

## 1.1 Introduction to package `qm`

Package version: 0.5

The `qm` package provides functions and standard definitions to solve quantum mechanics problems in a finite dimensional Hilbert space. For example, one can calculate the outcome of Stern-Gerlach experiments using the built-in definition of the  $S_x$ ,  $S_y$ , and  $S_z$  operators for arbitrary spin, e.g.  $\mathbf{s}=\{1/2, 1, 3/2, \dots\}$ . For spin-1/2 the standard basis states in the  $x$ ,  $y$ , and  $z$ -basis are available as  $\{x_p, x_m\}$ ,  $\{y_p, y_m\}$ , and  $\{z_p, z_m\}$ . One can create general ket vectors with arbitrary but finite dimension and perform standard computations such as expectation value, variance, etc. The angular momentum  $|j, m\rangle$  representation of kets is also available. It is also possible to create tensor product states for multiparticle systems and to perform calculations on those systems.

The `qm` package was written by Eric Majzoub, University of Missouri. (Email: majzoub@at-umsystem.edu) The package is loaded with: `load(qm);`

## 1.2 Functions and Variables for `qm`

`cvec (a1, a2, ...)` [Function]  
`cvec` creates a *column* vector of arbitrary finite dimension. The entries  $a_i$  can be any Maxima expression.

```
(%i4) cvec(1,2,3);
                                [ 1 ]
                                [  ]
(%o4)                          [ 2 ]
                                [  ]
                                [ 3 ]
```

`rvec (a1, a2, ...)` [Function]  
`rvec` creates a *row* vector of arbitrary finite dimension. The entries  $a_i$  can be any Maxima expression.

```
(%i4) rvec(1,2,3);
(%o4)          [ 1  2  3 ]
```

`ket (c1, c2, ...)` [Function]  
`ket` creates a *column* vector of arbitrary finite dimension. The entries  $c_i$  can be any Maxima expression. If the entries are simple symbols or coefficients of simple functions then they will be `declare`-ed complex. If one is having difficulty with getting the correct constants declared complex then one is suggested to use the `cvec` and `rvec` functions.

```
(%i4) ket(c1,c2);
                                [ c1 ]
                                [  ]
(%o4)                          [ c2 ]

(%i5) facts();
(%o5) [kind(hbar, real), hbar > 0, kind(c1, complex), kind(c2, complex)]
```

**bra** ( $c_1, c_2, \dots$ ) [Function]

**bra** creates a *row* vector of arbitrary finite dimension. The entries  $c_i$  can be any Maxima expression. If the entries are simple symbols or coefficients of simple functions then they will be **declare**-ed complex. If one is having difficulty with getting the correct constants declared complex then one is suggested to use the **cvec** and **rvec** functions.

```
(%i4) bra(c1,c2);
(%o4)          [ c1  c2 ]
```

**ketp** (*vector*) [Function]

**ketp** is a predicate function that checks if its input is a ket, in which case it returns **true**, else it returns **false**.

```
(%i4) b:bra(a,b);
(%o4)          [ a  b ]
(%i5) ketp(b);
(%o5)          false
```

**brap** (*vector*) [Function]

**brap** is a predicate function that checks if its input is a bra, in which case it returns **true**, else it returns **false**.

```
(%i4) b:bra(a,b);
(%o4)          [ a  b ]
(%i5) brap(b);
(%o5)          true
```

**dag** (*vector*) [Function]

**dag** is the quantum mechanical *dagger* function and returns the **conjugate transpose** of its input.

```
(%i4) dag(bra(%i,2));
(%o4)          [ - %i ]
               [      ]
               [  2   ]
```

**braket** ( $\psi, \phi$ ) [Function]

Given two kets  $\psi$  and  $\phi$ , **braket** returns the quantum mechanical bracket  $\langle \psi | \phi \rangle$ . The vector  $\psi$  may be input as either a **ket** or **bra**. If it is a **ket** it will be turned into a **bra** with the **dag** function before the inner product is taken. The vector  $\phi$  must always be a **ket**.

```
(%i4) braket(ket(a,b,c),ket(a,b,c));
(%o4)          c conjugate(c) + b conjugate(b) + a conjugate(a)
```

**norm** ( $\psi$ ) [Function]

Given a **ket** or **bra**  $\psi$ , **norm** returns the square root of the quantum mechanical bracket  $\langle \psi | \psi \rangle$ . The vector  $\psi$  must always be a **ket**, otherwise the function will return **false**.

```
(%i4) norm(ket(a,b,c));
(%o4)          sqrt(c conjugate(c) + b conjugate(b) + a conjugate(a))
```

### 1.2.1 Simple examples

The following additional examples show how to input vectors of various kinds and to do simple manipulations with them.

```
(%i4) rvec(a,b,c);
(%o4) [ a b c ]
(%i5) facts();
(%o5) [kind(hbar, real), hbar > 0]
(%i6) bra(a,b,c);
(%o6) [ a b c ]
(%i7) facts();
(%o7) [kind(hbar, real), hbar > 0, kind(a, complex), kind(b, complex),
kind(c, complex)]
(%i8) braket(bra(a,b,c),ket(a,b,c));
(%o8) c^2 + b^2 + a^2
(%i9) braket(ket(a,b,c),ket(a,b,c));
(%o9) c conjugate(c) + b conjugate(b) + a conjugate(a)
```

### 1.2.2 Spin-1/2 state kets and associated operators

Spin-1/2 particles are characterized by a simple 2-dimensional Hilbert space of states. It is spanned by two vectors. In the z-basis these vectors are {zp,zm}, and the basis kets in the z-basis are {xp,xm} and {yp,ym} respectively.

