Analysis of $n - n'$ Experiments at ILL/Grenoble

Based on: “New experimental limits on neutron - mirror neutron oscillations in the presence of mirror magnetic field” - Eur.Phys.J. C78 (2018) no.9, 717

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Mirror Matter

Theory based on two identical gauge sector: $G \times G'$ with identical field content by the lagrangian:

$$\mathcal{L}_{tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{mix}$$

Mirror Parity $P(G \leftrightarrow G')$ ($m_i = m_i'$, no new parameters)

$\mathcal{L}_{\mathbf{mix}} \Rightarrow$ Gravity is not the only common interaction [1]

- Photon Kinetic Mixing: $-\epsilon F^{\mu\nu} F'_{\mu\nu}$
- $n - n'$ Oscillation: $\frac{1}{M^5} (uud)(u'u'd')$
- $\nu - \nu'$ Oscillations: $\frac{1}{M} (\phi l)(l'\phi')$
- $\pi^0 - \pi'^0$ and $K^0 - K'^0$ Mixing

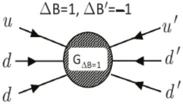
$\Rightarrow n - n'$ can give Baryon Asymmetry in both sector

$\Rightarrow \Omega'_B \gtrsim \Omega_B$ Mirror Baryons are natural candidate for Dark Matter

[1] mixed interaction strength can be taken at the limits not excluded by experiments and cosmology

$n - n'$ Oscillations

Mass Mixing $\epsilon(\bar{n}n' + \bar{n}'n)$ comes from B and B' violating six-fermions effective operator: $\frac{1}{M^5}(udd)(u'd'd')$.



$m_n = m_{n'} \to \tau_{nn'} \sim \epsilon^{-1} \sim (M/10TeV)^5 \times 1s$

Several Experiments searched $n - n'$ oscillations with UCN trap assuming $B' = 0$ at Earth, comparing UCN loss rates in *zero* and *non-zero* B.

PDG limit $\Rightarrow \tau_{nn'} = 414\,s$ at 90% C.L. [2]

This limit is invalid if Earth has $B' \neq 0$

[2] Serebrov *et al.* 2008

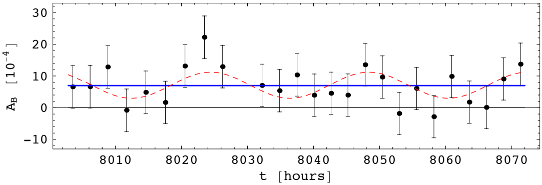
Analysis with $B' \neq 0$

Earth could capture Mirror Matter $\Rightarrow B' \neq 0$

$\Rightarrow$ Oscillation suppressed if $B = 0$ and resonantly amplified if $B \simeq B'$ and so UCN losses should depend on B and its orientation.

Some measurements show anomaly [3]

$\Rightarrow B \simeq 0.2\,G$ (Vertical) results: 5.2 σ Deviation $\rightarrow B' \simeq 0.1 \div 0.3\,G$ and $\tau \sim 20\,s$



[3] 5.2σ: Serebrov 2009 / Berezhiani, Nesti 2012; 3σ: Ban 2007

Oscillation Probability

$n - n'$ oscillation in vacuum with arbitrary $\mathbf{B}$ and $\mathbf{B}'$ is described by:

$$\frac{d\Psi}{dt} = H_{nn'}\Psi \qquad H_{nn'} = \begin{pmatrix} \mu\,\mathbf{B}\cdot\sigma & \epsilon \\ \epsilon & \mu\,\mathbf{B}'\cdot\sigma \end{pmatrix}$$

In homogeneous $\mathbf{B}$ and $\mathbf{B}'$, oscillation probability after flight time t:

$$P_{\mathbf{BB}'}(t) = \frac{\sin^2[(\omega-\omega')t]}{2\tau^2(\omega-\omega')^2}(1+\cos\beta) + \frac{\sin^2[(\omega+\omega')t]}{2\tau^2(\omega+\omega')^2}(1-\cos\beta)$$

where β is the angle between $\mathbf{B}$ and $\mathbf{B}'$. [4]

