0.005$	$-0.033 \pm 0.062 \pm 0.014$
0.056	1.92	$0.037 \pm 0.022 \pm 0.005$	$0.075 \pm 0.053 \pm 0.013$
0.063	2.07	$0.009 \pm 0.022 \pm 0.004$	$0.006 \pm 0.046 \pm 0.008$
0.071	2.22	$0.023 \pm 0.022 \pm 0.004$	$0.043 \pm 0.041 \pm 0.008$
0.079	2.48	$0.042 \pm 0.022 \pm 0.004$	$0.070 \pm 0.037 \pm 0.008$
0.090	2.78	$0.054 \pm 0.022 \pm 0.004$	$0.093 \pm 0.033 \pm 0.008$
0.101	3.11	$0.053 \pm 0.022 \pm 0.004$	$0.066 \pm 0.029 \pm 0.006$
0.113	3.43	$0.071 \pm 0.023 \pm 0.005$	$0.076 \pm 0.027 \pm 0.006$
0.128	3.74	$0.106 \pm 0.024 \pm 0.007$	$0.106 \pm 0.024 \pm 0.008$
0.144	4.06	$0.156 \pm 0.025 \pm 0.009$	$0.136 \pm 0.023 \pm 0.008$
0.172	4.59	$0.133 \pm 0.019 \pm 0.010$	$0.101 \pm 0.014 \pm 0.007$
0.218	5.27	$0.129 \pm 0.023 \pm 0.010$	$0.067 \pm 0.013 \pm 0.006$
0.276	5.93	$0.143 \pm 0.030 \pm 0.012$	$0.069 \pm 0.012 \pm 0.006$
0.350	6.61	$0.294 \pm 0.041 \pm 0.021$	$0.086 \pm 0.011 \pm 0.005$
0.443	7.26	$0.288 \pm 0.061 \pm 0.022$	$0.050 \pm 0.011 \pm 0.004$
0.555	8.23	$0.316 \pm 0.108 \pm 0.028$	$0.048 \pm 0.011 \pm 0.003$
0.707	9.11	$0.311 \pm 0.255 \pm 0.029$	$0.005 \pm 0.012 \pm 0.002$

TABLE II. Contributions to the systematic uncertainties of Γ_1^d, Γ_1^n and $\Gamma_1^p - \Gamma_1^n$.

uncertainty	$\delta\Gamma_1^d$	$\delta\Gamma_1^n$	$\delta(\Gamma_1^p - \Gamma_1^n)$
P_b	0.001	0.001	0.004
P_t	0.002	0.005	0.007
f	0.002	0.006	0.008
A_{rc}	0.002	0.006	0.007
F_2 and R	0.001	0.002	0.005
Extrapolation	0.001	0.004	0.006
Total	0.004	0.011	0.016