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P)(O77(?/409(65(03-9(J;190-6+(./77(564(J;- .L(/+, (93640(/+92 149)(

(
(a) Q\$(?6-+09R F 3-.3(65(031(567762-+8(/41(

[O(5411(?/40-.71(2-03(1+148>(a\b(/+, (9?-+("#\$(-9(04/=17-+8(-+(031(IC, -41.0-6+)(E31(9?-+(65(031(?/40-.71(/796(?6-+09(-+(031(IC, -41.0-6+)(H18-+++8(/0(I(c%(03141(-9(/9?-+(, 1?1+, 1+0(?601+0-/7(65(031(564 : (

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(" \$#" = " % \$# + ! , !", (

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(23141(_1(/+, ((/41(.6+90/+09B(| α | < 1B(/+, (% -9(031(;9; /7(X/;7-(: /04-I)(

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(/'(O99; : -+8(03/0(031(1+148>(a\b(-9(9 : /7714(03/+ (1-0314(=/7; 1(65(] !I'B(. /7. ; /7/01(/+(1I?4199-6+(564(031(41571.01, (2/=1)(

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(A'(X46=1(03/0(031(9?-+(65(031(41571.01, (2/=1(7-19(1+0-417>(-+(031(IC>(??/+1)(

(

(.'(_/7. ; /7/01(1I?1.0/0-6+(=/7; 19(564(%(/+, (&(564(031(41571.01, (2/=1)(H>(=-9; /7(-+9?1.0-6+(65(>6; 4(/+92149(, 1014 : -+1(231+(031(1I?1.0/0-6+(=/7; 1(564(& 2-77(A1(D146)(N+, 14(03191(.6+, -0-6+9(23/0(2-77(A1(031(1I?1.0/0-6+(=/7; 1(564(\$T((*9(>6; 4(/+9214(?3>9-. /77>(??/; 9-A71T(

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O77(?/409(65(03-9(J;190-6+(./77(564(J;-L(/+, (93640(/+92149)(

(a) Q\$(?6-+09R F 3-.3(65(031(567762-+8(/41(1-81+90/019(65(?/4-0>)(S64(03691(03/0(/41B(23/0

V) _6+9-, 14/(?/40-.71(.6+5-+1,(-+/(026(- : 1+9-6+/7(A6I(

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(]!IB>'(c%(%dIdKB(/+, (%d>dK(((

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(]!IB>'(c(e(603142-91(

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(E31(1-81+90/019(/+, (1-81+1+148-19(/41(8-=1+(A>(

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i) $O(\frac{?}{40} - .71(65(\frac{?}{99}(\frac{?}{+}, (1+148)>(\frac{?}{> 0(-9(+.-., 1+0(546 : (031(7150(6+(\frac{?}{601+0-7($
 $A/44-14(8=-1+(A>(($

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$$\begin{pmatrix} \# \\ " \\ \#_s \\ " \\ "!! \\ (\\ ! \\ (\end{pmatrix}$$

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$23141(V_o(-9(\frac{?}{+}(1+148>(\frac{?}{+}, (-9(\frac{?}{71+803)($
 $*+(031(7- : -0(03/0(<< B(, 1014 : -+1(031(1+148>(\frac{?}{, 1?1+, 1+.1(65(031(04/+9 : -99-6+($
 $?46A/A-7-0>))(($

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$^((j \ 6;(\frac{?}{>};91(031(91 : -.7/99-.7(\frac{?}{?46I- : /0-6+(-+(03-9(7- : -0)((E6(810(031(1+148>(\$
 $, 1?1+, 1+.1(>6;(\frac{?}{, 6(+60(3/=1(06(1=7; /01(\frac{?}{+>(-+0184/79)($