For trapped UCN, $P_{\mathbf{BB}'}(t)$ should be averaged over the distribution of neutron flight times t. Using the empirical formula (homogeneous field) $S(\omega) = \langle\sin^2(\omega t)\rangle_t = \frac{1}{2}\left[1 - e^{-2\omega^2\sigma_f^2}\cos(2\omega t_f)\right]$

we get: ($cos\beta = \pm 1$)

$$\bar{P}^{(\pm)}_{BB'} = \frac{S(\omega\mp\omega')}{\tau^2(\omega\mp\omega')^2}.$$

[4] $\tau = \epsilon^{-1}$, $\omega = \frac{1}{2}|\mu B|$ and $\omega' = \frac{1}{2}|\mu B'|$ and $\mu = -6\cdot 10^{-12}$ eV/G,

Magnetic Asymmetry: A

$n - n'$ oscillation can be tested via magnetic field dependence of UCN losses.

The amount of survived UCN in the trap after storage time t_* with applied magnetic field $\pm\mathbf{B}$ is given by:

$$N_{\pm\mathbf{B}}(t_*) = N(t_*)\exp(-n_*\bar{P}_{\pm\mathbf{BB'}})$$

n_* is average number of wall scatterings and of neutrons $N(t_*)$ is the number of UCN survived to regular losses(β-decay, wall absorption or upscattering) after being stored in the trap for t_* which does not depend on $\mathbf{B}$.

We can define Asymmetry between $N_{\mathbf{B}}(t_*)$ and $N_{-\mathbf{B}}(t_*)$

$$A_{\mathbf{B}}(t_*) = \frac{N_{-\mathbf{B}}(t_*) - N_{\mathbf{B}}(t_*)}{N_{-\mathbf{B}}(t_*) + N_{\mathbf{B}}(t_*)} \approx \frac{n_*}{2}(\bar{P}_{BB'} - \bar{P}_{-BB'})\cos\beta$$

Magnetic Asymmetry: E

We can also compare $N_B(t_*) = \frac{1}{2}\left[N_{\mathbf{B}}(t_*) + N_{-\mathbf{B}}(t_*)\right]$ with the counts $N_0(t_*)$ measured under zero magnetic field:

$$E_B(t_*) = \frac{N_0(t_*) - N_B(t_*)}{N_0(t_*) + N_B(t_*)} = n_*(\bar{\mathcal{P}}_{BB'} - \bar{\mathcal{P}}_{0B'})$$

E_B traces difference between probabilities in zero and non-zero fields, does not depend on unknown direction of B' (angle β)

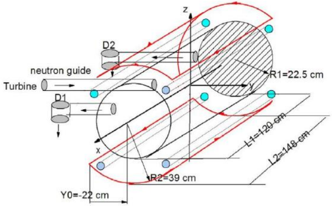
$\Rightarrow$ Effects of regular UCN losses cancel from ratios E_B and $A_{\mathbf{B}}$

$\Rightarrow$ Measuring them for different $\mathbf{B}$, one can obtain limits on τ and $\tau_\beta = \tau/\sqrt{|\cos\beta|}$ as a function of mirror field B'.

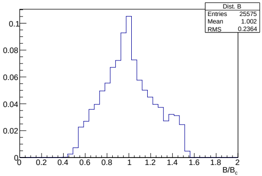
The Trap

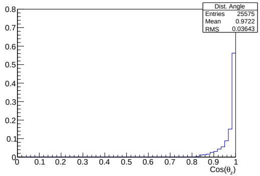
Research Reactor of ILL, UCN facility PF2, EDM Beamline

- Neutron guide
- UCN trap
- Detectors D1 and D2
- Magnetic shielding
- Be coated
- Controlled Magnetic Field



Not uniform $\mathbf{B}$ in the trap varying, from the central value B_c by about $\pm 0.5\,B_c$ at peripheral regions. And not uniformly Vertical.





