

Science and Technology **Facilities Council**



Neutrinoless double-beta decay Cheryl Patrick STFC Ernest Rutherford Fellow, University of Edinburgh

THE UNIVERSITY of EDINBURGH



PPAP Community meeting, September 21, 2022





Neutrinos - unanswered questions





Neutrino oscillations





Neutrinos - unanswered questions



beta decay







Standard-model double-beta decay $(2\nu\beta\beta)$



- Standard Model process
- Lepton number conserved
- Doubly weak = long half-life
- Observed in several isotopes; $T_{\frac{1}{2}} \sim 10^{20}$ years



	1																	
	1 H 1.008	2											13	14	15	16	17	
	3 Li 6.94	4 Be 9.0122											5 B 10.81	6 C 12.011	7 N 14.007	8 0 15.999	9 F 18.998	
	11 Na 22.990	12 Mg 24.305	3	4	5	6	7	8	9	10	11	12	13 Al 26.982	14 Si 28.085	15 P 30.974	16 S 32.06	17 Cl 35.45	
	19 K 39.098	⁴⁸ Ca	21 Sc 44.956	22 Ti 47.867	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.38	31 Ga 69.723	⁷⁶ Ge	33 As 74.922	⁸² Se	35 Br 79.904	
	37 Rb 85.468	38 Sr 87.62	39 Y 88.906	⁹⁶ Zr	41 Nb 92.906	¹⁰⁰ Mc	43 Tc (98)	44 Ru 101.07	45 Rh 102.91	¹¹⁰ Pc	47 Ag 107.87	¹¹⁶ Cd	49 In 114.82	¹²⁴ Sn	51 Sb 121.76	^{128,} ¹³⁰ Te	53 I 126.90	1; 1;
	55 Cs 132.91	56 Ba 137.33	57-71 *	72 Hf 178.49	73 Ta 180.95	74 W 183.84	75 Re 186.21	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (209)	85 At (210)	
	87 Fr (223)	88 Ra (226)	89-103 #	104 Rf (265)	105 Db (268)	106 Sg (271)	107 Bh (270)	108 Hs (277)	109 Mt (276)	110 Ds (281)	111 Rg (280)	112 Cn (285)	113 Nh (286)	114 Fl (289)	115 Mc (289)	116 Lv (293)	117 Ts (294)	
-	* Lanthanide series			57 La	58 Ce	59 Pr	150 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	
				138.91	140.12	140.91		(145)	150.36	151.96	157.25	158.93	162.50	164.93	167.26	168.93	173.05	1
		# Actir serie	iide s	89 Ac (227)	90 Th 232.04	91 Pa 231.04	238U	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	





Standard-model double-beta decay $(2\nu\beta\beta)$







Neutrinoless double-beta decay $(0\nu\beta\beta)$







Neutrinoless double-beta decay $(0\nu\beta\beta)$



- No neutrinos in final state
- Virtual Majorana neutrino exchanged (various models available)
- All $2\nu\beta\beta$ isotopes are $0\nu\beta\beta$ candidates
- Not yet observed $T_{\frac{1}{2}} > 10^{24}$ 10^{26} years



If seen, $\partial\nu\beta\beta$ would:

- be the first process observed to create matter without antimatter
- prove that neutrinos are Majorana fermions
- tell us about absolute neutrino mass













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Complementary to:

- Oscillations
- Cosmology
- β decay endpoints

















What do we know?

$$0\nu\beta\beta \operatorname{rate} \quad \frac{1}{T_{1/2}^{0\nu\beta\beta}} = G_{0\nu}(Q_{\beta\beta}, Z)g_A^4 |M_{0\nu}|^2 \frac{\langle m_{\beta\beta}}{m_e^2}$$





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We still don't know:

• Whether $\partial \nu \beta \beta$ exists at all (are neutrinos Majorana?)





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- At what mass scale it could show up
- The $\partial \nu \beta \beta$ mechanism









Core UK strategy



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LEGEND at LNGS, Italy (so far...)

76**Ge**







Thanks to Matteo Agostini for content

A discovery machine that will search the entire inverted hierarchy region



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LEGEND



How does LEGEND work?

Semiconductor HPGe Detectors:

- solid state TPC
- mm-scale event topology









How does LEGEND work?

Semiconductor HPGe Detectors:

- solid state TPC
- mm-scale event topology

Liquid-argon Scintillation Detector:

- ultra-clean, cryogenic liquid
- isotropic emission of XUV photons
- calorimetric energy measurement





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GERDA/MAJORANA (40/30 kg)

- Lowest background level in the field
- Best **energy resolution** in the field
- Best **discovery power** so far



Phys.Rev.Lett. 125 (2020) 25, 252502



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LEGEND-200 (200 kg)

- Approaching physics data taking
- Leading experiment for the next 5 years

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LEGEND-200 (200 kg)

- Approaching physics data taking
- Leading experiment for the next 5 years

LEGEND-1000 (1 ton)

- Inverted-hierarchy explorer: $m_{\beta\beta}=18$ meV
- Only experiment in both the EU APPEC roadmap and DOE long term plan

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Summer 2022 LEGEND-200 integration runs:

24 detectors (60kg) used for background studies

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Summer 2022 LEGEND-200 integration runs:

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- Ge and LAr detectors, electronics & DAQ

FEGE

Summer 2022 LEGEND-200 integration runs:

- 24 detectors (60kg) used for background studies
- Ge and LAr detectors, electronics & DAQ
- Analysis pipeline

LEGE

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LEGEND won DOE portfolio review

- DOE fully committed to LEGEND and will prioritise it over any other $0\nu\beta\beta$ experiments
- CD1 and CD3 review next year

LEGEND-200 (under construction,

LEGEND-1000 (construction 2023-2030, first data in 2028, 10 years of operations)

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LEGEND-UK

(Physics coordinator, WBS *level 2 managers)*

New scintillating materials

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SNO+ at Sudbury, Canada

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A highly scalable, cost-effective and sensitive approach to $\partial\nu\beta\beta$ (concept developed in the UK)

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SNQ

Diol Loading of ¹³⁰Te in Liquid Scintillator (developed in UK)

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SNQ

Diol Loading of ¹³⁰Te in Liquid Scintillator (developed in UK)

Cost-effective

• $\beta\beta$ isotope has high (34%) natural abundance • Liquid scintillator is also economical

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SNG

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- Detector **design** can be scaled up dramatically
- UK-developed techniques can increase **tellurium loading**

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Sensitive

• Single- vs multi-site discrimination keeps backgrounds low

NIM, 943, 162420 (2019)

SNO+ without tellurium

Initial phase - water-Cherenkov detector

⁸B solar neutrinos with extremely low backgrounds!

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SNQ

Since April 2021- full liquid-scintillator detector

SNO+ without tellurium

Initial phase - water-Cherenkov detector

⁸B solar neutrinos with extremely low backgrounds!

First ever demonstration of event-by-event solar vdirectional reconstruction in high light-yield LS

-0.8

-0.6

-0.4

-0.2

Events / 0.2 18

12

10

0 L -1

Data

0.6 g/L Data Set

----- MC

SNQ

Since April 2021- full liquid-scintillator detector

Solar neutrinos

Reactor neutrinos

Preparing for $\beta\beta$ -decay

Mixture of telluric acid in water and distilled butanediol is heated while water is flash-evaporated in the synthesis tank

> Transferred to mixing tank near solubility point to combine with LAB and 0.25mol DDA to complete solubilisation

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Te purification and loading systems constructed and starting commissioning

Delays to Te deployment:

- COVID disruption of supply chains
- Loss of key engineers at SNOLAB
- Extended commissioning & safety review
- Site access limitations

Loading to start in late 2024/early 2025

SNO+ sensitivity

SNO+ sensitivity

SuperNEMO, at LSM, French Alps

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etaeta source

Any solid $\beta\beta$ isotope

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Neutrinoless double-beta decay, PPAP 2022

SuperNEMO Demonstrator - 6.23kg ⁸²Se

The NEMO principle

Angle between tracks

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Neutrinoless double-beta decay, PPAP 2022

