Table E – Early Muonium rate constants

The record of early attempts to measure k_M before the direct Mu-decay method was perfected

[These muonium rate constants were determined in early 70-ies by two independent groups using indirect model-fitting procedures (12,13) which resulted in rate constants markedly different from current data.]

PART A – Muonium rate Constants kM determined by the Team from the Joint Nuclear Centre DUBNA

INORGANIC REAGENTS IN AQUEOUS SOLUTIONS

Code	Ion	Reaction proposed	Type of reaction	k_M (in $dm^3mol^{-1}s^{-1}$)	Notes about measurement	Reference number	K_H (in $dm^3mol^{-1}s^{-1}$)	Notes about measurement	Reference number	KIE = k_M / k_H
E1	Calcium ion - Ca^{2+}	N/A	N/A	$k < 1 \times 10^8$	N/A	1	N/A	N/A	N/A	N/A
E2	Chloride ion - Cl^-	N/A		$k < 1 \times 10^8$	N/A	1				
E3	Perchlorate ion – ClO_4	N/A		$k = 1.2 \times 10^9$	N/A	1				
E4	Copper ion – Cu^{2+} as $CuSO_4$	$Cu^{2+} + Mu \rightarrow Cu^+ + \mu^+$		5.6×10^9	N/A	1				
E5	Hydrogen ion – H^+ as $HClO_4$	$H^+ + Mu \rightarrow H + \mu^+$		6×10^8	N/A	1				
E6	Magnesium ion – Mg^{2+} as $MgCl_2$	N/A		$< 1 \times 10^8$	N/A	1				
E7	Nitrate ion – NO_3^-	$Mu + NO_3^- \rightarrow (OMu)^- + NO_2$		$(1.60 \pm 0.14) \times 10^{10}$	N/A	2				
E8	Nitrite ion – NO_2^-	$Mu + NO_3^- \rightarrow (OMu)^- + NO_2$		$(1.1 \pm 0.5) \times 10^{10}$	N/A	2				
E9	Hydroxyl ion - OH^- as NaOH	$OH^- + Mu \rightarrow (HMuO)^- \rightarrow H + (OMu)^-$		1.8×10^9	N/A	1				
E10	Sodium ion – Na^+ as NaCl	N/A		$< 10^8$	N/A	1				

E11	Sulphate ion – SO_4^{2-}	N/A		$k < 10^8$	N/A	1	
E12	Water – H_2O	$Mu + (H_2O)_n \rightarrow Mu(H_2O)_n \rightarrow HMuO + H + (H_2O)_{n-1}$		**a)** ($1.09 \times 10^8 \pm 13$ %) **b)** ($9.6 \times 10^7 \pm 14$ %) **c)** ($6.8 \times 10^7 \pm 17$ %)	**a)** T = 363 K **b)** T = 303 K **c)** T = 273 K (liquid) $E_a = (135 \pm 320)$ cal/mol^{-1} for T=273 K - 363K	4	
E13	Zinc ion – Zn^{2+} as $ZnSO_4$	N/A		$< 2 \times 10^8$	N/A	1	

ORGANIC REAGENTS – neat solvents unless stated otherwise

Code	Ion	Reaction proposed	Type of Reaction	k_M (in $dm^3mol^{-1}s^{-1}$)	Notes about measurement	Reference number	K_H (in $dm^3mol^{-1}s^{-1}$)	Notes about measurement	Reference number	KIE = k_M / k_H
E14	Aniline (aqueous solution)	$C_6H_5NH_2 + Mu \rightarrow$?	?	9×10^8	N/A	2				
E15	Benzene	$C_6H_6 + Mu \rightarrow MuH + C_6H_5$ $C_6H_6 + Mu \rightarrow MuC_6H_6$	abstraction and addition	**a)** $k^{abs} = (3.4 + 23\ \%/- 18\ \%) \times 10^8$ $k^{add} = (1.3 + 21\ \%/- 18\ \%) \times 10^9$ **b)** $k^{abs} = (3.0 \pm 1.1) \times 10^8$ $k^{add} = (3.1 \pm 0.4) \times 10^9$	N/A	**a)** 3 **b)** 6				
E16	Benzyl chloride (α-chlorotoluene)	$C_6H_5CH_2Cl + Mu \rightarrow$? $C_6H_5CH_2Cl + Mu \rightarrow MuC_6H_5CH_2Cl$	abstraction and addition	$k^{abs} = (2.5 \pm 0.7) \times 10^9$ $k^{add} = (2.5 \pm 0.3) \times 10^9$	N/A	6				
E17	Benzal chloride (α,α-dichlorotoluene	$C_6H_5CH_2Cl_2 + Mu \rightarrow$? $C_6H_5CHCl_2 + Mu \rightarrow MuC_6H_5CHCl_2$	abstraction and addition	$k^{abs} = (4.1 \pm 1.1) \times 10^9$ $k^{add} = (2.5 \pm 0.2) \times 10^9$	N/A	6				
E18	Benzotrichloride (α,α,α-trichlorotoluene	$C_6H_5CCl_3 + Mu \rightarrow$? $C_6H_5CCl_3 + Mu \rightarrow MuC_6H_5CCl_3$	abstraction and addition	$k^{abs} = (6.5 \pm 1.5) \times 10^9$ $k^{add} = (2.5 \pm 0.2) \times 10^9$	N/A	6				