The Measurements

Each measurement consists of five phases:

1. **Monitoring:** flux stability check and all open valves $t_m = 50\,s$
2. **Filling:** exit valves closed $t_f = 100\,s$
3. **Storage:** all the valves closed $t_s = 250\,s$
4. **Emptying:** exit valves open and counting $t_e = 150\,s$
5. **Background:** all valve open to check the trap is empty $t_m = 50\,s$

$\Rightarrow$ Series ($B1$, $B2$, $B3$) measured $A_{\mathbf{B}}$ employing respectively ($B_c = 0.21\,G$, $B_c = 0.12\,G$ and $B_c = 0.09\,G$) repeating the cycles $\{\mathbf{B}\} = \{-\mathbf{B}, +\mathbf{B}, +\mathbf{B}, -\mathbf{B}; +\mathbf{B}, -\mathbf{B}, -\mathbf{B}, +\mathbf{B}\}$

$\Rightarrow$ Series $B4$, ($B_c = 0.12\,G$), measured $A_{\mathbf{B}}$ and E_B repeating the cycles $\{\mathbf{0}|\mathbf{B}\} = \{\mathbf{0}, +\mathbf{B}, -\mathbf{B}, \mathbf{0}; \mathbf{0}, -\mathbf{B}, +\mathbf{B}, \mathbf{0}\}$, In series $B4$ only detector D1 was used and t_s was reduced to $150\,s$.

Time gap between $B3$ and $B4$ and after $B4$ was devoted to calibration for testing possible systematic effects that could render the detector counts sensitive to the magnetic field strength and its orientation.

Averaged number wall collisions

n_* was estimated via a Monte Carlo simulation of the UCN motion inside the trap[5]

$\Rightarrow$ Escape Probability: $P_{esc}(v_\perp) = 2\,\eta\,\frac{|v_\perp|}{\sqrt{v_{max}^2 - v_\perp^2} + 2\eta\,|v_\perp|}$

$\Rightarrow$ β-decay: $P_\beta = dt/\tau_n$, with $\tau_n = (880.2 \pm 1.0)$ s

We simulate main phases of measurements

Only the UCN that in the counting phase end up in one of detectors were taken into account for computing the mean value of n_* and its variance running a 1000 simulations per each configuration, with 5×10^5 neutron each.

- $B1, B2, B3$: $n_* = 2068 \pm 18$ for $t_S = 250$ s.
- $B4$: $n_* = 1487 \pm 15$ for $t_S = 150$

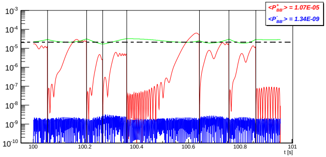
[5] Biondi 2018

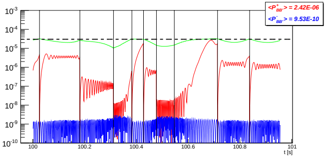
Evolution of Oscillation Probability

⇒ Magnetic field profile was not homogeneous so the empirical formula for average oscillation probability cannot be used

⇒ Evolution equation was numerically integrated between scatterings and used to calculate the evolution of oscillation probability as a function of B' following the neutron trajectories in the trap.

⇒ At each wall scattering (black vertical lines) the wave vector was reset to the pure state of neutron.



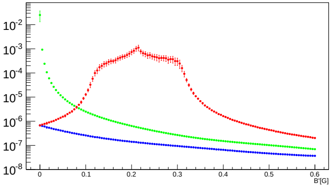


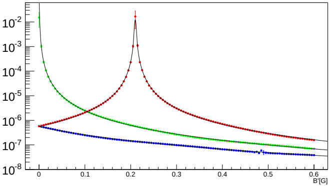
Evolution of $P^{+}_{BB'}$ ($\beta = 0$) and $P^{-}_{BB'}$ ($\beta = \pi$) for an UCN with $v = 4\,m/s$ with $B_c = 0.21\,G$ and $\tau = 10\,s$. $\mathbf{B}'$ (horizontal dash lines [T]) is taken as $B' = 0.2$ G (left) or $B' = 0.3$ G (right). Green curves show the profile of $\mathbf{B}$ [T] which the neutron crossed during its motion.

Averaged Oscillation Probability

Via MC simulations we computed mean values $\bar{P}^{(\pm)}_{BB'}$ and $\bar{P}_{0B'}$ between wall scatterings, averaged over distribution of the neutron flight time t and distribution of the B in the trap for a given value of B_c.

$$\bar{P}^{\pm}_{BB'} = \left(\frac{1\,\mathrm{s}}{\tau}\right)^2 \mathcal{S}_{\pm}(B') \qquad \bar{P}_{0B'} = \left(\frac{1\,\mathrm{s}}{\tau}\right)^2 \mathcal{S}_0(B')$$





e.g. for $B_c = 0.21\,G$, $S_+(B')$, $S_-(B')$ and $S_0(B')$ correspond to mean values of the probabilities normalized $\tau = 1\,s$.