SuperNEMO Demonstrator - 2034 Geiger cells

How SuperNEMO works

712 optical modules

 σ/E 1.8% at 3 MeV

How SuperNEMO works

discrimination between $\beta\beta$

mechanisms and nuclear effects; background rejection

712 optical modules

 σ/E 1.8% at 3 MeV

SuperNEMO for nuclear effects

Intermediate states in $2\nu\beta\beta$ decay

NEMO-3 - ⁵⁵Se (Run 1) - 464 g, 5.25 y -+- Data (2050) -+- Data (2050) ≥ 200 External BGs 180 160 140 120 100 HSD Radon BGs Radon BGs Internal BGs Internal BGs **2**νββ Signal 2vββ Signal χ^2 / ndf = 35.32 / 16 S/B = 6.2S/B = 6.1 $\int_{10}^{10} \chi^2 / ndf = 35.32 / 16$ $x^{2}/ndf = 12.34/16$ 40 20 DataMC M 1.5 ŧ:_₽:∮:┿., 2.5 E, / MeV Various excited states Mostly ground state SuperNEMO will have 5σ sensitivity Phys Rev Lett 122, 192501 (2019) g_A quenching - - -SuperNEMO's individual *e*-Excluded by 5. 0.7 spectrum will be more KamLAND-Zen_{0.5} sensitive 0.4 0.3 0.20.015 005 0.01 Lines and points \rightarrow nuclear models $\stackrel{\bullet}{\rightarrow}$

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Neutrinoless double-beta decay, PPAP 2022

SuperNEMO for nuclear effects

Intermediate states in $2\nu\beta\beta$ decay

Eur. Phys. J. C (2018) 78: 821

🛶 Data (2050) — Data (2050) External BGs External BGs Radon BGs Radon BGs Internal BGs 160 140 Internal BGs | 2vββ Signal 2vββ Signal χ^2 / ndf = 12.34 / 16 χ^2 / ndf = 35.32 / 16 S/B = 6.2ndf = 35.32/16 x²/ndf = 12.34/1 40 -2.5 E_e / MeV Various excited states Mostly ground state SuperNEMO will have 5σ sensitivity Phys Rev Lett 122, 192501 (2019) g_A quenching shell model (GCN) shell model (MC) QRPA (CD-Bonn) ORPA (Argonne) xcluded, KamLAND-Zen SuperNEMO's individual *e*-Excluded by 5.6 0.7 spectrum will be more KamLAND-Zen_{0.5} sensitive 0.4 0.3 0.015 0.01 Lines and points \rightarrow nuclear models $M^{2\nu}_{\rm GT-3}$

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... and exotic physics

Precision $2\nu\beta\beta$ measurements can reveal BSM effects...

- Lorentz-invariance violation
- Exotic $\partial \nu \beta \beta$ mechanisms
- Right-handed neutrinos (see below)
- Scalar currents...

Best technology to understand $\partial \nu \beta \beta$ mechanism if it's discovered