**zp, zm, xp, xm, yp, ym** [Function]  
 Return the ket of the corresponding vector in the z-basis.

```
(%i4) zp;
(%o4) [ 1 ]
[ 0 ]
(%i5) zm;
(%o5) [ 0 ]
[ 1 ]
```

```
(%i4) yp;
                                [ 1 ]
                                [ ---- ]
                                [ sqrt(2) ]
(%o4)                            [ ]
                                [ %i ]
                                [ ---- ]
                                [ sqrt(2) ]

(%i5) ym;
                                [ 1 ]
                                [ ---- ]
                                [ sqrt(2) ]
(%o5)                            [ ]
                                [ %i ]
                                [ - ---- ]
                                [ sqrt(2) ]

(%i4) braket(xp,zp);
                                1
(%o4)                            ----
                                sqrt(2)
```

Switching bases is done in the following example where a z-basis ket is constructed and the x-basis ket is computed.

```
(%i4) psi:ket(a,b);
                                [ a ]
(%o4)                            [ ]
                                [ b ]

(%i5) psi_x:'xp*braket(xp,psi)+'xm*braket(xm,psi);
                                b      a      a      b
(%o5)      (----- + -----) xp + (----- - -----) xm
              sqrt(2)   sqrt(2)      sqrt(2)   sqrt(2)
```

### 1.2.3 Pauli matrices and Sz, Sx, Sy operators

**sigmax, sigmay, sigmaz** [Function]  
Returns the Pauli x,y,z matrix.

**Sx, Sy, Sz** [Function]  
Returns the spin-1/2 Sx,Sy,Sz matrix.

```
(%i4) sigmay;
```

$$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$$

```
(%o4)
```

```
(%i5) Sy;
```

$$\begin{bmatrix} 0 & -\frac{i \hbar}{2} \\ \frac{i \hbar}{2} & 0 \end{bmatrix}$$

```
(%o5)
```

### 1.2.4 SX, SY, SZ operators for any spin

**SX, SY, SZ (s)** [Function]  
**SX(s)** for spin **s** returns the matrix representation of the spin operator **Sx**, and similarly for **SY(s)** and **SZ(s)**. Shortcuts for spin-1/2 are **Sx,Sy,Sz**, and for spin-1 are **Sx1,Sy1,Sz1**.

Example:

```
(%i4) SY(1/2);
```

$$\begin{bmatrix} 0 & -\frac{i \hbar}{2} \\ \frac{i \hbar}{2} & 0 \end{bmatrix}$$

```
(%o4)
```

```
(%i5) SX(1);
```

$$\begin{bmatrix} \hbar & 0 & 0 \\ 0 & -\frac{\hbar}{\sqrt{2}} & \hbar \\ \hbar & \frac{\hbar}{\sqrt{2}} & 0 \end{bmatrix}$$

```
(%o5)
```

### 1.2.5 Expectation value and variance

**expect (O,psi)** [Function]  
 Computes the quantum mechanical expectation value of the operator **O** in state **psi**,  $\langle \text{psi} | O | \text{psi} \rangle$ .

```

(%i4) ev(expect(Sy,xp+ym),ratsimp);
(%o4)                                     - hbar

qm_variance (0,psi) [Function]
Computes the quantum mechanical variance of the operator 0 in state psi,
sqrt(<psi|02|psi> - <psi|0|psi>2).
(%i4) ev(qm_variance(Sy,xp+ym),ratsimp);
(%o4)                                     %i hbar
                                     -----
                                     2

