Superconducting qubits Hub

VQD setup

Set the main directory as the current directory

```
In[1]:= SetDirectory[NotebookDirectory[]];
```

Load the QuESTLink package
One may also use the off-line questlink.m file, change it to the location of the local file

```
In[2]:= Import["https://qtechtheory.org/questlink.m"]
```

This will download a binary file **quest_link** from the repo; some error will show if the system tries to override the file

Use **CreateLocalQuESTEnv[quest_link_file]** to use the existing binary

```
In[3]:= CreateDownloadedQuESTEnv[];
```

Load the **VQD** package; must be loaded after QuESTlink is loaded

```
In[4]:= Get["../vqd.wl"]
```

Set the default configuration of the virtual superconducting device

frequency unit: ***MHz***
time unit: ***μs***

```
In[5]:= Options[SuperconductingHub] = {
        (* The number of qubits should match all assignments. Qubits are numbered from 0 to N-1 *)
        QubitNum → 6
        ,
        (* The T1 time *)
        T1 → <|0 → 63, 1 → 93, 2 → 109, 3 → 115, 4 → 68, 5 → 125|>
        ,
        (* The T2 time with Hahn echo applied *)
        T2 → <|0 → 113, 1 → 149, 2 → 185, 3 → 161, 4 → 122, 5 → 200|>
        ,
        (* Excited population probability in the initialisation, also the thermal state *)
        ExcitedInit → <|0 → 0.032, 1 → 0.021, 2 → 0.008, 3 → 0.009, 4 → 0.025, 5 → 0.007|>
        ,
        (* Qubit frequency of each qubit  *)
        QubitFreq → <|0 → 4500, 1 → 4900, 2 → 4700, 3 → 5100, 4 → 4900, 5 → 5300|>
        ,
        (* Exchange coupling strength of the resonators on each edge. Use [Esc]o-o[Esc] for the edge notation *)
        ExchangeCoupling → <|0 ⟷ 1 → 4, 0 ⟷ 2 → 1.5, 1 ⟷ 3 → 1.5, 2 ⟷ 3 → 4, 2 ⟷ 4 → 1.5, 3 ⟷ 5 → 1.5, 4 ⟷ 5 → 4|>
        ,
        (* Transmon Anharmonicity *)
        Anharmonicity → <|0 → 296.7, 1 → 298.6, 2 → 297.4, 3 → 298.3, 4 → 297.2, 5 → 299.1|>
        ,
        (* Fidelity of qubit readout *)
        FidRead → <|0 → 0.9, 1 → 0.92, 2 → 0.96, 3 → 0.97, 4 → 0.93, 5 → 0.97|>
        ,
        (* Measurement duration. It is done without quantum amplifiers *)
        DurMeas → 5
        ,
        (* Duration of the Rx and Ry gates are the same regardless the angle. Rz is virtual and perfect. *)
        DurRxRy → 0.05
        ,
        (* Duration of the cross resonance ZX gate that is fixed regardless the angle. The error is sourced from the passive noise only. *)
        DurZX → 0.5
        ,
        (* Duration of the siZZle gate is fixed regardless the angle that is fixed regardless the angle. The error is sourced from the passive noise only. *)
        DurZZ → 0.5
        ,
        (* switches to turn on/off standard passive noise, i.e., T1 and T2 decay *)
        StdPassiveNoise → True
        ,
        (* switches to turn on/off the cross-talk ZZ-noise *)
        ZZPassiveNoise → True
       };
```