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531 = 0.17

0.025 0.03

0.02

SuperNEMO Demonstrator status: Calorimeter calibration

Timing

ITALY	G:0.1.15	G:0.1.14	G:0.1.1	3 G:0.1.12	G:0.1.11	G:0.1	.10 G	i:0.1.9	G:0.1.8	G:0.1.7	G:0.1	.6 G:	0.1.5	G:0.1.4	G:0.1.3	G:0.1.	2 G:	0.1.1	G:0.1.0	MOL	JNTAIN	I
X:0.1.0.15X:0.1.1.15	M:0.19.12	1:0.18.12M:	0.17.12M:0.	16.12 <mark>M:0.15.1</mark>	2M:0.14.12	M:0.13.12	M:0.12.1	2M:0.11.12	2M:0.10.12	M:0.9.12	M:0.8.12	M:0.7.12	M:0.6.12	M:0.5.12	M:0.4.12	M:0.3.12	M:0.2.12	M:0.1.12	M:0.0.12	X:0.0.1.1	15X:0.0.0.1	15
X:0.1.0.14X:0.1.1.14	M:0.19.11	1:0.18.11 M:	0.17.11M:0.	16.11 <mark>M:0.15.⁻</mark>	1M:0.14.11	M:0.13.11	M:0.12.11	14.33	M:0.10.11	M:0.9.11	M:0.8.11	M:0.7.11	M:0.6.11	M:0.5.11	M:0.4.11	9.29 N:0.3.11	4.27 N:0.2.11	2.07 M:0.1.11	M:0.0.11	X:0.0.1.1	4 X:0.0.0 .1	14
X:0.1.0.13X:0.1.1.13	<mark>M:0.19.10</mark> M	17.60 1 I:0.18.10 <mark>M</mark> :	6.71 13 0.17.10 <mark>M:0.</mark>	.80 11.53 16.10 <mark>M:0.15.1</mark>	0M:0.14.10	13.35 M:0.13.10	12.27 M:0.12.10	12.08 0M:0.11.10	8.86 M:0.10.10	9.65 M:0.9.10	6.41 M:0.8.10	4.10 M:0.7.10	3.89 M:0.6.10	4.79 M:0.5.10	1.32 M:0.4.10	-2.80 1:0.3.10	0.21 M:0.2.10	-1.18 M:0.1.10	-3.46 M:0.0.10	X:0.0.1.1	3X:0.0.0.1	13
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X:0.1.0.5 X:0.1.1.5	M:0.19.4 M 11.84	л:0.18.4 М: 9.91 8	0.17.4 M:0 8.00 8.	.16.4 M:0.15. 60 7.14	4 M:0.14.4 6.23	M:0.13.4 5.50	м:0.12.4 6.10	M:0.11.4 3.21	M:0.10.4 3.91	M:0.9.4 -2.08	M:0.8.4 0.29	м:0.7.4 2.31	M:0.6.4 -2.09	M:0.5.4 -3.83	M:0.4.4 -2.36	M:0.3.4 -7.13	M:0.2.4 -8.86	M:0.1.4 -7.34	M:0.0.4 -9.57	X:0.0.1.	5 X:0.0.0.	5
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X:0.1.0.1 X:0.1.1.1	M:0.19.1 M	A:0.18.1 M	0.17.1 M:0	.16.1 M:0.15.	1 M:0.14.1 0.98	M:0.13.1 1.71	M:0.12.1 -0.56	M:0.11.1	M:0.10.1 - 0.91	M:0.9.1 -3.44	M:0.8.1 -4.16	M:0.7.1 -3.64	M:0.6.1 -7.87	M:0.5.1 -6.27	M:0.4.1	M:0.3.1	M:0.2.1 • 12.74	M:0.1.1 -11.35	M:0.0.1 -13.96	X:0.0.1.	1 X:0.0.0.	1
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row _↑										0.02				0.02		1					NS:	J
column	G:0.0.15	G:0.0.14	G:0.0.1	3 G:0.0.12	G:0.0.11	G:0.0	.10 G	i:0.0.9	G:0.0.8	G:0.0.7	G:0.0	.6 G:	0.0.5	G:0.0.4	G:0.0.3	G:0.0.	2 G:	0.0.1	G:0.0.0	wall:mod wall:mod	ule.side.o	ol.rc w
ITALY TUNNEL	G:0.1.15	G:0.1.14	G:0.1.13	G:0.1.12	G:0.1.11	G:0.1.	.10 G	:0.1.9	G:0.1.8	G:0.1.7	G:0.1	.6 G:	:0.1.5	G:0.1.4	G:0.1.3	G:0.1	.2 G	à:0.1.1	G:0.1.0] мо	UNTAI	N
ITALY TUNNEL	G:0.1.15 M:0.19.12	G:0.1.14	G:0.1.13	G:0.1.12	G:0.1.11 2 <mark>M:0.14.12</mark>	G:0.1.	.10 G	:0.1.9 2 <mark>4:0.11.12</mark>	G:0.1.8	G:0.1.7	G:0.1	.6 G: M:0.7.12	:0.1.5 M:0.6.12	G:0.1.4	G:0.1.3	G:0.1	.2 G	à:0.1.1 2 M:0.1.1	G:0.1.0	MO	UNTAI	N 0.15
ITALY TUNNEL X:0.1.0.15X:0.1.1.15 X:0.1.0.14X:0.1.1.14	G:0.1.15 M:0.19.12 0.84 1 M:0.19.11	G:0.1.14 0.18.12 <mark>M:0. 1.07 0.</mark> 0.18.11 <mark>M:0.</mark>	G:0.1.13 17.12 M:0.1 71 0.7 17.11 M:0.1	G:0.1.12 6.12 76 0.68 6.11 0.68	G:0.1.11 2 <mark>M:0.14.12 0.80 1M:0.14.11</mark>	G:0.1. W:0.13.12 0.65 W:0.13.11	.10 G M:0.12.12 0.81 M:0.12.11	:0.1.9 2 <mark>M:0.11.12 0.76</mark>	G:0.1.8 2 <mark>M:0.10.12 0.78</mark> M:0.10.11	G:0.1.7 M:0.9.12 0.91 M:0.9.11	G:0.1 M:0.8.12 0.79 M:0.8.11	.6 G: M:0.7.12 1.02 M:0.7.11	:0.1.5 M:0.6.12 0.75 M:0.6.11	G:0.1.4 2 M:0.5.12 1.06	G:0.1.3 M:0.4.12 0.73 M:0.4.11	G:0.1 M:0.3.12 0.68 M:0.3.11	.2 G M:0.2.12 0.90 M:0.2.11	à:0.1.1 2 M:0.1.1 0.92 1 M:0.1.1	G:0.1.0 C:0.12 C:0.1	MO 2 K:0.0.1 X:0.0.1	DUNTAI	N).15).14
ITALY TUNNEL X:0.1.0.18X:0.1.1.15 X:0.1.0.14X:0.1.1.14 X:0.1.0.13X:0.1.1.13	G:0.1.15 M:0.19.12 0.84 M:0.19.11 M:0.19.11 M:0.19.10 M:0.19.10	G:0.1.14 0.18.12 M:0 1.07 0 0.18.11 M:0 0.42 0 0.18.10 M:0	G:0.1.13	G:0.1.12 6.12M:0.15.1 76 0.68 6.11M:0.15.1 9 0.60 6.10M:0.15.1	G:0.1.11 2M:0.14.12 0.80 M:0.14.11 0.60 M:0.14.10	G:0.1. 0.65 0.67 0.67 0.67	.10 G M:0.12.12 0.81 M:0.12.11 0.61 M:0.12.10	:0.1.9 2 <mark>M:0.11.12 0.76</mark> 1M:0.11.11 0.63 2M:0.11.10	G:0.1.8 20:0.10.12 0.78 0.55 0.55 0.10.10	G:0.1.7 M:0.9.12 0.91 M:0.9.11 0.53 M:0.9.10	G:0.1 M:0.8.12 0.79 M:0.8.11 0.56 M:0.8.10	.6 G: M:0.7.12 1.02 M:0.7.11 0.61 M:0.7.10	0.1.5 M:0.6.12 0.75 M:0.6.11 0.56	G:0.1.4 4 4 4 4 4 4 4 5.12 1.06 1 0.70 0 10.5.10 10.70 10.5.10 10.70 10.5.10 10.70 10.5.10	G:0.1.3 M:0.4.12 0.73 M:0.4.11 0.63 M:0.4.10	G:0.1 M:0.3.12 0.68 M:0.3.11 0.66 M:0.3.10	.2 G M:0.2.12 0.90 M:0.2.11 0.45	 3:0.1.1 M:0.1.1 0.92 M:0.1.1 0.58 M:0.1.1 	G:0.1.0 2 M:0.0.12 1 M:0.0.11 1 M:0.0.11 0.66 0 M:0.0.10	MO 2 X:0.0.1 X:0.0.1	UNTAI	N).15).14).13
ITALY TUNNEL K:0.1.0.14K:0.1.1.14 K:0.1.0.14K:0.1.1.13 K:0.1.0.12K:0.1.1.12	G:0.1.15 M:0.19.12 M:0.19.11 M:0.19.11 M:0.19.10 M:0.19.10 M:0.19.10 M:0.19.10 M:0.19.10 M:0.19.10 M:0.19.10 M:0.19.11 M:0.19.12 M	G:0.1.14 0.18.12 M:0. 0.18.11 M:0 0.42 0 0.18.10 M:0 0.60 0,	G:0.1.13	G:0.1.12 6.12 M:0.15.1 0.68 6.11 M:0.15.1 9 0.60 6.10 M:0.15.1 9 0.62	G:0.1.11 2M:0.14.12 0.80 M:0.14.11 0.60 0M:0.14.10	G:0.1. W:0.13.12 0.65 W:0.13.11 0.67 W:0.13.10 0.72 W:0.13.0	10 G M:0.12.12 0.81 M:0.12.11 0.61 M:0.12.10 0.62	:0.1.9 2 <mark>M:0.11.12 0.76</mark> 1M:0.11.11 0.63 0M:0.11.10 0.56	G:0.1.8 20.78 0.78 0.55 0.67 0.67	G:0.1.7 M:0.9.12 0.91 M:0.9.11 0.53 M:0.9.10 0.60	G:0.1 M:0.8.12 0.79 M:0.8.11 0.56 M:0.8.10 0.68	.6 G: M:0.7.12 1.02 M:0.7.11 0.61 M:0.7.10 0.55	0.1.5 M:0.6.12 0.75 M:0.6.11 0.56 M:0.6.10 0.73	G:0.1.4	G:0.1.3 M:0.4.12 0.73 M:0.4.11 0.63 M:0.4.10 0.64	G:0.1 M:0.3.12 0.68 M:0.3.11 0.66 M:0.3.10 0.64	.2 G M:0.2.12 0.90 M:0.2.11 0.45 M:0.2.10 0.59	 a:0.1.1 M:0.1.1 0.92 M:0.1.1 0.58 M:0.1.1 0.53 M:0.1.1 	G:0.1.0	MO 2 X:0.0.1 X:0.0.1 X:0.0.1 X:0.0.1	UNTAI .15X:0.0.0 .14X:0.0.0 .13X:0.0.0 M:1.0.12 2.26	N 0.15 0.14 0.13 ME1.1.1 1.97