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"%)($*+(\frac{?}{(. 140/-+(04-/+8;7/4(: 671. ; 71B(\frac{?}{+(171.046+(-9(5411(06(36?(546 : (9-01(06(9-01)((E31($
 $419;70+8(1-81+090/019(\frac{?}{+}, (1-81+148-19(564(031(171.046+(\frac{?}{41^(($

$$" = !(\frac{?}{| \#} \rangle \frac{\#}{\sqrt{!}} |\# \rangle |" \rangle |! \rangle ($$

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$$E_2 \quad e(\frac{?}{| \rangle} \frac{?}{\sqrt{!}} |\# \rangle |" \rangle |! \rangle ($$

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$/'(O0(B(031(90/01(=1.064(-9(($
 $|\psi(0)\rangle = -(2|1\rangle + |2\rangle + |3\rangle)))($

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$E31(1+148>(-9(: 1/9;41,)((F \ 3/0(=7;19(\frac{?}{+}(A1(56;+, (\frac{?}{+}, (2-03(23/0(?46A/A-7-0-19T($

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$A'(<1014 : -+1(((8=-1+((/A6=1)($

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"[(E26(?/40-.719(65(:/9919((/+,(: (/41(41904-.01,(06(:6=1(-+(6+10,-:1+9-6+(/+,(3/=1(.664,-+/019(/+,(:6:1+0/())((E31(W/:-706+/-/(65(031(9>901:(-9(8=-1+(A>(

((\$! $\frac{""}{"#!}$ "" ((B(

(((23141(1(%B(/+,((/+,((/41(.6+90/+09)((/(*+/(.6;?71(65(7+19B(90/01(23/0B(?3>9-./77>B(03-9(W/:-706+/-/(,19.4-A19)((A'(nA0/-+(031(1+148>(1-81+="/;19(65(03-9(W/:-706+/-/(((.'(<4/2(/+(1+148>(71=17(,-/84/: (564(031(./91())(

(("Z)(/'(F4-01(,62+(031(W/:-706+/-/(564(/.3/481,(?/40-.71((-+/(.6+90/+0(:/8+10-.(5-17,())(!W-+0^((: -+ : /7(.6;?7-+8'(

((A'(E/L-+8(031(5-17,(,-41.0-6+(/9(031(DC/I-9(/+,(/,6?0-+8(/+>(.6+=1+-1+0(8/;81B(967=1(564(031(1-81+="/;19(65(03-9(9>901:))

((.'(F3/0(/41(031(,181+14/.-19(65(1/.3(1-81+="/;1(T((,'(M;??691(/+(/,,-0-6+/7(171.04-.(5-17,((-9(/??7-1,B(?/4/7717(06())(F3/0(-9(031(+12(W/:-706+/-/(+/, (362(/41(031(1-81+="/;19(:6,-5-1,T(

(("V)(O(9?-+C"#\$(?/40-.71(-9(-+(/+(1-81+90/01(65(&(2-03(1-81+="/;1(#\$(O(:/8+10-.(5-17,(?(-9(/??7-1,(/76+8(031(C,-41.0-6+(564(/0-:1((/+, (031(?/40-.71(/77621,(06(?41.199)(O(03/0(?6-+0B(031(5-17,(-9(4/?-,7>(92-0.31,(-+06(031(C,-41.0-6+(/+, (031(?/40-.71(/77621,(06(?41.199(564(/+60314(-+014="/() (F3/0(-9(031(?46A/A-7-0>(03/0(/+&(:1/9;41:1+0(+62(2-77(9362(03/0(031(-+0-/7(9?-+(3/9(57-??1,(06(o #\$(T(