Elementary guide

Native gates

Initialisation and readout

$\text{Init}_{0,1,\ldots,n}$, M_q

Single-qubit gates, θ ϵ [-π ,π]
$Rx_q[\theta]$, $Ry_q[\theta]$, $Rz_q[\theta]$

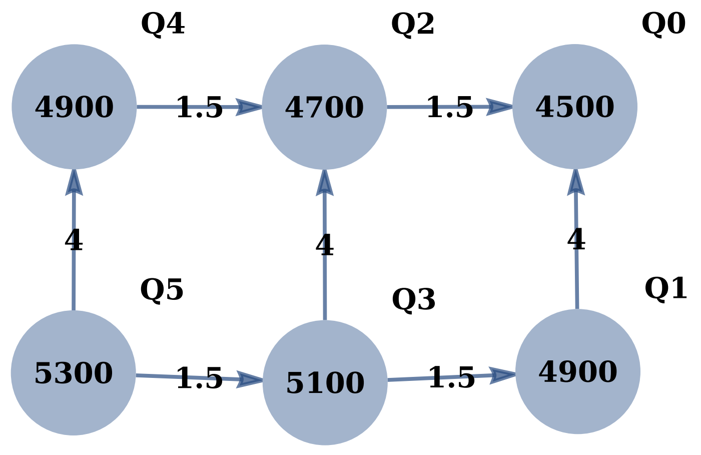
Two-qubit gates: siZZler and cross-resonant gates
$ZZ_{q1,q2}$, $ZX_{q1,q2}$

others: doing nothing
$Wait_q$[duration]

Instantiate the VQD and show gates connectivity: the arrows show direction of cross-resonant ZX gates$_{control,target}$

In[6]:=
```
dev = SuperconductingHub[];
```

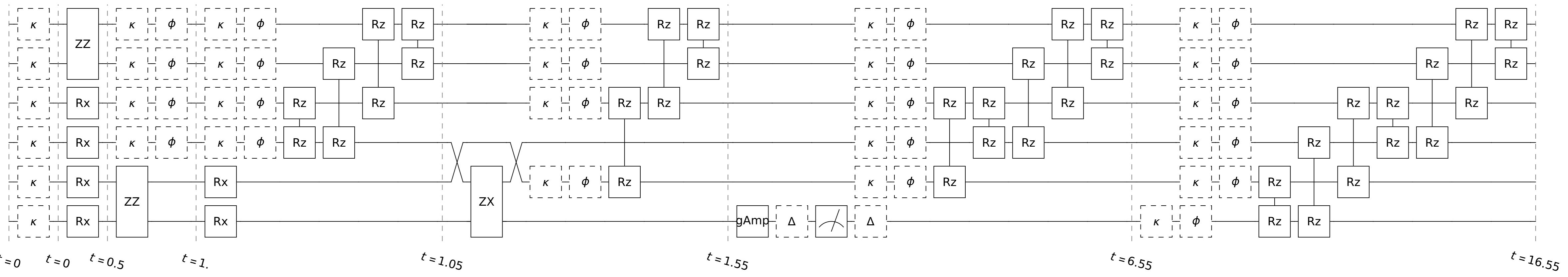
In[7]:=
```
g = dev[Connectivity]
```

Out[7]=


Passive noise is extensive

In[8]:=
```
noisycirc =
   InsertCircuitNoise[
    {Init˛И˛И˒И˒И˓И˒ , Rx˛[π], Rx˛[π], Rx˒[π / 2], ZZ˛И˛ , Rx˛[π / 4], Rx˛[π], Rx˒[π], ZX˒И˛ , ZZ˓И˒ , M˛ , Wait˛[10]},
    SuperconductingHub[], ReplaceAliases → False];
```

In[9]:=
```
DrawCircuit[noisycirc]
```

Out[9]=


State initialisation means putting the system into its thermal state

In[10]:=
```
DestroyAllQuregs[];
ρinit = CreateDensityQureg[6];
ρ = CreateDensityQureg[6];
```