ITALY TUNNEL K:0.1.0.14K:0.1.1.15 K:0.1.0.14K:0.1.1.14 K:0.1.0.13K:0.1.1.13 K:0.1.0.14K:0.1.1.11	G:0.1.15	G:0.1.14	G:0.1.13	G:0.1.12 6.12 M:0.15.1 6.11 M:0.15.1 9 0.60 6.10 M:0.15.1 9 0.70 0.70 M:0.15.1 9 0.70 0.70 M:0.15.1 9 0.70 M:0.15.1 9 0.	G:0.1.11 20.80 M:0.14.11 0.60 20.0.14.10 0.60 0.60	G:0.1. 0.65 W:0.13.11 0.67 W:0.13.10 0.72 M:0.13.9 0.71	10 G M:0.12.12 0.81 M:0.12.11 0.61 M:0.12.10 0.62 M:0.12.9 0.46	:0.1.9 2M:0.11.12 0.76 M:0.11.11 0.63 0M:0.11.10 0.56 0M:0.11.9 0.55	G:0.1.8 2.0.78 M:0.10.11 0.55 M:0.10.10 0.67 M:0.10.9 0.53	G:0.1.7 M:0.9.12 0.91 M:0.9.11 0.53 M:0.9.10 0.60 M:0.9.9 0.46	G:0.1 M:0.8.12 0.79 M:0.8.11 0.56 M:0.8.10 0.68 M:0.8.9 0.66	.6 G: M:0.7.12 1.02 M:0.7.11 0.61 M:0.7.10 0.55 M:0.7.9 0.64	0.1.5 M:0.6.12 0.75 M:0.6.11 0.56 M:0.6.10 0.73 M:0.6.9 0.65	G:0.1.4 2 M:0.5.12 1.06 1 M:0.5.11 0.70 0 M:0.5.10 0.58 M:0.5.9	G:0.1.3 M:0.4.12 0.73 M:0.4.11 0.63 M:0.4.10 0.64 M:0.4.9 0.68	G:0.1 0.68 M:0.3.11 0.66 M:0.3.10 0.64 M:0.3.9 0.55	M:0.2.12 0.90 M:0.2.11 0.45 M:0.2.10 0.59 M:0.2.9 0.49	 a:0.1.1 A:0.1.1 A:0.1.1 A:0.1.1 A:0.1.1 A:0.58 A:0.1.3 A:0.53 A:0.1.4 A:0.49 A:0.49 	G:0.1.0	MO 2 K:0.0.1 X:0.0.1 X:0.0.1 X:0.0.1 X:0.0.1 X:0.0.1	UNTAI .15X:0.0.0 .14X:0.0.0 .13X:0.0.0 .13X:0.0.0 M:1.0.12 2.26 M:1.0.11 2.10	N 0.15 0.14 0.13 M:1.11 1.97 M:1.11 1.54
ITALY TUNNEL X:0.1.0.19X:0.1.1.15 X:0.1.0.19X:0.1.1.14 X:0.1.0.13X:0.1.1.13 X:0.1.0.13X:0.1.1.13 X:0.1.0.11X:0.1.1.11 X:0.1.0.11X:0.1.1.11 X:0.1.0.10X:0.1.1.10 X:0.1.0.19X:0.1.1.9	G:0.1.15	G:0.1.14	G:0.1.13	6:12 M:0.15.1 6 0.68 6:11 M:0.15.1 9 0.60 6:10 M:0.15.1 9 0.62 16.9 M:0.15.8 9 0.70 16.8 M:0.15.8	G:0.1.11 0.80 0.90 0.	G:0.1. 0.65 W:0.13.11 0.67 W:0.13.10 0.72 M:0.13.9 0.71 M:0.13.8 0.51	.10 G M:0.12.12 0.81 M:0.12.11 0.61 M:0.12.10 0.62 M:0.12.9 0.46 M:0.12.8 0.46	:0.1.9 2M:0.11.12 0.76 M:0.11.11 0.63 0M:0.11.10 0.55 M:0.11.8 0.55	G:0.1.8 20.78 M:0.10.12 0.78 M:0.10.11 0.55 M:0.10.10 0.67 M:0.10.9 0.53 M:0.10.8 0.51	G:0.1.7 M:0.9.12 0.91 M:0.9.11 0.53 M:0.9.10 0.60 M:0.9.9 0.46 M:0.9.8 0.63	G:0.1	.6 G: M:0.7.12 1.02 M:0.7.11 0.61 M:0.7.10 0.55 M:0.7.9 0.64 M:0.7.8 0.57	0.1.5 M:0.6.11 0.75 M:0.6.11 0.56 M:0.6.10 0.73 M:0.6.9 0.65 M:0.6.8	G:0.1.4	G:0.1.3	G:0.1 0.68 M:0.3.11 0.66 M:0.3.10 0.64 M:0.3.9 0.55 M:0.3.8 0.68	2 C M:0.2.12 0.90 M:0.2.11 0.45 M:0.2.10 0.59 M:0.2.8 M:0.2.8	i:0.1.1 i:0.1.1 0.92 i:0.1.1 0.58 i:0.1.1 0.53 i:0.1.3 0.49 i:0.1.4 0.49 i:0.40	G:0.1.0	MO	UNTAI .15 (0.0.0) .14 (0.0.0) .13 (0.0.0) .13 (0.0.0) .13 (0.0.0) .14 (0.0.0) .14 (0.0.0) .14 (0.0) .14 (0.0)	N 0.15 0.13 M01.1.1 1.97 M01.1.1 1.54 M01.1.1
ITALY TUNNEL X:0.1.0.15X:0.1.1.15 X:0.1.0.14X:0.1.1.14 X:0.1.0.14X:0.1.1.13 X:0.1.0.12X:0.1.1.12 X:0.1.0.11X:0.1.1.11 X:0.1.0.11X:0.1.1.11 X:0.1.0.10X:0.1.1.10 X:0.1.0.9 X:0.1.1.9 X:0.1.0.8 X:0.1.1.8	G:0.1.15 M:0.19.12 M:0.19.11 M:0.19.10 M:0.19.0 M:0.19.3 M:0.19.8 M:0.19.8 M:0.19.7 M:0	G:0.1.14 0.18.12 M:0 1.07 0 0.18.11 M:0 0.42 0 0.18.10 M:0 0.63 0 0.18.8 M:0 0.63 0 0.18.8 M:0 0.18.8 M:0 0.18.7 M:0 0.18.7 M:0 0.18.7 M:0 0.18.7 M:0 0.18.7 M:0 0.18.7 M:0 0.18.7 M:0 0.18.1 M:	G:0.1.13	6.12 M:0.15.1 6 0.68 6.11 M:0.15.1 9 0.60 6.10 M:0.15.1 9 0.62 16.9 M:0.15.3 9 0.62 16.8 M:0.15.5 9 0.62 16.9 M:0.15.5 9 0.66 16.7 M:0.15.5 9 0.66	G:0.1.11 0.80 M:0.14.12 0.60 M:0.14.10 M:0.14.9 0.60 M:0.14.8 0.56 M:0.14.7 0.50	G:0.1. 0.65 W:0.13.11 0.67 W:0.13.10 0.72 M:0.13.9 0.71 M:0.13.8 0.51 M:0.13.7 0.73	.10 G M:0.12.12 0.81 M:0.12.11 0.61 M:0.12.10 0.62 M:0.12.9 0.46 M:0.12.7 0.65	:0.1.9 2M:0.11.12 0.76 M:0.11.11 0.63 0M:0.11.9 0.55 M:0.11.9 1.10 0.55 M:0.11.8 0.58 M:0.11.7 0.54	G:0.1.8 20.78 M:0.10.12 0.78 M:0.10.11 0.55 0.67 M:0.10.9 0.53 M:0.10.8 0.51 M:0.10.7 0.58	G:0.1.7 0.91 M:0.9.11 0.53 M:0.9.10 0.60 M:0.9.9 0.46 M:0.9.8 0.63 M:0.9.7 0.60	G:0.1	.6 G: M:0.7.12 1.02 M:0.7.11 0.61 M:0.7.10 0.55 M:0.7.9 0.64 M:0.7.8 0.57 M:0.7.7	0.1.5 M:0.6.11 0.75 M:0.6.11 0.56 M:0.6.20 0.65 M:0.6.8 0.66 M:0.6.7 0.51	G:0.1.4 2 M:0.5.12 1.06 4 M:0.5.11 0.70 M:0.5.10 0 M:0.5.10 0 M:0.5.10 0 M:0.5.10 0.58 M:0.5.8 0.66 M:0.5.7 0.63 M:0.5.7	G:0.1.3 M:0.4.12 0.73 M:0.4.11 0.63 M:0.4.10 0.64 M:0.4.9 0.68 M:0.4.8 0.63 M:0.4.7 0.64	G:0.1 0.68 M:0.3.11 0.66 M:0.3.10 0.64 M:0.3.9 0.55 M:0.3.8 0.68 M:0.3.7 0.62	.2 C M:0.2.11 0.90 M:0.2.11 0.45 M:0.2.1 0.59 M:0.2.9 M:0.2.8 M:0.2.7 0.49	i::0.1.1 i::0.1.1 0.92 1::0.92 1::0.92 1::0.92 1::0.92 1::0.1.1 0.53 1::0.1.1 0.53 1::0.1.1 0.53 1::0.1.1 0.49 1::0.1.1 0.49 1::0.1.1 0.40 1::0.57	G:0.1.0	MO	UNTAI .15 (0.0.0 .14 (0.0.0 .13 (0.0.0 .13 (0.0.0 .13 (0.0.0 .13 (0.0.0 .13 (0.0.0 .13 (0.0.0 .14 (0.0.0 .14 (0.0.0) .14 (0.	N 0.15 0.14 0.13 M01.11 1.97 M01.11 1.54 M01.11