E19	Bromobenzene	$C_6H_5Br + Mu \rightarrow ?$ $C_6H_5Br + Mu \rightarrow MuC_6H_5Br$	abstraction and addition	**a)** k_M^{abs} = (1.7 +30 %/- 20 %) x 10^9 k^{add} = 1.3 x 10^9 **b)** k_M^{abs} = (1.0 ± 0.3) x 10^9 k^{add} = (4.7 ± 1.9) x 10^8	N/A	**a)** 3 **b)** 5	N/A
E20	Bromocyclohexane	χ–$C_6H_{11}Br + Mu \rightarrow ?$	abstraction	(5.0 ± 0.6) x 10^9	N/A	6	
E21	Bromoform	$CHBr_3 + Mu \rightarrow ?$	abstraction	**a)** (1.6 + 27 %/- 19 %) x 10^{10} **b)** (3.0 ± 23 %) x 10^{10} **c)** (1.1± 0.2) x 10^{10}	**a)** N/A **b)** at T=303K $E_a \geq$ (0.67 ± 0.05) kcal mol^{-1} for T=77K - 303K **c)** N/A	**a)** 3 **b)** 4 **c)** 7	
E22	n-Butylbenzene	$C_6H_5C_4H_9 + Mu \rightarrow MuH + ?$ $C_6H_5C_4H_9 + Mu \rightarrow MuC_6H_5C_4H_9$	abstraction and addition	k^{abs} = (1.8 ± 0.6) x 10^9 k^{add} = (2.5 ± 0.3) x 10^9	N/A	6	
E23	Chlorobenzene	$C_6H_5Cl + Mu \rightarrow ?$ $C_6H_5Cl + Mu \rightarrow MuC_6H_5Cl$	abstraction and addition	**a)** k^{abs} = (7.4 + 30 %/- 20 %) x 10^8 k^{add} = 1.3 x 10^9 **b)** k^{abs} = (5.7 ± 1.0) x 10^8 k^{add} = (6.0 ± 1.4) x 10^8	N/A	**a)** 3 **b)** 5	
E24	Chlorocyclohexane	c–$C_6H_{11}Cl + Mu \rightarrow ?$	abstraction	(2.7 ± 0.3) x 10^9	N/A	6	

E25	Chloroform	$CHCl_3$ + Mu →	abstraction	**a)** (5.0 + 31 %/-24 %) x 10^9 **b)** (4.2 ± 31) x 10^9	N/A	**a)** 3 **b)** 7	N/A
E26	1,3-Cyclohexadien	c–C_6H_8 + Mu → MuH + c–C_6H_7 χ–C_6H_8 + Mu → c–C_6H_8Mu	abstraction and addition	k^{abs} = (1.3 ± 0.2) x 10^9 k^{add} = (2.1 ± 0.3) x 10^9	N/A	6	
E27	1,4-Cyclohexadien	c–C_6H_8 + Mu → MuH + c–C_6H_7 c–C_6H_8 + Mu → c–C_6H_8Mu	abstraction and addition	k^{abs} = (2.4 ± 0.4) x 10^9 k^{add} = (2.1 ± 0.3) x 10^9	N/A	6	
E28	Cyclohexane	c–C_6H_{12} + Mu → MuH + c–C_6H_{11}	abstraction	**a)** (1.2 + 19 % / -15%) x 10^9 **b) i)** (1.15 ± 18 %) x 10^9 ii) (9.4 ± 15 %) x 10^9 ic) (2.4 ± 0.2)	**a)** N/A **b)** i) T= 303 K **ii)** T= 280 K E_a = (1410 ± 50) kcal mol^{-1} **c)** N/A	**a)** 3 **b)** 4 **c)** 6	
E29	Cyclohexanol	c-$C_6H_{11}OH$ + Mu → MuH + ?	abstraction	(2.3 ± 0.2) x 10^9 *(value estimated)*	N/A	6	
E30	Cyclohexanon	c-$C_6H_{10}O$ + Mu → MuH + c–C_6H_9O c-$C_6H_{10}O$ + Mu → c-$C_6H_{10}OMu$	abstraction and addition	k^{abs} = (2.3 ± 0.2) x 10^9 k^{add} = (0.42 ± 0.07) x 10^9	N/A	6	