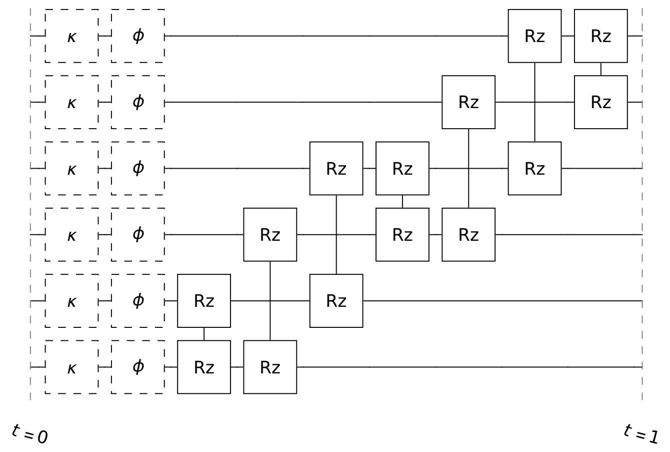
The population prepared state should be in the mixture *ρ_thermal= p|0X0|+(1-p)|1X1|*, where *p* is specified in **ExcitedInit.**
This is done by applying **Init** operator to each qubit which is done only in the very beginning.

```
In[13]:= Values@OptionValue[SuperconductingHub, ExcitedInit]
Out[13]=
         {0.032, 0.021, 0.008, 0.009, 0.025, 0.007}

In[14]:= (* the init operator in terms of noise *)
         noisycirc = InsertCircuitNoise[{Init        }, SuperconductingHub[], ReplaceAliases → True]
Out[14]=
         {{0,
           {Kraus_0[{{{0.98387, 0.}, {0., 0.}}, {{0., 0.98387}, {0., 0.}}, {{0., 0.}, {0., 0.178885}}, {{0., 0.}, {0.178885, 0.}}}], Kraus_1[{{{0.989444, 0.}, {0., 0.}}, {{0., 0.989444}, {0., 0.}}, {{0., 0.}, {0., 0.144914}}, {{0., 0.}, {0.144914, 0.}}}],
            Kraus_2[{{{0.995992, 0.}, {0., 0.}}, {{0., 0.995992}, {0., 0.}}, {{0., 0.}, {0., 0.0894427}}, {{0., 0.}, {0.0894427, 0.}}}],
            Kraus_3[{{{0.99549, 0.}, {0., 0.}}, {{0., 0.99549}, {0., 0.}}, {{0., 0.}, {0., 0.0948683}}, {{0., 0.}, {0.0948683, 0.}}}],
            Kraus_4[{{{0.987421, 0.}, {0., 0.}}, {{0., 0.987421}, {0., 0.}}, {{0., 0.}, {0., 0.158114}}, {{0., 0.}, {0.158114, 0.}}}],
            Kraus_5[{{{0.996494, 0.}, {0., 0.}}, {{0., 0.996494}, {0., 0.}}, {{0., 0.}, {0., 0.083666}}, {{0., 0.}, {0.083666, 0.}}}]}, {}}, {0, {}, {}}}

In[15]:= (* initialise matrix as a random mix state of 6 qubits, then apply the initialisation command *)
         SetQuregMatrix[ρinit, RandomMixState[6]];

In[16]:= (* apply the noisy circuit, then check the diagonal of the density matrix *)
         ApplyCircuit[ρinit, ExtractCircuit @ noisycirc];
         Diagonal @ Chop@ Re @ GetQuregMatrix[ρinit]
Out[17]=
         {0.901981, 0.0298175, 0.0193479, 0.0006396, 0.00727404, 0.000240464, 0.000156031, 5.15806 × 10^-6, 0.00819155, 0.000270795, 0.000175713, 5.80868 × 10^-6, 0.0000660609,
          2.18383 × 10^-6, 1.41704 × 10^-6, 4.68442 × 10^-8, 0.0231277, 0.000764552, 0.0004961, 0.0000164, 0.000186514, 6.16575 × 10^-6, 4.00081 × 10^-6, 1.32258 × 10^-7, 0.00021004, 6.94346 × 10^-6,
          4.50545 × 10^-6, 1.4894 × 10^-7, 1.69387 × 10^-6, 5.59957 × 10^-8, 3.63343 × 10^-8, 1.20113 × 10^-9, 0.00635837, 0.000210194, 0.00013639, 4.50876 × 10^-6, 0.0000512772, 1.69511 × 10^-6, 1.09992 × 10^-6,
          3.6361 × 10^-8, 0.0000577451, 1.90893 × 10^-6, 1.23866 × 10^-6, 4.09474 × 10^-8, 4.65686 × 10^-7, 1.53946 × 10^-8, 9.98918 × 10^-9, 3.30221 × 10^-10, 0.000163035, 5.38959 × 10^-6, 3.49718 × 10^-6,
          1.15609 × 10^-7, 1.3148 × 10^-6, 4.34645 × 10^-8, 2.82031 × 10^-8, 9.32333 × 10^-10, 1.48064 × 10^-6, 4.89469 × 10^-8, 3.17605 × 10^-8, 1.04993 × 10^-9, 1.19407 × 10^-8, 3.94733 × 10^-10, 2.56133 × 10^-10, 0}

In[18]:= (* Sanity check: the diagonals should be as follows *)
         Reverse @ Chop @ Diagonal[KroneckerProduct @@ ({{#, 0}, {0, 1 - #}} & /@ (Reverse @ Values @ OptionValue[SuperconductingHub, ExcitedInit]))]
Out[18]=
         {0.901981, 0.0298175, 0.0193479, 0.0006396, 0.00727404, 0.000240464, 0.000156031, 5.15806 × 10^-6, 0.00819155, 0.000270795, 0.000175713, 5.80868 × 10^-6, 0.0000660609,
          2.18383 × 10^-6, 1.41704 × 10^-6, 4.68442 × 10^-8, 0.0231277, 0.000764552, 0.0004961, 0.0000164, 0.000186514, 6.16575 × 10^-6, 4.00081 × 10^-6, 1.32258 × 10^-7, 0.00021004, 6.94346 × 10^-6,
          4.50545 × 10^-6, 1.4894 × 10^-7, 1.69387 × 10^-6, 5.59957 × 10^-8, 3.63343 × 10^-8, 1.20113 × 10^-9, 0.00635837, 0.000210194, 0.00013639, 4.50876 × 10^-6, 0.0000512772, 1.69511 × 10^-6, 1.09992 × 10^-6,
          3.6361 × 10^-8, 0.0000577451, 1.90893 × 10^-6, 1.23866 × 10^-6, 4.09474 × 10^-8, 4.65686 × 10^-7, 1.53946 × 10^-8, 9.98918 × 10^-9, 3.30221 × 10^-10, 0.000163035, 5.38959 × 10^-6, 3.49718 × 10^-6,
          1.15609 × 10^-7, 1.3148 × 10^-6, 4.34645 × 10^-8, 2.82031 × 10^-8, 9.32333 × 10^-10, 1.48064 × 10^-6, 4.89469 × 10^-8, 3.17605 × 10^-8, 1.04993 × 10^-9, 1.19407 × 10^-8, 3.94733 × 10^-10, 2.56133 × 10^-10, 0}
```