```

### 1.2.6 Angular momentum representation of kets and bras

To create kets and bras in the  $|j,m\rangle$  representation you can use the following functions.

```

jm_ket (j,m) [Function]
jm_ket creates the ket  $|j,m\rangle$  for total spin  $j$  and z-component  $m$ .

jm_bra (j,m) [Function]
jm_bra creates the bra  $\langle j,m|$  for total spin  $j$  and z-component  $m$ .

(%i4) jm_bra(3/2,1/2);
(%o4)                                     [ 3  1 ]
                                     [jm_bra, [ -  - ]]
                                     [ 2  2 ]

jm_ketp (jmket) [Function]
jm_ketp checks to see that the ket has the 'jmket' marker.

jm_brap (jmbra) [Function]
jm_brap checks to see that the bra has the 'jmbra' marker.

jm_check (j,m) [Function]
jm_check checks to see that  $m$  is one of  $\{-j, \dots, +j\}$ .

jm_braket (jmbra,jmket) [Function]
jm_braket takes the inner product of the jm-kets.

(%i4) K:jm_ket(zp,zm);
(%o4)                                     [ [ 1 ] ]
                                     [ [  ] ]
                                     [ [ 0 ] ]
jmket, [ [  ] ]
                                     [ [ 0 ] ]
                                     [ [  ] ]
                                     [ [ 1 ] ]

(%i5) B:jm_bra(zp,zm);
(%o5)                                     [ [ 1 ] [ 0 ] ]
jmbra, [ [  ] [  ] ]
                                     [ [ 0 ] [ 1 ] ]

(%i6) jm_braket(B,K);
(%o6)                                     1

```

### 1.2.7 Angular momentum and ladder operators

SP (**s**) [Function]

SP is the raising ladder operator  $S_+$  for spin **s**.

SM (**s**) [Function]

SM is the raising ladder operator  $S_-$  for spin **s**.

Examples of the ladder operators:

```
(%i4) SP(1);
      [ 0  sqrt(2) hbar      0      ]
      [                      ]
(%o4)  [ 0      0      sqrt(2) hbar ]
      [                      ]
      [ 0      0      0      ]

(%i5) SM(1);
      [      0      0      0 ]
      [                      ]
(%o5)  [ sqrt(2) hbar      0      0 ]
      [                      ]
      [      0      sqrt(2) hbar  0 ]
```

### 1.3 Rotation operators

RX, RY, RZ (**s,t**) [Function]

RX(**s**) for spin **s** returns the matrix representation of the rotation operator  $R_x$  for rotation through angle **t**, and similarly for RY(**s,t**) and RZ(**s,t**).

```
(%i4) RZ(1/2,t);
Proviso: assuming 64*t # 0

(%o4)  [      %i t      ]
      [ - ---- ]
      [      2      ]
      [ %e      0      ]
      [                      ]
      [      %i t      ]
      [ ---- ]
      [      2      ]
      [ 0      %e      ]
```

### 1.4 Time-evolution operator

UU (**H,t**) [Function]

UU(**H,t**) is the time evolution operator for Hamiltonian **H**. It is defined as the matrix exponential `matrixexp(-%i*H*t/hbar)`.

```
(%i4) UU(w*Sy,t);
Proviso: assuming 64*t*w # 0
[      t w      t w ]
[ cos(---) - sin(---) ]
[      2      2 ]
(%o4) [ ]
[      t w      t w ]
[ sin(---)  cos(---) ]
[      2      2 ]
```

## 1.5 Tensor products

Tensor products are represented as lists in Maxima. The ket tensor product  $|z+,z+\rangle$  is represented as `[tpket,zp,zp]`, and the bra tensor product  $\langle a,b|$  is represented as `[tpbra,a,b]` for kets `a` and `b`. The list labels `tpket` and `tpbra` ensure calculations are performed with the correct kind of objects.

**ketprod** ( $k_1, k_2, \dots$ ) [Function]  
**ketprod** produces a tensor product of kets  $k_i$ . All of the elements must pass the **ketp** predicate test to be accepted.

**braprod** ( $b_1, b_2, \dots$ ) [Function]  
**braprod** produces a tensor product of bras  $b_i$ . All of the elements must pass the **brap** predicate test to be accepted.

**braketprod** (B,K) [Function]  
**braketprod** takes the inner product of the tensor products B and K. The tensor products must be of the same length (number of kets must equal the number of bras).

Examples below show how to create tensor products and take the bracket of tensor products.

```
(%i4) ketprod(zp,zm);
[ 1 ] [ 0 ]
(%o4) [tpket, [[ ], [ ]]]
[ 0 ] [ 1 ]

(%i5) ketprod('zp,'zm);
(%o5) [tpket, [zp, zm]]

(%i4) kill(a,b,c,d);
(%i5) braprod(bra(a,b),bra(c,d));
(%o5) [tpbra, [[ a b ], [ c d ]]]

(%i6) braprod(dag(zp),bra(c,d));
(%o6) [tpbra, [[ 1 0 ], [ c d ]]]
```



```

(%i4) zpb:dag(zp);
(%o4)          [ 1  0 ]
(%i5) zmb:dag(zm);
(%o5)          [ 0  1 ]
(%i6) K:ketprod('zp,'zm);
(%o6)          [tpket, [zp, zm]]
(%i7) B:braprod(zpb,zmb);
(%o7)          [tpbra, [[ 1  0 ], [ 0  1 ]]]
(%i8) B:braprod('zpb,'zmb);
(%o8)          [tpbra, [zpb, zmb]]
(%i9) braketprod(K,B);
(%o9)          false
(%i10) braketprod(B,K);
(%o10)          (zmb . zm) (zpb . zp)

```

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(Index is nonexistent)