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ITALY TUNNEL X:0.1.0.18X:0.1.1.18 X:0.1.0.14X:0.1.1.14 X:0.1.0.13X:0.1.1.13 X:0.1.0.13X:0.1.1.13 X:0.1.0.13X:0.1.1.13 X:0.1.0.11X:0.1.1.11 X:0.1.0.10X:0.1.1.10 X:0.1.0.10X:0.1.1.10 X:0.1.0.10X:0.1.1.10 X:0.1.0.10X:0.1.1.10 X:0.1.0.10X:0.1.1.10 X:0.1.0.10X:0.1.1.10 X:0.1.0.10X:0.1.1.10	G:0.1.15 M:0.19.12 M:0.19.11 M:0.19.11 M:0.19.10 M:0.19.0 M:	G:0.1.14 0.18.12 M:0 1.07 0. 0.18.11 M:0 0.42 0. 0.18.10 M:0 0.63 0. 0.18.8 M:0 0.63 0. 0.18.8 M:0 0.56 0. 0.18.6 M:0 0.55 M:0 0.55 M:0 0.55 M:0	G:0.1.13	6:12 M:0.15.1 6 0.68 6:11 M:0.15.1 9 0.60 6:10 M:0.15.1 9 0.62 16:9 0.15.1 9 0.15.2 16:9 M:0.15.3 16:0 M:0.15.5 16:0 M:0.15.5 16:0 M:0.15.5 16:0 M:0.15.5 16:0 M:0.15.5 16:5 M:0.15.5 16:5 M:0.15.5 16:5 M:0.15.5 16:5 M:0.15.5	G:0.1.11 0.80 M:0.14.12 0.80 M:0.14.11 0.60 M:0.14.9 0.60 M:0.14.8 0.56 M:0.14.7 0.50 M:0.14.6 0.622 M:0.14.5 0.60	G:0.1. 0.65 0.65 0.67 0.67 0.72 0.71 0.71 0.71 0.73 0.73 0.73 0.73 0.73 0.73 0.73 0.66 0.66 0.66 0.55	.10 G M:0.12.12 0.81 M:0.12.11 0.61 M:0.12.10 0.62 M:0.12.8 0.65 M:0.12.7 0.63 M:0.12.6 0.65 M:0.12.5 0.62	:0.1.9 2 10.76 10.076 10.011.11 10.63 10.0.11.9 10.055 10.0.11.9 10.055 10.0.11.9 10.056 10.0.11.9 10.058 10.0.11.6 10.56 10.056 10.056 10.058 10.056 10.056 10.056 10.056 10.056 10.056 10.056 10.056 10.058 10.056 10.056 10.058 10.056 10.056 10.056 10.058 10.056 10.056 10.058 10.056 10.056 10.058 10.056 10.056 10.058 10.056 10.056 10.058 10.056 10.056 10.058 10.056 10.056 10.058 10.056 10.056 10.058 10.056 10.056 10.058 10.056 10.056 10.058 10.056 10.056 10.056 10.058 10.056 10.056 10.058 10.056 10.056 10.058 10.056 10.056 10.058 10.056 10.056 10.056 10.058 10.056 10.056 10.056 10.056 10.058 10.056 10.056 10.056 10.056 10.058 10.056 10.0	G:0.1.8 20.78 10.078 10.010 10.55 10.010 10.55 10.010 10.07 10.03 10.010.8 10.010.7 10.58 10.010.7 10.58 10.010.7 10.58 10.010.7 10.58 10.010 10.05 10.010 10.05 10.010 10.05 10.010 10.05 10.010 10.05 10.010 10.05 10.	G:0.1.7 0.91 0.91 M:0.9.11 0.53 M:0.9.10 0.60 M:0.9.9 0.46 M:0.9.8 0.63 M:0.9.7 0.60 M:0.9.5 0.55	G:0.1 M:0.8.12 0.799 M:0.8.11 0.56 M:0.8.9 0.66 M:0.8.7 0.51 M:0.8.6 0.66 0.51	.6 G: M:0.7.12 M:0.7.11 O.61 M:0.7.9 O.64 M:0.7.9 M:0.7.7 M:0.7.7 M:0.7.7 M:0.7.5 O.63	0.1.5 M:0.6.11 0.75 M:0.6.11 0.56 M:0.6.41 0.73 M:0.6.9 0.65 M:0.6.8 0.66 M:0.6.7 0.51 M:0.6.6 0.57 M:0.6.2	G:0.1.4 1.06 1.06 1.06 1.06 1.06 1.070 1.05.11 0.70 1.05.10 1.05.11 1.05.11 0.70 1.05.11 0.70 1.05.11 0.70 1.05.11 0.70 1.05.11 0.70 1.05.11 0.53	G:0.1.3 M:0.4.12 0.733 M:0.4.11 0.633 M:0.4.6 0.644 M:0.4.7 M:0.4.8 0.633	G:0.1 0.68 M:0.3.11 0.66 M:0.3.10 0.64 M:0.3.9 0.55 M:0.3.8 0.68 M:0.3.7 0.62 M:0.3.6 0.65 M:0.3.5 0.61	.2 C M:0.2.11 0.90 M:0.2.11 M:0.2.13 M:0.2.9 M:0.2.9 M:0.2.9 M:0.2.9 M:0.2.6 M:0.2.5	a:0.1.1 2 M:0.1.1 0.92 4 M:0.1.1 0.58 0 1 0.53 1 0.49 1 0.49 1 0.49 1 0.40 1 0.57 1 0.57 1 0.55	G:0.1.0 2 M:0.0.12 0.90 1 M:0.0.11 0.66 0 M:0.0.11 0 M:0.0.11 0 M:0.0.11 0 M:0.0.11 0 M:0.0.11 0 M:0.0.11 0 M:0.0.21 0 M:0.0.31 0 M:0.0.31 0 M:0.0.31 0 M:0.0.41 0 M:0.0.52 7 M:0.0.56 0 M:0.0.59 5 M:0.0.44	MO	DUNTAI .15 (0.0.0 .14 (0.0.0 .13 (0.0.0 .13 (0.0.0 .13 (0.0.0 .13 (0.0.0 .13 (0.0.0 .13 (0.0.0 .13 (0.0.0 .13 (0.0.0 .14 (0.0.0	N 0.15 0.13 0.13 0.13 0.13 0.13 1.97 0.13 1.54 Met.13 1.55 Met.13 1.62
LTALY TUNNEL X:0.1.0.18X:0.1.1.18 X:0.1.0.14X:0.1.1.14 X:0.1.0.13X:0.1.1.13 X:0.1.0.13X:0.1.1.13 X:0.1.0.13X:0.1.1.13 X:0.1.0.11X:0.1.1.11 X:0.1.0.10X:0.1.1.10 X:0.1.0.10X:0.1.1.10 X:0.1.0.8 X:0.1.1.8 X:0.1.0.8 X:0.1.1.8 X:0.1.0.6 X:0.1.1.6 X:0.1.0.5 X:0.1.1.5	G:0.1.15 M:0.19.12 M:0.19.11 M:0.19.11 M:0.19.10 M:0.19.0 M:	G:0.1.14	G:0.1.13	6:12 M:0.15.1 16 0.68 6:11 M:0.15.1 19 0.60 6:10 M:0.15.1 19 0.60 6:10 M:0.15.1 19 0.62 16:9 M:0.15.5 16:9 0.66 16:7 M:0.15.5 16:6 M:0.15.6 16:5 M:0.15.6 16:5 M:0.15.6 16:5 M:0.15.6 16:5 M:0.15.6 16:6 M:0.15.6 16:6 M:0.15.6 16:6 M:0.15.6 16:6 M:0.15.6 16:6 M:0.15.6	G:0.1.11 0.80 M:0.14.12 0.80 M:0.14.11 0.60 M:0.14.9 0.60 M:0.14.8 0.56 M:0.14.7 0.50 M:0.14.6 0.62 M:0.14.5 0.60 M:0.14.4 0.61	G:0.1. W:0.13.12 0.65 W:0.13.11 0.67 W:0.13.10 0.72 M:0.13.10 0.71 M:0.13.7 0.73 M:0.13.7 0.73 M:0.13.5 0.55 M:0.13.4 0.64	.10 G M:0.12.12 0.81 M:0.12.11 0.61 M:0.12.10 0.62 M:0.12.8 0.65 M:0.12.7 0.63 M:0.12.6 0.65 M:0.12.5 0.62 M:0.12.5 0.62	:0.1.9 2 10.76 10.0.76 10.0.11.11 0.63 10.0.11.10 0.55 10.0.11.8 10.0.11.8 10.58 10.0.11.6 0.56 10.0.11.6 0.56 10.0.11.6 0.56 10.0.11.6 10.58	G:0.1.8 20.78 10.10.12 0.78 10.0.10.11 0.55 10.0.10.9 0.53 10.0.10.9 0.53 10.0.10.8 0.51 10.0.10.7 0.58 10.0.10.5 0.47 10.0.10.4 10.0.10.5 10.0.10.5 10.0.10.5 10.0.10.5 10.0.10.5 10.0.10.5 10.0.10.5 10.0.10.5 10.0.10.5 10.0.10.5 10.0.10.5 10.0.10.5 10.0.10.5 10.0.10.5 10.0.10 10.0.5 10.0.10 10.0.5 10.0.10 10.0.5 10.0.10 10.0.5 10.0.10 10.0.5 10.0.10 10.0.5 10.0.10 10.0.5 10.5 10.5 10.5 10.5 10.5 10.5 10.5 10.5 10.	G:0.1.7 0.91 0.91 0.93 0.93 0.60 0.60 0.60 0.60 0.60 0.60 0.60 0.55 0.55	G:0.1 M:0.8.12 0.799 M:0.8.11 0.56 M:0.8.9 0.66 M:0.8.7 0.51 M:0.8.6 0.65 M:0.8.5 0.51	.6 G: M:0.7.12 M:0.7.11 O.5 M:0.7.9 O.64 M:0.7.8 O.57 M:0.7.7 M:0.7.6 O.62 M:0.7.5 O.63 M:0.7.4 O.58	0.1.5 M:0.6.11 0.75 M:0.6.11 0.56 M:0.6.4 M:0.6.9 0.65 M:0.6.8 0.66 M:0.6.7 0.51 M:0.6.6 0.57 M:0.6.4 0.55	G:0.1.4 1.06 1.06 1.06 1.06 1.06 1.06 1.070 1.051 1.051 1.051 1.053 1.0553 1.053 1.053 1.053 1.054 1.0553 1.053	G:0.1.3 M:0.4.12 0.733 M:0.4.11 0.633 M:0.4.10 0.644 0.63 M:0.4.2 M:0.4.3 0.63 M:0.4.4 0.63 M:0.4.5 0.67	G:0.1 0.68 M:0.3.11 0.66 M:0.3.10 0.64 M:0.3.9 0.55 M:0.3.8 0.68 M:0.3.7 0.62 M:0.3.6 0.65 M:0.3.5 0.61 M:0.3.4 0.58	.2 C M:0.2.12 0.90 M:0.2.11 0.49 M:0.2.10 M:0.2.9 M:0.2.9 M:0.2.9 M:0.2.9 M:0.2.5 M:0.2.5 M:0.2.5	a:0.1.1 2 M:0.1.1 0.92 1 0.92 1 M:0.1.1 0.53 1 M:0.1.3 0.49 1 M:0.1.4 0.49 1 M:0.1.3 0.49 1 M:0.1.4 0.40 M:0.1.4 0.40 M:0.1.4 0.57 M:0.1.4 0.57 M:0.1.4 0.55 M:0.1.4	G:0.1.0 2 M:0.0.12 0.90 1 M:0.0.11 0.66 0 M:0.0.11 0 M:0.0.21 0 M:0.0.31 0 M:0.0.41 0 M:0.0.52 1 M:0.0.66 0.59 0.444 4 M:0.0.44	MO	DUNTAI .15 (0.0.0 .14 (0.0.0 .13 (0.0.0 .13 (0.0.0 .13 (0.0.0 .13 (0.0.0 .13 (0.0.0 .13 (0.0.0 .13 (0.0.0 .14 (0.0.0	N 0.15 0.13 0.13 0.13 0.13 0.13 1.97 0.13 1.54 0.13 1.64 0.13 1.64