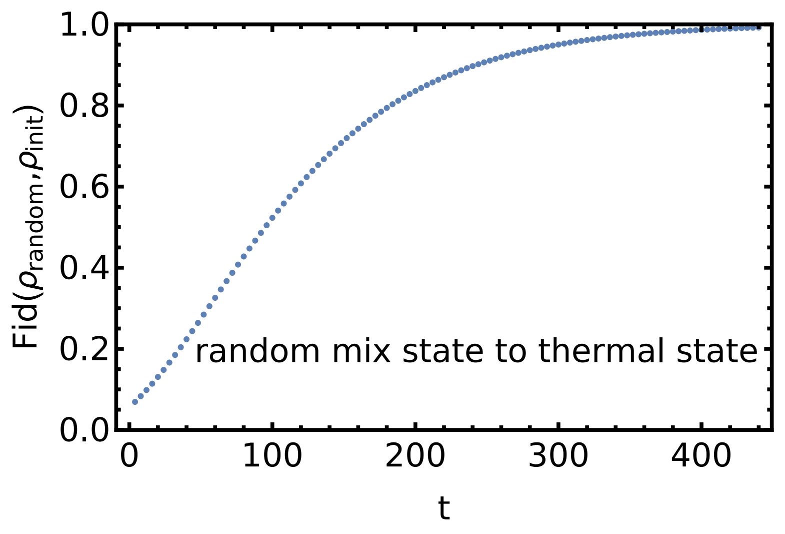
Thermal state (initial state in ρinit) can be prepared by waiting

```
In[19]:= noisycirc = InsertCircuitNoise[{ Wait_#[1] & /@ Range[0, 5]}, SuperconductingHub[], ReplaceAliases → True]
Out[19]=
         {{0, {Kraus_0[{{{0.98387, 0.}, {0., 0.976092}}, {{0., 0.123466}, {0., 0.}}, {{0.177471, 0.}, {0., 0.178885}}, {{0., 0.}, {0.0224483, 0.}}}], Deph_0[0.00440526],
             Kraus_1[{{{0.989444, 0.}, {0., 0.984139}}, {{0., 0.102325}, {0., 0.}}, {{0.144137, 0.}, {0., 0.144914}}, {{0., 0.}, {0.0149866, 0.}}}], Deph_1[0.00334447], R[0.131923, Z_0 Z_1],
             Kraus_2[{{{0.995992, 0.}, {0., 0.991434}}, {{0., 0.0951803}, {0., 0.}}, {{0.0890334, 0.}, {0., 0.0894427}}, {{0., 0.}, {0.00854745, 0.}}}], Deph_2[0.00269541], R[-0.0277977, Z_0 Z_2],
             Kraus_3[{{{0.99549, 0.}, {0., 0.991171}}, {{0., 0.0926285}, {0., 0.}}, {{0.0944568, 0.}, {0., 0.0948683}}, {{0., 0.}, {0.00882732, 0.}}}], Deph_3[0.00309597], R[-0.0273321, Z_1 Z_3],
             R[0.133003, Z_2 Z_3], Kraus_4[{{{0.987421, 0.}, {0., 0.980187}}, {{0., 0.119303}, {0., 0.}}, {{0.156956, 0.}, {0., 0.158114}}, {{0., 0.}, {0.0191038, 0.}}}], Deph_4[0.00408161], R[-0.0276241, Z_2 Z_4],
             Kraus_5[{{{0.996494, 0.}, {0., 0.992516}}, {{0., 0.0889512}, {0., 0.}}, {{0.083332, 0.}, {0., 0.083666}}, {{0., 0.}, {0.00746837, 0.}}}], Deph_5[0.00249376], R[-0.0274045, Z_3 Z_5], R[0.132693, Z_4 Z_5]}, {}}, {1, {}, {}}}
```

```
In[20]:= DrawCircuit[noisycirc]
Out[20]=
```