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(IP'(E31(?46, ; .0(65(026(;+0/4>(6?14/0649(-9(;+0/4>)(
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(!&'(K10((/+, (A1(.6 : : ;0-+8(314 : -0-/(6?14/0649)((E31+(/77(1-81+5;+.0-6+9(65(
((/41(9- : ;70/+16;97>(1-81+5;+.0-6+9(65()(
(
(!['(<6(031(6?14/0-6+9(65(-+=149-6+(/+, (.6+8/0-6+(.6 : : ;01T((E3/0(-9B(/99; : -+8(03/0(
(031(6?14/064((?69919919(/+(-+=1491B(, 619(! T(
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\$\$)(E31(846;+, (90/01(2 /=1(5;+.0-6+(65(031(3>, 4681+(/06 : B(2-03(?601+0-/7(1+148>(
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((3/9(031(5;+.0-6+/7(564 : (
(B(
((2-03(031(H634(4/, -;9(B(/+, ((/+64 : /7-D/0-6+(5/.064)(
(/'((N9-+8(031(9(2 /=1(4/, -/7(M.34m, ++814(1J; /0-6+B(5-+, ((/+, (031(1+148>(\ (-+(
(014 : 9(65(031(: /99(B(.3/481(B(/+, (h)(
(
(A'((g 64 : /7-D1(031(2 /=1(5;+.0-6+(06(41?4191+0(6+1(?/40-.71B(, 1014 : -++8()((
(_/7. ;7/01(031(171.04-. (. ;441+0(, 1+9-0>)(
(
(.'((Y=-1+(03/0(031(?4606+(4/, -;9(-9(/5/.064(" % (9 : /7714(03/+031(H634(4/, -;9B(
(./7. ;7/01(031(?46A/A-7-0>(65(5-+, ++8(031(171.046+(-+(031(+; .71;9)((Y=-1(>6;4(
(419;70(06(6+1(9-8+-5-./+0(5-8;41)((
(
\$P)((O(9?-+(C .3/481, (?/40-.71(-9(-+(031(%c (

\$&(' \=/7; /01(031(17/90-. (, -55141+0-/7(9. /0014-+8(. 4699C91. 0-6+(-+(031(5-490(H64+(
/??46I- : /0-6+(564(031(9. /0014-+8(65(?/40-. 719(65(: /99(: (546 : (/ (j ;L/ 2 /(
?601+0-/7()((

\$Z) (/' (O(9?+c

$$\hat{H} = \left(\frac{eB}{m} \right) \hat{S}_x$$

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 (O99; : 1(031(+0-7(90/01(-9(| # " "!) | !))(
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 (/'(_/7.;7/01(| !))(
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 (A'(_/7.;7/01(⟨ ! ⟩ /9(/(5;+.0-6+(65(0- : 1)((F 3/0(-9(031(?41.199-6+(541J;1+.>T(
 (.'(_/7.;7/01(031(0- : 1C,1?1+,1+0(+.140/-+0>(+ ! B(" ' ! ⟨ # ! ⟩ ⟨ # ! ⟩ !)(
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 (.'(*5(: 1/9;41 : 1+09(65(*(/+, (% /41(: /, 1(6+(/(90/01(23691(2 /=1(5;+.0-6+(-9(
 # \$ - ! " \$ % & " # \$ φ ! (23/0/41(031(?699-A71(=/7;19(56;+, T(
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 (P%)(O(7-03-; : (/06 : (-(-09(846;+, ((90/01(-9(?7/.1, (-+(/(9 : /77(90/0-.(171.04-.(5-17, (d)((H>(
 9?1.0469.6?-.(: 1/9;41 : 1+0B(031(846;+, (90/01(1+148>(-9(56;+, (06(93-50(-+(1+148>(
 /..64, +8(06((
 (
 (_____ = _____ B(
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 (23141(#(-9(/(.6+90/+0B(031(/06 : -. (?67/4-D/A-7-0>)(S46 : (031(1I?14- : 1+0(-0(-9(56;+, (
 03/0(#(c(\$&!s ' B(23141(s(-9(/+(O+89046 :)(
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(/'(O99; : -+8(/+(171.04-.(-?671(-+014/.0-6+(B(;91(031(567762 -+8(
-+564 : /0-6+(06(,14-=1(/(9- : ?71(564 : ;7/(564(#^(
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((C(E31(+1/4190(1I.-01,(90/01(06(031(846;+,(90/01(-9/((90/01(2-03(/+(1+148>(
91?/4/0-6+(65(h)(
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-E31(6+7>(4171= /+0(+6+C= /+-93-+8(,-?671(: /04-I(171 : 1+0(-9((
(
A'((E31(9?6+0/+16;9(7-510- : 1(65(031(90/01B(c(\$V B(-9(417/01,(06(031(
, -?671(04/+9-0-6+(: 6 : 1+0(A>(031(\ -+901-+(A .6155-. -1+0B(
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23141(c(\$ / /+,(c(ZV%)