E31	Cyclohexene	$c–C_6H_{10}$ + Mu → MuH + $c–C_6H_9$ $c–C_6H_{10}$ + Mu → $c–C_6H_{10}Mu$	abstraction and addition	k^{abs} = (2.0 ± 0.4) x 10^9 k^{add} = (1.0 ± 0.2) x 10^9	N/A	6	N/A
E32	Dichloroethane	$C_2H_4Cl_2$ + Mu → ?	abstraction	(7.0 + 45 %/- 34 %) x 10^8	N/A	3	
E33	Diethyldithiocarbamate sodium salt aqueous solution	$(C_2H_5)_2NCS_2Na$ + Mu → ?	?	(1.7 ± 0.7) x 10^9	N/A	2	
E34	Dimethyl benzene	$C_6H_4(CH_3)_2$ + Mu → MuH + ? $C_6H_4(CH_3)_2$ + Mu → $MuC_6H_4(CH_3)_2$	abstraction and addition	k^{abs} = (9.2 ± 2.3) x 10^8 k^{add} = (2.5 ± 0.8) x 10^9	N/A	6	
E35	DPPH (2,2-Diphenyl-1-picrylhydrazyl) in benzene and chloroform solutions	DPPH + Mu → ?	?	**a)** (1.1± 29%) x 10^{11} **b)** (7.6 ± 2.2) x 10^{10}	N/A	**a)** 3 **b)** 7	
E36	EDTA ethylenediaminotetracetic acid disodium salt aqueous solution	EDTA + Mu → ?	?	1.6 x10^9	N/A	2	
E37	Ethylbenzene	$C_6H_5C_2H_5$ + Mu → MuH + ? $C_6H_5C_2H_5$ + Mu → $MuC_6H_5C_2H_5$	abstraction and addition	k^{abs} = (1.05 ± 0.30) x 10^9 k^{add} = (2.40 ± 0.80) x 10^9	N/A	6	

E38	Fluorobenzene	$C_6H_5F + Mu \rightarrow C_6H_5F + Mu \rightarrow MuC_6H_5F$	abstraction and addition	$\mathbf{k^{abs}} = (6.0 \pm 1.3) \times 10^8$ $\mathbf{k^{add}} = (1.9 \pm 0.3) \times 10^9$	N/A	5	N/A
E39	Fluorocylohexane	$c\text{–}C_6H_{11}F + Mu \rightarrow ?$	abstraction	$(2.1 \pm 0.3) \times 10^9$	N/A	6	
E40	Hexamethylbenzene	$C_6(CH_3)_6 + Mu \rightarrow MuH + ?$ $C_6(CH_3)_6 + Mu \rightarrow MuC_6(CH_3)_6$	abstraction and addition	$\mathbf{k^{abs}} = (1.85 \pm 0.34) \times 10^9$ $\mathbf{k^{add}} = (1.5 \pm 0.5) \times 10^9$	N/A	N/A	
E41	Iodobenzene	$C_6H_5I + Mu \rightarrow ?$ $C_6H_5I + Mu \rightarrow MuC_6H_5I$	abstraction and addition	$\mathbf{k^{abs}} = (1.3 \pm 0.1) \times 10^9$ $\mathbf{k^{add}} = (3.4 \pm 0.1) \times 10^8$	N/A	5	
E42	Iodocyclohexane	$c\text{–}C_6H_{11}I + Mu \rightarrow ?$	abstraction	$(13.2 \pm 4.0) \times 10^9$	N/A	6	
E43	Methanol	$CH_3OH + Mu \rightarrow MuH + ?$	abstraction	**a)** $(2.7 + 21\ \%/- 16\ \%) \times 10^8$ **b)** $(2.4 \pm 0.2) \times 10^9$	N/A	**a)** 3 **b)** 7	
E44	Methylene iodide	CH_2I_2	abstraction	$(9.5 + ?/- 85\ \%) \times 10^{10}$	N/A	3	
E45	n-Octane	$C_8H_{18} + Mu \rightarrow MuH + C_8H_{17}$	abstraction	**a)** $(1.1 + 18\ \%/- 12\ \%) \times 10^9$ **b)** $(2.9 \pm 0.4) \times 10^9$	N/A	**a)** 3 **b)** 7	