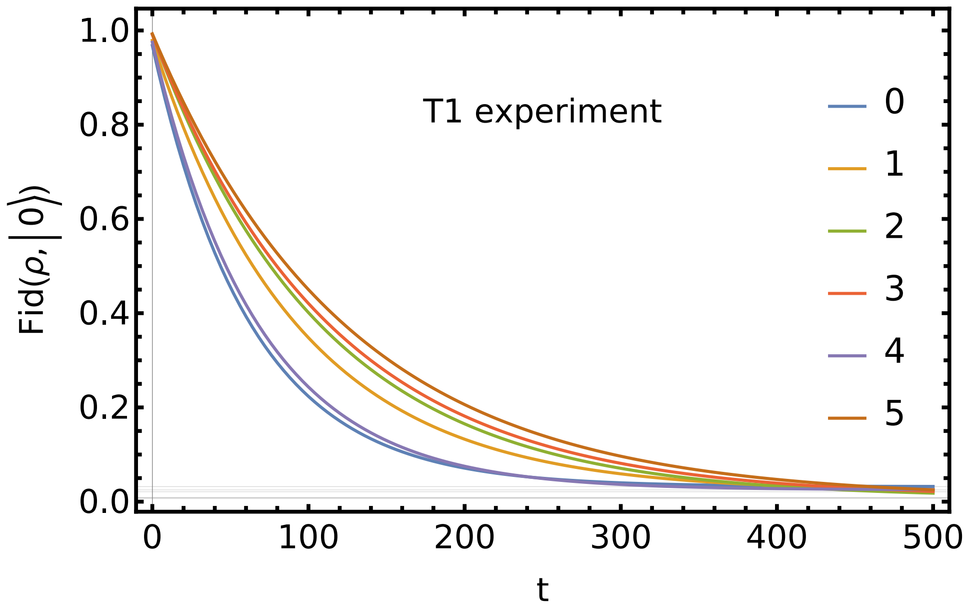


```
In[21]:= (* wait for t, then check fidelity to the thermal state ρinit *)
         δt = 4;
         SetQuregMatrix[ρ, RandomMixState[6]];
         data = Table[
            ApplyCircuit[ρ, ExtractCircuit @ InsertCircuitNoise[Wait#[δt] & /@ Range[0, 5], SuperconductingHub[], ReplaceAliases → True]];
            {t, CalcFidelityDensityMatrices[ρ, ρinit]}
            , {t, δt, 440, δt}];

In[24]:= ListPlot[data,
          PlotRange → {Automatic, {0, 1}}, Frame → True, FrameLabel → {"t", "Fid(ρrandom,ρinit)"},
          FrameStyle → Directive[Black, Thick], ImageSize → 400, BaseStyle → {17}, Epilog → Inset["random mix state to thermal state", Scaled[{0.55, 0.2}]]
         ]
Out[24]=
```