P\$)('O+(171.046+ -9(?41?/41,(-+(/+(1-81+90/01(65(M (2-03(1-81+=/7;1((

/+, (9;A@1.01, (06(/(;+-564 : (: /8+10-.(5-17, ((564(/(0- : 1(E)((O0(03/0(?6-+0B(
031(5-17, (-9(9; , , 1+7>(460/01, (0346;83(i% (06(((O5014(/+60314(0- : 1(-+014=/7(
EB(031(171.046+f9(9?-+(-+(031(IC, -41.0-6+(-9(: 1/9;41,)((F 3/0(-9(031(?46A/A-7-0>(65(
6A0/-++8(031(=/7;1(T((W-+0^((*(0(2-77(A1(;915;7(06(.6+9-, 14(M (1-81+90/019(564(031(
5-490(0- : 1(-+014=/7(/+, (M (1-81+90/019(564(031(91.6+,)(

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A'(S64(H(c(\$%%(YB(/0(23/0(1/47-190(=/7;1(65(E(2-77(03-9(?46A/A-7-0>(A1(/(: /I- : ; : T(
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PP)(O0(0- : 1(B(/(3>, 4681+(/06 : (-9(-+(031(90/01(
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23141(031(L109

W621=14B(031(6A914=1,(71=179(9362(9 : /77(9?7-00-+89(A10211+(031(,181+14/01(71=179)((
E3191(9?7-00-+89(/41(L+62+(/9(5-+1(904;.0;41B(3>?145-+1(904;.0;41(/+, (031(K/ : A(
93-50)(

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(/'(\ I??/-+(031(?3>9-. /7(64-8-+(65(03191(9?7-00-+89)((F 3/0(-+014/ .0-6+9(-+(/ , , -0-6+(
06(031(_ 6;76 : A(-+014/0-6+(-5(/+>(/41(419?6+9-A71(564(03191(9?7-00-+89T(
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(A'(F 3>(/41(03191(9?7-00-+89(9 : /77T((n4,14(03191(9?7-00-+89(-+(014 : 9(65(031(64,14(65(
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/' _6 : ?;01(031(1+148>(.6441.0-6+(564(031(9>901 : (-+(5-490(64,14(?140;4A/0-6+(
03164>)(
(
A' F 3/0(-9(031(=/7;1(65(031(1+148>(.6441.0-6+((-+(91.6+, (64,14(?140;4A/0-6+(
03164>T(
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' _6 : ?/41(031(1+148>(.6441.0-6+9(6A0/-+1, (-+(!/'(/+, (!A'(2-03(031(1I/.0(1+148>(1-81+
=/7;19(65(031(3/4 : 6+-.(69.-77/064(/996.-/01, (2-03(031(W/ : -706+-/()(
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&%(_6+9-,14/(6+1C,- : 1+9-6+/7(9J ;/41(2177(?601+0-7(65(2-,03(a(/+, (,1?03() (F 1(
-+01+, (06(90; ,>(031(?46?140-19(65(031(A6;+, (90/01(65(/(?/40-.71(-+(03-9(2177(231+(-09
2-,03(/??46/.319(D146)((
(
'((M362(03/0(03141(-+, 11, (1I-909(6+7>(6+1(A6;+, (90/01(/+, (. /7. ;7/01(-09(1+148>)(
_31.L(03/0((= /4-19(2-03(031(9J ;/41(65(031(/41/((65(031(2177)(
(
A'((W62(. /+(031(?41.1, -+8(.6+9-,14/0-6+9(A1(/??7-1, (06(/(?/40-.71(?/.1, (-+(031(
?601+0-7)(
(
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&")((E31(04/+9-0-6+((x (