E46	3-Phenylhexane	$C_6H_5CH(C_2H_5)C_3H_7 + Mu \rightarrow MuH + ?$ $C_6H_5CH(C_2H_5)C_3H_7 + Mu \rightarrow MuC_6H_5(C_2H_5)C_3H_7$	abstraction and addition	$k^{abs} = (1.8 \pm 0.6) \times 10^9$ $k^{add} = (2.5 \pm 0.3) \times 10^9$	N/A	6	
E47	Tetramethylbenzene	$C_6H_2(CH_3)_4 + Mu \rightarrow MuH + ?$ $C_6H_2(CH_3)_4 + Mu \rightarrow MuC_6H_2(CH_3)_4$	abstraction and addition	$k^{abs} = (1.08 \pm 0.24) \times 10^9$ $k^{add} = (2.3 \pm 0.7) \times 10^9$	N/A	6	
E48	Toluene	$C_6H_5CH_3 + Mu \rightarrow MuH + ?$ $C_6H_5CH_3 + Mu \rightarrow MuC_6H_5CH_3$	abstraction and addition	$k^{abs} = (7.7 \pm 0.2) \times 10^8$ $k^{add} = (2.5 \pm 0.7) \times 10^9$	N/A	6	
E49	Trimethylbenzene	$C_6H_3(CH_3)_3 + Mu \rightarrow MuH$ $C_6H_3(CH_3)_3 + Mu \rightarrow MuC_6H_3(CH_3)_3$	abstraction and addition	$k^{abs} = (1.03 \pm 0.22) \times 10^9$ $k^{add} = (2.4 \pm 0.7) \times 10^9$	N/A	6	

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PART B – Muonium rate Constants kM determined by Brewer, J.H et al

Code	Ion	Reaction	Type of reaction	k_M (in $dm^3mol^{-1}s^{-1}$)	Notes about measurement	K_H (in $dm^3mol^{-1}s^{-1}$)	Notes about measurement	KIE = k_M / k_H
E51	Perchlorate ion - ClO^-_4	$ClO^-_4 + Mu \rightarrow ?$	?	~ $4 \times 10^{10} dm^3mol$				
E52	Iron perchlorate – $Fe(ClO_4)_3$	$Fe^{+3} + Mu \rightarrow \mu^+ + Fe^{+2}$	Reduction	~ $(4.4 \pm 0.8) \times 10^{10}$				
E53	Iron trichloride – $FeCl_3$	$Fe^{+3} + Mu \rightarrow \mu^+ + Fe^{+2}$	Reduction	$(2.1 \pm 0.2) \times 10^{10}$				
E54	Hydrogen peroxide	$H_2O_2 + Mu \rightarrow MuO + H_2O$ $H_2O_2 + Mu \rightarrow MuH_2O_2$	abstraction and addition	$(1.09 \pm 0.15) \times 10^{10}$		N/A		
E55	Water	$H_2O + Mu \rightarrow ?$	?	$< 10^7$				
E56	Nitrate ion - NO^-_3 as HNO_3	$NO^-_3 + Mu \rightarrow ?$	abstraction and unidentified process	$(1.3 \pm 0.6) \times 10^{11} dm^3mol$				
E57	Bromine (Br_2) in benzene	$Br_2 + Mu \rightarrow MuBr + Br$	Abstraction	$(9.4 \pm 0.3) \times 10^{10}$				
E58	Iodine (I_2) in benzene	$I_2 + Mu \rightarrow MuI + I$	Abstraction	5.7×10^{10}				
E59	Iodine (I_2) in methanol	$I_2 + Mu \rightarrow MuI + I$	Abstraction	$(1.34 \pm 0.2) \times 10^{10}$				
E60	Benzene (neat)	$C_6H_6 + Mu \rightarrow C_6H_6Mu$	Addition	$(8 \pm 5.3) \times 10^8$				
E61	Methanol (neat)	$CH_3OH + Mu \rightarrow MuH + ?$	Abstraction	$< 10^7$				

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