Free induction decay: T1 experiment

```
In[25]:= δt = 4;
         SetQuregMatrix[ρ, RandomMixState[6]];
         dataT1 = Table[
            dev = SuperconductingHub[];
            ApplyCircuit[ρ, ExtractCircuit @ InsertCircuitNoise[{Init0,1,2,3,4,5}, dev, ReplaceAliases → True]];
            ApplyCircuit[ρ, ExtractCircuit @ InsertCircuitNoise[Rx#[π] & /@ Range[0, 5], dev, ReplaceAliases → True]];
            ApplyCircuit[ρ, ExtractCircuit @ InsertCircuitNoise[Wait#[t] & /@ Range[0, 5], dev, ReplaceAliases → True]];
            {t, CalcProbOfOutcome[ρ, #, 1]} & /@ Range[0, 5]
            , {t, 0, 500, δt}];

In[28]:= (* expected probability at T → ∞, denoted by grey lines *)
         expectedprob = Values@OptionValue[SuperconductingHub, ExcitedInit];
         ListPlot[Transpose[dataT1],
          Frame → True, PlotLegends → Placed[Range[0, 5], {0.9, 0.5}], GridLines → {expectedprob}, Frame → True, FrameLabel → {"t", "Fid(ρ, |0⟩)"},
          FrameStyle → Directive[Black, Thick], ImageSize → 500, BaseStyle → {17}, Epilog → Inset["T1 experiment", Scaled[{0.5, 0.8}]], Joined → True
         ]
Out[29]=
```