$\Rightarrow$ The simulation is consistent with the empirical formula

$\Rightarrow$ A wide profile of B distribution it is sensitive to a larger range of B'.

Data Sets

Asymmetries were computed comparing subsequent measurements.

- $N_{\mathbf{B}} = N_{\mathbf{B}}^{(1)} + N_{\mathbf{B}}^{(2)} \to A_B, E_B$
- Poisson Stat. $\Delta N_{\mathbf{B}} = \sqrt{N_{\mathbf{B}}}$
- $N_{\mathbf{B}}^{(1)}/N_{\mathbf{B}}^{(2)}$: stability check
- $M_{\mathbf{B}}, (N/M)_{\mathbf{B}} \to A_B^{nor}, E_B^{nor}$
- Eliminating Drift $\to$ Average within octets $\{\mathbf{B}\}$ $\{\mathbf{0}|\mathbf{B}\}$

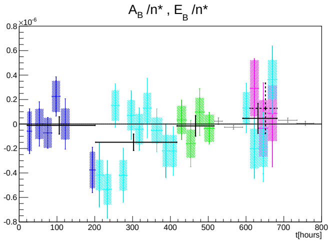
Series $[N_{oct}]$	Stat. $[\times 10^{-8}]$	Dist. $[\times 10^{-8}]$
A_{B1}/n_* [74]	-1.59 ± 5.40 (1.57)	-1.12 ± 7.09
A_{B1}^{nor}/n_* [74]	0.43 ± 5.89 (1.73)	0.99 ± 7.67
A_{B2}/n_* [124]	-14.9 ± 3.80 (2.90)	-14.9 ± 6.40
A_{B2}^{nor}/n_* [124]	-16.6 ± 4.14 (2.84)	-16.6 ± 6.70
A_{B3}/n_* [57]	-0.03 ± 5.79 (1.92)	-1.54 ± 8.39
A_{B3}^{nor}/n_* [57]	1.93 ± 6.32 (1.83)	0.96 ± 9.07
A_{B4}/n_* [43]	4.18 ± 7.47 (2.20)	4.57 ± 12.1
A_{B4}^{nor}/n_* [43]	8.61 ± 9.28 (2.50)	8.67 ± 14.3
E_{B4}/n_* [28]	13.0 ± 13.0 (2.20)	12.8 ± 20.4
E_{B4}^{nor}/n_* [28]	13.7 ± 13.7 (1.94)	13.7 ± 22.4

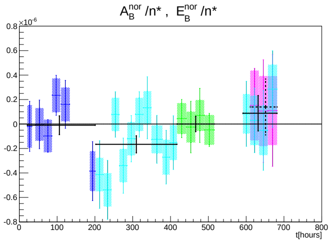
1^{st} Column: Asymmetry transformed into probabilities, n_*, N_{oct}.
2^{st} Column: Results of constant fit and $\chi^2/d.o.f.$
3^{st} Column: Mean values and variances obtained from distribution

$\chi^2/d.o.f.$ are too large: data have larger dispersion than what expected from statistics, central values in 3^{st} and 2^{st} column are consistent, errors well coincide if enlarged by $\sqrt{\chi^2/d.o.f.}$.

Binning

The measured asymmetries are combined in bins of comparable size.





$B1\ (B_c = 0.21\,G)$, $B2,\ B4\ (B_c = 0.12\,G)$, $B3\ (B_c = 0.09\,G)$, Calibration, E_{B4}/n_*

$\Rightarrow$ Shaded squares show mean values per each bin and statistical errors, larger error-bars indicate the dispersion in each bin.

$\Rightarrow$ Black(dashed black) crosses show the mean values of $A_{\mathbf{B}}/n_*$ and $A_{\mathbf{B}}^{nor}/n_*$ (E_B/n_* and E_B^{nor}/n_*) and respective errors per each series obtained directly from the dispersion of the measured values.