LTALY TUNNEL X:0.1.0.15 X:0.1.1.15 X:0.1.0.14 X:0.1.1.13 X:0.1.0.14 X:0.1.1.13 X:0.1.0.12 X:0.1.1.13 X:0.1.0.12 X:0.1.1.13 X:0.1.0.10 X:0.1.1.11 X:0.1.0.10 X:0.1.1.11 X:0.1.0.10 X:0.1.1.11 X:0.1.0.8 X:0.1.1.18 X:0.1.0.7 X:0.1.1.7 X:0.1.0.6 X:0.1.1.6 X:0.1.0.5 X:0.1.1.5 X:0.1.0.4 X:0.1.1.4	G:0.1.15 M:0.19.12 M:0.19.11 M:0.19.11 M:0.19.01 M:0.19.0 M:0.19.0 M:0.19.0 M:0.19.2 M:0.19.4 M:0.19.7 M:0.19.7 M:0.19.4 M:0.19.7 M:	G:0.1.14 0.18.12 %:0 0.10.7 0 0.18.11 %:0 0.42 0 0.18.10 %:0 0.60 0 0.18.10 %:0 0.60 0 0.18.8 %:0 0.60 0 0.18.8 %:0 0.56 0 0.56 0 0.55 0	G:0.1.13	6:12 M:0.15.1 76 0.68 6:11 M:0.15.1 9 0.60 6:10 M:0.15.1 9 0.62 16:9 0.62 16:9 0.15.1 9 0.62 16:9 M:0.15.2 16:6 M:0.15.3 16:6 M:0.15.3 16:5 0.66 16:4 M:0.15.4 16:5 0.66 16:4 M:0.15.3 16:5 0.66 16:4 M:0.15.3 16:5 0.66 16:4 M:0.15.3 16:5 0.66 16:4 M:0.15.3	G:0.1.11 0.80 M:0.14.11 0.60 M:0.14.10 M:0.14.9 0.60 M:0.14.8 0.56 M:0.14.8 0.50 M:0.14.6 0.62 M:0.14.5 0.60 M:0.14.4 0.61	G:0.1. G:0.13.12 0.65 W:0.13.11 0.67 W:0.13.10 0.72 M:0.13.9 0.71 M:0.13.8 0.51 M:0.13.7 0.73 M:0.13.7 0.73 M:0.13.5 0.555 M:0.13.4 0.64	.10 G M:0.12.11 0.81 M:0.12.11 0.61 M:0.12.10 0.62 M:0.12.9 0.46 M:0.12.8 M:0.12.6 0.63 M:0.12.5 0.62 M:0.12.4 0.58 M:0.12.3 0.68	:0.1.9 20.76 10.76 10.0.76 10.0.11.11 0.63 10.0.11.9 10.0.55 10.0.11.8 10.0.11.6 0.56 10.0.11.6 0.56 10.0.11.6 0.56 10.0.11.6 0.56 10.0.11.6 10.56 10.0.56 10.0.56 10.0.11.7 10.58 10.0.11.7 10.58 10.0.11.7 10.58 10.0.56 10.0.58 10.0.11.6 10.56 10.0.56 10.0.58 10.0.11.7 10.58 10.0.56 10.0.56 10.0.58 10.0.11.7 10.58 10.0.56 10.0.56 10.0.56 10.0.58 10.0.11.7 10.58 10.0.56 10.0.56 10.0.58 10.0.11.7 10.56 10.0.56 10.0.58 10.0.11.7 10.55 10.0.56 10.0.11.7 10.58 10.0.11.8 10.0.56 10.0.56 10.0.56 10.0.58 10.0.11.8 10.0.56 10.0.56 10.0.58 10.0.11.8 10.0.56 10	G:0.1.8 20.78 30.10.12 0.78 30.010.11 0.55 30.010.10 30.67 30.58 30.010.7 30.58 30.010.5 30.47 30.64	G:0.1.7 0.91 0.91 0.53 0.60 0.60 0.60 0.60 0.60 0.55 0.55 0.55	G:0.12 0.79 M:0.8.12 0.56 M:0.8.10 0.68 M:0.8.3 0.66 M:0.8.4 0.51 M:0.8.4 0.51 M:0.8.7 0.51 M:0.8.6 0.66 M:0.8.7 0.51 M:0.8.6 0.52	.6 G: M:0.7.12 M:0.7.10 0.61 M:0.7.9 0.64 M:0.7.8 0.57 M:0.7.7 M:0.7.6 0.62 M:0.7.5 0.63 M:0.7.3 0.63	0.1.5 M:0.6.11 0.75 M:0.6.11 0.56 M:0.6.3 M:0.6.9 0.65 M:0.6.8 0.66 M:0.6.7 0.51 M:0.6.6 0.57 M:0.6.4 M:0.6.4 M:0.6.4	G:0.1.4 1.06 1.06 1.06 1.06 1.06 1.06 1.06 1.06 1.06 1.06 1.06 1.070	G:0.1.3 M:0.4.12 0.73 M:0.4.11 0.63 M:0.4.10 0.64 M:0.4.10 M:0.4.11 0.63 M:0.4.12 M:0.4.11 0.63 M:0.4.2 M:0.4.3 M:0.4.3 M:0.4.3	G:0.1 0.68 M:0.3.11 0.66 M:0.3.10 0.64 M:0.3.9 0.55 M:0.3.8 0.68 M:0.3.7 0.62 M:0.3.6 0.65 M:0.3.5 0.61 M:0.3.4 0.58	.2 C M:0.2.11 0.90 M:0.2.11 0.45 M:0.2.9 M:0.2.9 M:0.2.9 M:0.2.9 M:0.2.6 M:0.2.5 M:0.2.5 M:0.2.5 M:0.2.5 M:0.2.5 M:0.2.4 M:0.2.4	3:0.1.1 2 M:0.1.1 0.92 4 M:0.1.1 0.58 5 M:0.1.1 0.53 4 M:0.1.3 0.49 4 M:0.1.4 0.49 4 M:0.1.4 0.49 4 M:0.1.4 0.57 4 M:0.1.4 0.55 4 M:0.1.4 0.55 M:0.1.4 0.48 M:0.1.4	G:0.1.0 2 M:0.0.12 0.900 1 M:0.0.11 0.666 0 M:0.0.10 0 M:0.0.11 0 M:0.0.21 0 M:0.0.25 0 M:0.0.25 0 M:0.0.44 4 M:0.0.33 0.64 M:0.0.34	K:0.0.1 X:0.0 X:0.0 X:0.0 X:0.0	DUNTAI .15 (0.0.0) .14 (0.0.0) .13 (0.0.0) .13 (0.0.0) .13 (0.0.0) .13 (0.0.0) .1.0.11 2.26 .1.0.11 2.26 .1.0.11 1.88 .1.88 .1.88 .1.88 .1.88	N 0.15 0.13 0.13 0.13 0.13 0.13 0.13 0.13 0.13
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M:0.8.11 0.56 M:0.8.12 M:0.8.11 0.61 M:0.8.9 0.61 M:0.8.9 0.61 M:0.8.1 M:0.8.3 0.51 M:0.8.4 0.67 M:0.8.2 0.67 M:0.8.2 0.67 M:0.8.2 0.67	.6 G: M:0.7.12 M:0.7.11 O.5 M:0.7.9 O.64 M:0.7.8 O.57 M:0.7.7 M:0.7.6 O.62 M:0.7.4 O.63 M:0.7.4 O.63 M:0.7.3 O.63 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.3 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.64 M:0.7.2 O.65 M:0.7.2 O.64 M:0.7.2 M:0	0.1.5 M:0.6.1 0.75 M:0.6.1 0.56 M:0.6.9 0.65 M:0.6.8 0.66 M:0.6.7 M:0.6.6 0.57 M:0.6.5 M:0.6.4 0.55 M:0.6.4 0.55 M:0.6.4 0.55 M:0.6.4 0.55 M:0.6.4 0.55 M:0.6.4 0.55	G:0.1.4 2 M:0.5.12 1.06 4 M:0.5.11 0 M:0.5.10 0 M:0.5.10 0 M:0.5.10 0 M:0.5.10 0 M:0.5.10 0 M:0.5.10 0 M:0.5.8 0.66 0.64 M:0.5.3 0.64 M:0.5.4 0.66 M:0.5.3 0.48 0.48 M:0.5.2 0.53 M:0.5.4 0.66 M:0.5.4 0.66 M:0.5.5	G:0.1.3 M:0.4.12 0.73 M:0.4.11 0.63 M:0.4.9 0.64 M:0.4.9 0.63 M:0.4.9 0.63 M:0.4.9 0.63 M:0.4.10 M:0.4.3 M:0.4.4 0.63 M:0.4.2 0.65 M:0.4.1 0.64 0.79 M:0.4.4 0.79 M:0.4.5 0.63 M:0.4.4 0.65 M:0.4.2 0.65 M:0.4.1 0.680	G:0.1 0.68 0.66 0.65 0.55 0.55 0.61 0.65 0.65 0.61 0.65 0.65 0.65 0.65 0.65 0.65 0.65 0.65	.2 .2 M:0.2.11 0.90 M:0.2.11 0.45 M:0.2.10 M:0.2.11 M:0.2.12 M:0.2.13 M:0.2.24 M:0.2.3 M:0.2.3 M:0.2.4 M:0.2.2 0.55 M:0.2.10 M:0.2.20 M:0.2.11 0.52	a::0.1.1 2 M:0.1.1 0.92 4 M:0.1.1 0.58 0 M:0.1.1 0.53 0 M:0.1.1 0.53 M:0.1.1 0.53 M:0.1.3 0.49 M:0.1.4 0.40 M:0.1.3 0.40 M:0.1.4 0.57 M:0.1.4 0.55 M:0.1.4 0.55 M:0.1.4 0.48 M:0.1.3 0.48 M:0.1.4 0.50 M:0.1.4 0.50 M:0.1.5 0.48 M:0.1.4 0.50 M:0.1.4 0.50	G:0.1.0 2 M:0.0.12 0.900 1 M:0.0.11 0 M:0.0.11 0 M:0.0.11 0 M:0.0.11 0 M:0.0.110 0 M:0.0.11 0 M:0.0.11 0 M:0.0.11 0 M:0.0.21 1 M:0.0.21 0 M:0.0.55 0 M:0.0.44 0 0.660 3 M:0.0.21 0.58 M:0.0.22 0.58 M:0.0.21 1 M:0.0.21 0.58 M:0.0.21 0 M:0.0.21 0 M:0.0.21 0.58 M:0.0.21 0 M:0.0.21 0 M:0.0.21 0 M:0.0.21 0 M:0.0.21 0 M:0.0.21 0 M:0.21	K:0.0.1 K:0.1 K:0.1 K:0.1 K:0.1 K:0.1 </th <th>DUNTAI .14 (0.0.0) .13 (0.0.0) .13 (0.0.0) M:1.0.12 2.26 M:1.0.11 2.10 M:1.0.11 1.88 M:1.0.7 1.88 M:1.0.7 1.88 M:1.0.6 1.75 1.67 M:1.0.4 1.73</th> <th>N 0.14 0.14 0.13 Met.1.1 1.57 Met.1.3 1.62 Met.1.4 Met.1.4 Met.1.4 1.58 Met.1.4</th>	DUNTAI .14 (0.0.0) .13 (0.0.0) .13 (0.0.0) M:1.0.12 2.26 M:1.0.11 2.10 M:1.0.11 1.88 M:1.0.7 1.88 M:1.0.7 1.88 M:1.0.6 1.75 1.67 M:1.0.4 1.73	N 0.14 0.14 0.13 Met.1.1 1.57 Met.1.3 1.62 Met.1.4 Met.1.4 Met.1.4 1.58 Met.1.4