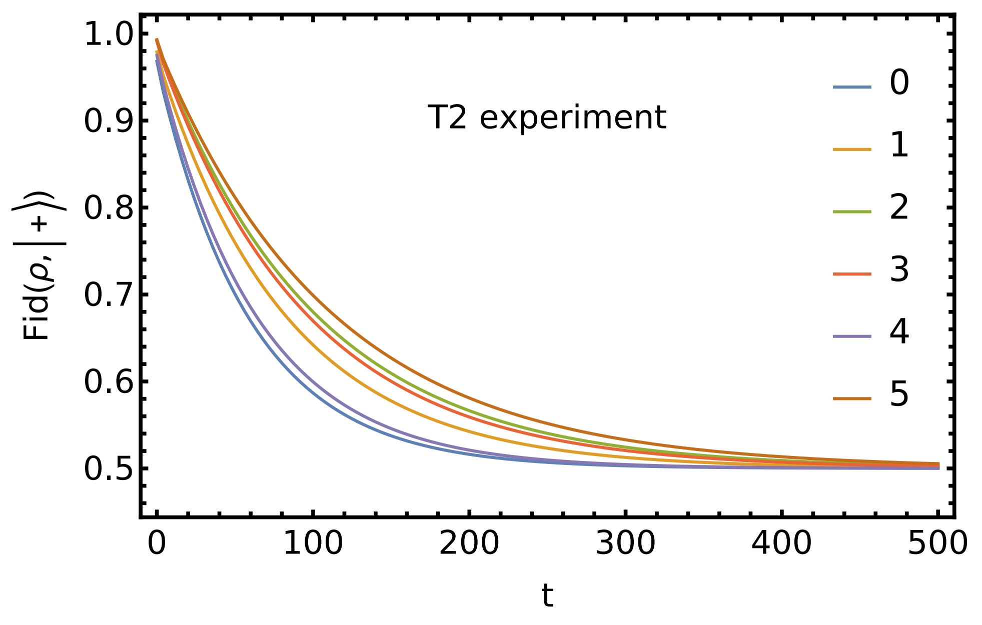


Free induction decay: T2 experiment

```
In[30]:= δt = 4;
         SetQuregMatrix[ρ, RandomMixState[6]];
         dataT2 = Table[
            dev = SuperconductingHub[];
            ApplyCircuit[ρ, ExtractCircuit @ InsertCircuitNoise[{Init0,1,2,3,4,5}, dev, ReplaceAliases → True]];
            ApplyCircuit[ρ, ExtractCircuit @ InsertCircuitNoise[Flatten[Ry#[π / 2] & /@ Range[0, 5]], dev, ReplaceAliases → True]];
            ApplyCircuit[ρ, ExtractCircuit @ InsertCircuitNoise[Wait#[t] & /@ Range[0, 5], dev, ReplaceAliases → True]];
            ApplyCircuit[ρ, ExtractCircuit @ InsertCircuitNoise[Flatten[Ry#[-π / 2] & /@ Range[0, 5]], dev, ReplaceAliases → True]];
            {t, CalcProbOfOutcome[ρ, #, 0]} & /@ Range[0, 5]
            , {t, 0, 500, δt}];
```

```
In[33]:= ListPlot[Transpose[dataT2], PlotLegends → Placed[Range[0, 5], {0.9, 0.55}], PlotRange → All, Frame → True, FrameStyle → Directive[Black, Thick],
          ImageSize → 500, FrameLabel → {"t", "Fid(ρ, |+⟩)"}, BaseStyle → {17}, Epilog → Inset["T2 experiment", Scaled[{0.5, 0.8}]], Joined → True]
```

Out[33]=



Paper supplement: VQE of H_2 on the superconducting qubit (https://arxiv.org/abs/2306.07342)

Modules

Gate parameters θ are restricted to values $\theta \in [-\pi, \pi]$

```
angleToMinusPiToPi[angle_] := Mod[angle + π, 2 π] - π
```

Load the pre-run data on VQE

```
In[35]:= (* exact ground state energies *)
         gsH2 << "../supplement/VQEonSuperconductingHub/gsH2.mx";
         (* noiseless *)
         vqeH20 << "../supplement/VQEonSuperconductingHub/run1/vqeH20.mx";
          (*realistic noise *)
         vqeH21 << "../supplement/VQEonSuperconductingHub/run1/vqeH21.mx";
         (* static noise only *)
         vqeH22 << "../supplement/VQEonSuperconductingHub/run1/vqeH22.mx";
```

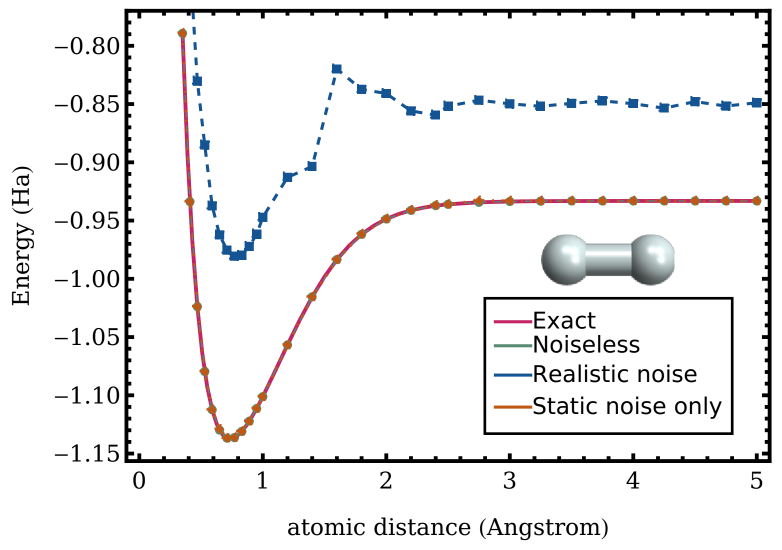
```
In[39]:= data = Join[
             {Values@gsH2[[All, {"distance", "groundstate"}]]},
              Values @ #[[All, {"distance", "cost"}]] & /@ {vqeH20, vqeH21, vqeH22}
           ];
```

```
In[40]:= colors = {🟥, 🟩, 🟦, 🟧};
```