Deviations from null Hypothesis

In absence of $n-n'$ oscillations we expects that the values $A_{\mathbf{B}}$ and E_B should be consistent with zero within statistical errors

$\Rightarrow$ In series $B2$ (the largest), values A_{B2}/n_* and $A^{\mathrm{nor}}_{B2}/n_*$ are significantly deviated from zero by about 4.0σ, but, constant fits is not good $\chi^2/\mathrm{d.o.f.} \simeq 2.9$ signature of strong dispersion between bins

$\Rightarrow$ Even using distributions, or averaging between bins, both values still have more than 2σ deviations so, this discrepancy is pretty robust against the methods of the analysis

$\Rightarrow$To be conservative, in the following we use the mean values and variances obtained from the distribution of $A_{\mathbf{B}}$ and E_B.

$\Rightarrow$We average between the results of series $B2$ and $B4$ ($B_c = 0.12\,G$)

$$\frac{\cos\beta}{2}(\bar{P}_{BB'} - \bar{P}_{-BB'}) = (-10.4 \pm 5.70) \times 10^{-8}$$
$$\frac{\cos\beta}{2}(\bar{P}_{BB'} - \bar{P}_{-BB'})^{nor} = (-11.8 \pm 6.10) \times 10^{-8}.$$

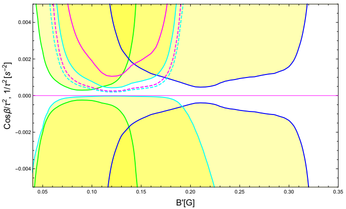
$\Rightarrow$ Less than 2σ deviation from zero, we can set a 95 % C.L. on τ_β as a function of B'

Exclusion Regions

Experimental values of E_B/n_* and $A_\mathbf{B}/n_*$ can be transformed into the $n - n'$ oscillation parameters τ^2 and $\tau^2/\cos\beta$

$$\frac{1}{\tau^2} = \frac{E_B}{n_*}\left[\frac{S_+(B')+S_-(B')}{2} - S_0(B')\right]^{-1}$$

$$\frac{\cos\beta}{\tau^2} = \frac{A_\mathbf{B}}{n_*}\left[S_+(B') - S_-(B')\right]^{-1}$$



Exclusion regions for positive and negative $\cos\beta$

$B1$ ($B_c = 0.21\,G$), $B3$ ($B_c = 0.09\,G$), 95 % C.L. limits on $\cos\beta/\tau^2$

E_{B4}/n_* Dash curve shows values of $1/\tau^2$ as function of B' while solid line corresponds to 95 % C.L upper limit on $1/\tau^2$

$B2$ and $B4$ average ($B_c = 0.12\,G$), Dash curve shows central values of $\cos\beta/\tau^2$ with about 2σ deviation from zero, while solid contours confine corresponding 95 % C.L. area.

Global Fit

Assuming that B' is constant at Earth during the years passed from previous experiments to our measurements, we can combine our results with limits from previous works

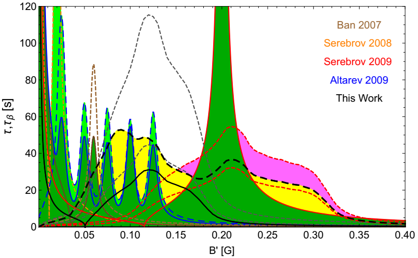
$\Rightarrow$ Global fit of our experimental data: (black solid) 95 % C.L. lower limits on τ and (black dashed) τ_β

$\Rightarrow$Parameter areas excluded by the previous experiments:

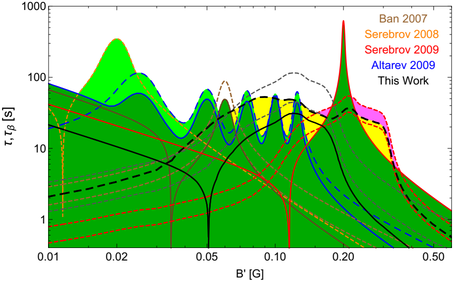
τ (solid line)

$\tau_\beta = \tau/\sqrt{\cos\beta}$ (dashed line)