Time-delay calibration

Cheryl Patrick, U	University of Edinburg	gh
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X:0.0.	.1.14X:0.0.	0.14										
X:0.0.	.1.13 X :0.0.	0.13										
X:0.0	M:1.0.12 2.26	M:1.1.12 1.97	M:1.2.12 2.58	M:1.3.12 2.03	M:1.4.12 2.47	M:1.5.12 2.21	M:1.6.12 1.96	M:1.7.12 2.26	M:1.8.12 1.98	M:1.9.12 2.67	M:1.10.12 2.04	MET.11.13 2.07
X:0.0	M:1.0.11	M:1.1.11	M:1.2.11	M:1.3.11	M:1.4.11	M:1.5.11	M:1.6.11	M:1.7.11	M:1.8.11	M:1.9.11	M:1.10.11	M:1.11.1
X:0.0	2.10	1.54	1.71	1.72	1.61	1.61	1.57	1.52	1.54	1.65	1.64	1.59
X:0.0	M:1.0.10	M:1.1.10 1.57	M:1.2.10 1.48	M:1.3.10 1.56	M:1.4.10 1.52	M:1.5.10 1.52	M:1.6.10 1.57	M:1.7.10 1.41	M:1.8.10 1.55	M:1.9.10 1.50	M:1.10.10 1.50	мн.н.н. 1.54
X:0.0	M:1.0.9	M:1.1.9	M:1.2.9	M:1.3.9	M:1.4.9	M:1.5.9	M:1.6.9	M:1.7.9	M:1.8.9	M:1.9.9	M:1.10.9	M:1.11.9
X:0.0	1.88	1.62	1.52	1.67	1.52	1.53	1.46	1.39	1.47	1.45	1.57	1.58
X:0.0	M:1.0.8	M:1.1.8	M:1.2.8	M:1.3.8	M:1.4.8	M:1.5.8	M:1.6.8	M:1.7.8	M:1.8.8	M:1.9.8	M:1.10.8	M:1.11.8
	1.88	1.64	1.67	1.67	1.58	1.65	1.52	1.54	1.55	1.56	1.59	1.65
X:0.0	M:1.0.7	M:1.1.7	M:1.2.7	M:1.3.7	M:1.4.7	M:1.5.7	M:1.8.7	M:1.7.7	M:1.8.7	M:1.9.7	M:1.10.7	M:1.11.7
X:0.0	1.81	1.63	1.55	1.64	1.56	1.64	1.53	1.64	1.61	1.53	1.60	1.63
X:0.0	M:1.0.6	M:1.1.6	M:1.2.6	M:1.3.6	M:1.4.6	M:1.5.6	M:1.6.6	M:1.7.6	M:1.8.6	M:1.9.6	M:1.10.6	M:1.11.6
x∙oo	1.75	1.62	1.62	1.61	1.70	1.52	1.62	1.53	1.61	1.62	1.60	1.72
	M:1.0.5	M:1.1.5	M:1.2.5	M:1.3.5	M:1.4.5	M:1.5.5	M:1.6.5	M:1.7.5	M:1.8.5	M:1.9.5	M:1.10.5	M:1.11.5
X:0.0	1.67	1.58	1.57	1.64	1.62	1.53	1.50	1.42		1.52	1.75	1.59
X:0.0	M:1.0.4	M:1.1.4	M:1.2.4	M:1.3.4	M:1.4.4	M:1.5.4	M:1.6.4	M:1.7.4	M:1.8.4	M:1.9.4	M:1.10.4	M:1.11.4
	1.73	1.49	1.51	1.61	1.50	1.47	1.48	1.47	1.72	1.56	1.71	1.60
IOTA vall:m	M:1.0.3	M:1.1.3	M:1.2.3	M:1.3.3	M:1.4.3	M:1.5.3	M:1.6.3	M:1.7.3	M:1.8.3	M:1.9.3	M:1.10.3	M:1.11.3
/all:m	1.74	1.52	1.55	1.52	1.52	1.45	1.51	1.47	1.56	1.51	1.54	1.59
	M:1.0.2	M:1.1.2	M:1.2.2	M:1.3.2	M:1.4.2	M:1.5.2	M:1.6.2	M:1.7.2	M:1.8.2	M:1.9.2	M:1.10.2	M:1.11.2
	1.60	1.65	1.43	1.51	1.58	1.47	1.53	1.48	1.41	1.54	1.58	1.57
	M:1.0.1	M:1.1.1	M:1.2.1	M:1.3.1	M:1.4.1	M:1.5.1	M:1.6.1	M:1.7.1	M:1.8.1	M:1.9.1	M:1.10.1	M:1.11.1
	1.62	1.63	1.43	1.56	1.53	1.62	1.60	1.55	1.48	1.44	1.49	1.53
	M:1.0.0	M:1.1.0	M:1.2.0	M:1.3.0	M:1.4.0	M:1.5.0	M:1.6.0	M:1.7.0	M:1.8.0	M:1.9.0	M:1.10.0	M:1.11.0
	1 02	1.82	1.90	214	2.05	2.04	1 05	1.97	1 99	1.74	2.04	1 00