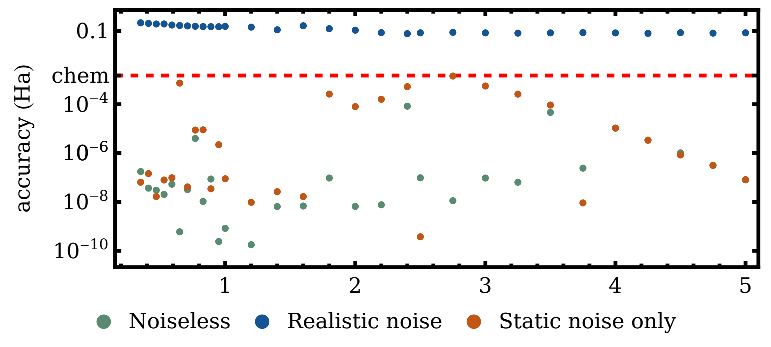
```
In[41]:= (* molecule image *)
         H2 = ImageResize[MoleculePlot3D[Molecule[ConstantArray["H", 2], Bond[{#, # + 1}, "Single"] & /@ Range[1], AtomCoordinates → ({.8 * #, 0, 0} & /@ Range[0, 1])]], 140];
```

Hydrogen dissociation plots

```
In[42]:= Show[
  ListPlot[Values /@ gsH2[[All, {"distance", "groundstate"}]], Joined → True, PlotStyle → Directive[colors[[1]], Thickness → Scaled[0.006]], BaseStyle → {11, FontFamily → "Serif"}, Epilog → Inset[H2, Scaled[{0.8, 0.92}]]],
  ListPlot[Values@#[[All, {"distance", "cost"}]] & /@ {vqeH20, vqeH21, vqeH22}, PlotMarkers → {Automatic, 5}, PlotStyle → {Directive[colors[[2]]
      , Dashed, Thickness → Scaled[0.002]], Directive[colors[[3]], Dashed], Directive[colors[[4]], Dotted]}, Joined → True],
  Frame → True, FrameStyle → Directive[Black, Thick], Background → White
  ,
  Epilog → Inset[Column[{H2, LineLegend[colors, {"Exact", "Noiseless", "Realistic noise", "Static noise only"}, Spacings → 0., LegendFunction → Framed, LegendMargins → 0]}, Alignment → Center], Scaled[{0.75, 0.28}]],
  BaseStyle → {12, FontFamily → "Serif"}, FrameLabel → {"atomic distance (Angstrom)", "Energy (Ha)"}, ImageSize → 400, AspectRatio → 0.7, ImagePadding → {{60, 5}, {45, 5}}
 ]
 (*Export["vqeh2.pdf",%]*)
Out[42]=
```



```
In[43]:= yticks = {{10^-10, "10^-10"}, {10^-8, "10^-8"}, {10^-6, "10^-6"}, {10^-6, "10^-6"}, {10^-4, "10^-4"}, {0.0015, "chem"}, {0.1, "0.1"}};
 ListLogPlot[
  {
   Transpose @ {vqeH20[[All, "distance"]], vqeH20[[All, "cost"]] - vqeH20[[All, "groundstate"]]},
   Transpose @ {vqeH21[[All, "distance"]], vqeH21[[All, "cost"]] - vqeH21[[All, "groundstate"]]},
   Transpose @ {vqeH22[[All, "distance"]], vqeH22[[All, "cost"]] - vqeH21[[All, "groundstate"]]}},
  Frame → True, FrameStyle → Directive[Black, Thick], Background → White, PlotRange → All,
  GridLines → {None, {0.0015}}, GridLinesStyle → Directive[Thick, Dashed, Red], FrameTicks → {{yticks, Automatic}, {Automatic, Automatic}},
  FrameLabel → {None, "accuracy (Ha)"}, PlotLegends → PointLegend[Automatic, {"Noiseless", "Realistic noise", "Static noise only"}, LegendMargins → 0, LegendMarkerSize → 15],
  ImageSize → 400, AspectRatio → 0.4, LabelStyle → {11, FontFamily → "Serif"}, ImagePadding → {{60, 5}, {15, 5}}, PlotStyle → colors[[2 ;;]]
 ]
 (*Export["vqeh2err.pdf",%]*)
Out[44]=
```


accuracy (Ha)
chem
10^-4
10^-6
10^-8
10^-10
● Noiseless
● Realistic noise
● Static noise only