!A'(* ,1+0-5>(031(?/4-0-19(65(031(567762--+8^

(65(031(3>,4681+(/06 :)

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!. '(S-+, (031(1-81+=/7; 19(65(!./+(A1(, 6+1(/7 : 690(A>(-+9?1.0-6+'((

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&&((!/'_6+9-,14/(9>901 : (2-03(/+(/+8;7/4(: 6 : 1+0; : (65"(,19.4-A1,(-+(031 %C41?4191+0/0-6+(

A>((

(F 3/0(-9(031(?46A/A-7-0>(03/0(/+ s(

?601+0-/7((-+(031(M.34m, -+814(1J; /0-6+(-9(+60(41/7(A;0(.6 : ?71IB((c((k(yB(2-03(/+, (y(?69-0=1(41/7(.6+90/+09)(M362(03/0(031(1J; /0-6+(65(.6+0-+; -0>(+62(8-=19(-- = - (-) P B(/+, (417/01(031(7-510- : 1(06(031(a7-+12-, 03b(y)(

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(!A'(F 3/0(-9(031(1+148>(;+.140/-+0>(64(7-+12-, 03(-+(1] (65(/(?/40-.71(03/0(3/9(/(, 1./>(7-510- : 1(65("\$(: -+9)(F 3/0(?/40-.71(-9(03-9T(

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&i)(S64(/(?/40-.71(-+(/(A6I(!%B(/'B(.6+9-, 14(/+(-+0-/7(+64 : /7-D1, (2/=1(5;+.0-6+(! B(%'(c((Q9-+!z # 'R)(

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!. '(F 3/0(-9(031(?46A/A-7-0>(03/0(/+(1+148>(: 1/9; 41 : 1+0(6+(031(90/01(8-=19(T(!
^E3141(-9(+6(+11, (06(-+0184/01(9-+ ! '(-5(>6; (24-01(9-+(-+(1I?6+1+0-/79(-+(B(/+, (5; 40314(?62 149(-+(/(?62 14(914-19(1I?/+9-6+)(

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[%)(!/'((F 31+(026(, -55141+0(90/019(93/41(031(9/ : 1(1+148>B(031>(/41(9/-, (06(A1(a, 181+14/01)b(X46=1(03/0(6+1C, - : 1+9-6+/7(A6;+, (90/019(65(/(J; /+0; : (9>901 : (-+(/+ /4A-04/4>(?601+0-/7(! '(, 6(+60(3/=1(9; .3(, 181+14/.>)(

(
(^O99; : 1(03-9(2 141(+60(04; 1B(24-01(031(0- : 1C-+, 1?1+, 1+0(M.34m, -+814(1J; /0-6+(564(A603((/+, (B(: ; 70-?7>(1/.3(A>(031(60314(5;+.0-6+B(9; A04/.0B(/+, (-+0184/01(6=14(/77)G11?(-+(: -+, (03/0(A6;+, (90/01(2/=1(5;+.0-6+9(=/+93(/0! e(06(A1(+64 : /7-D/A71B(/+, (567762(031(768-.06(.6+.7; , 1(03/0((/+, (/41(+60(, -90-+.0)(

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(!A'((\ 90/A7-93(031(419; 70(03/0(A102 11+(/+>(026(9; ..199-=1(+6, 19(65(/(6+1C , - : 1+9-6+/7(A6;+, (90/01(2/=1(5;+.0-6+(, ! 'B(031(2/=1(5;+.0-6+(-! '(65(/(3-8314(1+148>(90/01B(. 1(, B(2-77(3/=1(/0(71/90(6+1(+6, 1)(