_					
13.12	^{M:0.12.12}	^{M:0.11.12}	^{M:0.10.12}	м:0.9.12	M
. 53	14.33	14.33	11.22	12.81	1
.3.11	^{4:0.12.11}	^{M:0.11.11}	M:0.10.11	м:0.9.11	M
. 35	12.27	12.08	8.86	9.65	
13.10	^{M:0.12.10}	^{M:0.11.10}	м:0.10.10	M:0.9.10	M
. 00	13.03	13.76	11.11	9.80	
13.9	м:0.12.9	м:0.11.9	м:0.10.9	M:0.9.9	N
. 16	10.81	8.17	8.40	6.68	
13.8	M:0.12.8	M:0.11.8	M:0.10.8	м:0.9.8	N
30	9.31	6.66	6.48	4.18	
13.7	м:0.12.7	M:0.11.7	м:0.10.7	м:0.9.7	N
04	5.99	4.96	3.97	1.76	
13.6 60	M:0.12.6 8.28	M:0.11.6 5.55	M:0.10.6	м:0.9.6 1.21	N
13.5	M:0.12.5	M:0.11.5	м:0.10.5	м:0.9.5	N
09	3.23	4.66	4.58	-0.03	
13.4	M:0.12.4	M:0.11.4	м:0.10.4	м:0.9.4	N
50	6.10	3.21	3.91	-2.08	
13.3 97	M:0.12.3 1.87	M:0.11.3	M:0.10.3 -2.32	м:0.9.3 - 3.64	N
13.2 16	M:0.12.2 4.26	M:0.11.2 2.08	M:0.10.2 -0.29	M:0.9.2	N
13.1 71	M:0.12.1	M:0.11.1 -0.75	™:0.10.1 - 0.91	M:0.9.1 -3.44	N
13.0	M:0.12.0	M:0.11.0	M:0.10.0	м:0.9.0	N -
16	3.64	2.11	- 0.47	0.02	

SuperNEMO Demonstrator status: Tracker

RUN 807 // TRIGGER 458

Cheryl Patrick, University of Edinburgh

- Dramatic progress over the last year after setbacks due to Covid, faulty hardware...
- Entire tracker successfully tested at high voltage
- 2/3 of detector undergoing commissioning / calibration
- Final 1/3 to be connected shortly
- ~99% of connected channels operational

Real tracker-calorimeter data!

		-										
M:0.0.*	M:0.1.*	M:0.2.*	M:0.3.*	M:0.4.*	M:0.5.*	M:0.6.*	M:0.7.*	M:0.8.*	M:0.9.*	M:0.10.*	M:0.11.*	
.1.*												
.0 												
.0.*												
.1.*												
M:1.0.*	M:1.1.*	M:1.2.*	M:1.3.*	M:1.4.*	M:1.5.*	M:1.6.*	M:1.7.*	M:1.8.*	M:1.9.*	M:1.10.*	M:1.11.*	

RUN 807 // TRIGGER 840+841

Getting ready for physics data

Cheryl Patrick, University of Edinburgh

Under construction

Iron shielding ordered; quality control looking promising

Polyethylene / water design in final review

Getting ready for physics data

Cheryl Patrick, University of Edinburgh

	M:0.0.*	М:0.1.*	M:0.2.*	M:0.3.*	M:0.4.*	M:0.5.*	M:0.6.*	M:0.7.'	M:0.8.*	M:0.9.*	M:0.1
X:0.	0.1.* •										
X:0.											
X:1.			******* ******* ******							$\begin{array}{c} \bullet \bullet$	
X:1.											
	M:1.0.*	M:1.1.'	N:1.2.*	M:1.3.*	M:1.4.*	M:1.5.*	M:1.6.*	M:1.7.'	M:1.8.*	M:1.9.*	M:1.1

Other UK activities

Cheryl Patrick, University of Edinburgh

NEXT high-pressure gaseous ¹³⁶Xe TPC

NEXT Collaboration, JHEP 01 (2021) 189 NEXT Collaboration, JHEP 10 (2019) 052

- Energy plane: 60 PMTs behind prophing einer w plane With ocured electronics completed, windows coating ong
- Tracking plane: 56 boards with 64 SIPMs ead built and TPB-coated, electronics completed a

TPC installation UK-led

• NEXT-HD's first module can reach $T_{\frac{1}{2}} > 10^{27}$ yr $0\nu\beta\beta$ sensitivity with 4 ton.yr exposure

- NEXT-HD's first module can reach $T_{\frac{1}{2}} > 10^{27}$ yr $0\nu\beta\beta$ sensitivity with 4 ton.yr exposure
- NEXT-BOLD: seeks 10²⁸-year sensitivity through **barium tagging technology**

NEXT ton-scale and beyond

- NEXT-HD's first module can reach $T_{\frac{1}{2}} > 10^{27}$ yr $0\nu\beta\beta$ sensitivity with 4 ton.yr exposure
- NEXT-BOLD: seeks 10²⁸-year sensitivity through **barium tagging technology**
- Unambiguous signature for $\beta\beta \rightarrow$ background free
- R&D needed to scale up to 1-ton detectors...

LUX-ZEPLIN dark-matter detector

Cheryl Patrick, University of Edinburgh

The day job:

• 7-ton liquid-xenon TPC for direct dark-matter detection

The side hustles:

• Two $\beta\beta$ xenon isotopes: ¹³⁴Xe and ¹³⁶Xe

¹³⁶Xe at LZ

Current LZ xenon detector (8.9% ¹³⁶Xe) won't see $0\nu\beta\beta$

Cheryl Patrick, University of Edinburgh

Phys. Rev. C 102, 014602 (2020)

Current LZ xenon detector (8.9% ¹³⁶Xe) won't see $0\nu\beta\beta$

Cheryl Patrick, University of Edinburgh

• After WIMP search: enrich with 90% ¹³⁶Xe?

• Potential for 10²⁷-year sensitivity - beyond current best limit

¹³⁴Xe at LZ

- Abundance 10.4%
- $2\nu\beta\beta$ predicted with very long half-life
- Experimental limit $T_{\frac{1}{2}\nu} > 8.7 \times 10^{20}$ years (EXO-200)

LZ's nautral-Xe detector could improve the limit at short exposure for $2\nu\beta\beta$ and $0\nu\beta\beta$

arXiv:2104.13374 [physics.ins-det]

Cheryl Patrick, University of Edinburgh

1) Continued support for SNO+ and SuperNEMO Demonstrator exploitation

- Substantial prior UK investment
- Two completely unique physics programmes

supernemo

collaboration

1) Continued support for SNO+ and SuperNEMO Demonstrator exploitation

- Substantial prior UK investment
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2) Next-generation: LEGEND

- Supported by both US and EU roadmaps
- LEGEND-200 exploitation
- LEGEND-1000 preparations

collaboration

1) Continued support for SNO+ and SuperNEMO Demonstrator exploitation

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2) Next-generation: LEGEND

- Supported by both US and EU roadmaps
- LEGEND-200 exploitation
- LEGEND-1000 preparations

3) R&D: new techniques to go beyond inverted hierarchy

- Isotope-loaded liquid scintillator (SNO+ technique) especially promising
- and...?

supernemo

collaboration