New regions excluded in this work



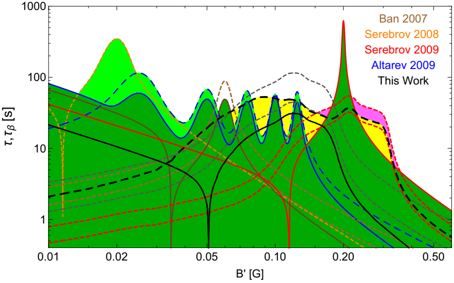
Comparison I



Ban et al. 2007 Vertical homogeneous field ($B = 0.06\, G$)
No significant deviation found in E_B, 95 % C.L. lower limit on τ (solid)
3σ deviation of $A_{\mathbf{B}}$, 95 % C.L. allowed area (dashed)

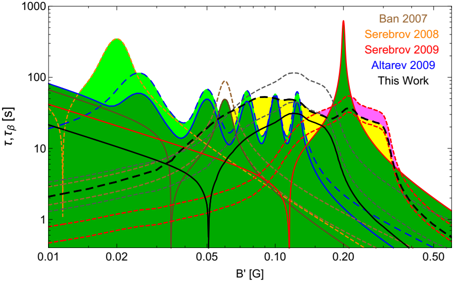
Serebrov et al. 2008 Horizontal homogeneous field ($B = 0.02\, G$)
$\tau > 386\, s$ at 95 % C.L. ($B' = 0$) No alternation of B direction, so, no direct limits on τ and τ_β for $B' \neq 0$. We show parameter area (dashed curve) which would be excluded at 95 % C.L. assuming vertical B'

Comparison II



Serebrov et al. 2009 (solid curve) 95 % C.L. lower limit on τ, from $\{\mathbf{0}|\mathbf{B}\}$ mode with horizontal homogeneous $B = 0.2\,G$, (dashed lines) 2σ area corresponding 5.2σ anomaly recalculated accounting for the non-homogeneity of B, from $\{\mathbf{B}\}$ measurements with vertical non-homogeneous B ($B_c = 0.2\,G$), Was itnterpreted as a signal of $n - n'$ oscillation with $B' \simeq 0.1\,G$ assuming the homogeneity of the applied B (Berezhiani, Nesti 2012)

Comparison III

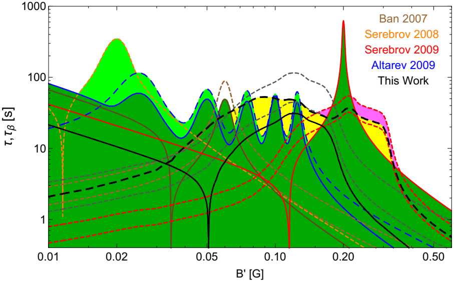


Altarev et al. 2009 (solid) 95 % C.L. lower limits on τ and (dashed) for τ_β, using vertical homogeneous magnetic field, varying from 0 to $0.125\,G$ alternating direction.

These limits exclude $\tau < 12\,s$ and $\tau_\beta < 15\,s$ for any B' in the interval$(0 \div 0.13)\,G$.

For $B' = 0.01\,G$ we have $\tau > 80\,s$ and approaching $\tau > 386\,s$ for $B' = 0$ as obtained in *Serebrov et al. 2008* at 95 % C.L.

Comparison IV



$\Rightarrow$(dashed) contours limit 2σ area corresponding to 2.5σ deviation in series $B2$. Compatible with the 5.2σ anomaly for a small parameter area around $B' = 0.16$ G and $\tau_\beta = 30\,s$

$\Rightarrow$ Our Results enhance previous experimental limits: for any B' in the interval $(0.08 \div 0.17)\,G$ we get a lower limit on $n - n'$ oscillation time $\tau > 17\,s$ (95 % C.L.), and $\tau_\beta > 27\,s$ for any B' between $(0.06 \div 0.25)\,G$ (95 % C.L.)

Conclusions

Our aim was to test 5.2σ anomaly from *Serebrov et al. 2009* interpretable as signal for $n - n'$ oscillation in the presence mirror magnetic field.

- Other experiments did not exclude all relevant parameter space
- We can combine our results with limits of previous works: only assuming that mirror magnetic field B' was constant during the past years
- We enhanced previous experimental limits: for any B' in the interval $(0.08 \div 0.17)\, G$ we get a lower limit on $n - n'$ oscillation time $\tau > 17\, s$ (95 % C.L.), and $\tau_\beta > 27\, s$ for any B' in the interval $(0.06 \div 0.25)\, G$ (95 % C.L.)

But still we could not completely exclude the 5.2σ parameter area

Thank You!