

8]Y'YI hfYa ghYb CfhY XYf 9fXY

K]f Yf_i b XYb X]Y YI hfYa ghYb C fhY XYf 9fXY" J YffØW_hY
FY]gYn]Y Yž Ub XYbYb A YbgWX Yb K Y[Y Z]b XYbž]b fUi Yb i bX
ZY]b XgY`][Yb I a [YVi b[Yb ni YI]gh]YfYb = W k Uf gWx cb
]a a Yf ZUgn]b]Yfhj cb fUi Yb I a [YVi b[Yb i bX VYgcb XYfg
j cb XYb 9bhXYW_Yfbž X]Y g]W]\ bYb [YghY``h`\ UVYb" 5`g`]W\
X]Y UV[Y`Y[YbghYb C fhY XYf 9fXY YfZcfgWx hYžgh]Y»]Wx Ui Z
a Y\fYfY YI hfYa Y I a [YVi b[Ybž X]Y Y]b ZUWX b]Wx h ZØf X]Y
a YbgWx`]Wx Y 6Yg]YX`i b[c XYf F Y]gY [YgWx UZZYb k i fXYb"
K]f A YbgWx Yb g]b X YXc Wx Y]b Y F UggY XYf 5 i gXUi Yf i bX
Z]b XYb c Zh K Y[Yž i a i]b X]YgYb fUi Yb i b X ZY]b XgY`][Yb
@Ab XYfb ni ØVYf YVYb" <]Yf g]b X bi f Y]b][Y XYf YI hfYa ghYb
C fhY XYf 9f XY" ? À`hYghYf C fh XYf 9f XYGck Yh]gWx Y K cghc_!
GhUh]c b ž 5 b hUf_h]q Y Ua d \(\text{Y}\)`]d/

K]f 'Yf_i bXYb 'X]Y 'YI hfYa ghYb 'C fhY 'XYf '9fXY" 'J Yff@W_hY $FY]gYn]Y `Y\check{z} `Ub `XYbYb `A YbgWXYb `K Y[Y `Z]bXYb\check{z}]b `fUi Yb `i bX ZY]bXgY`][Yb `I a [YVi b[Yb `ni `YI]gh]YfYb$

⇒W. k Uf 'gW\cb']a a Yf 'ZUgn]b]Yfh'j cb'fUi Yb'l a [YVi b[Yb'i bX VYgcbXYfg'j cb'XYb'9bhXYW_Yfbž'X]Y'g]W\']\bYb'[YghY``h'\UVYb" 5`g']W\'X]Y'UV[Y`Y[YbghYb'CfhY'XYf'9fXY'YfZcfgW\hYž'gh]Y»']W\'Ui Z a Y\fYfY'Yl hfYa Y'l a [YVi b[Ybž'X]Y'Y]bZUW\'b]W\h'ZØf'X]Y a YbgW\`]W\Y'6Yg]YX`i b['cXYf'FY]gY'[YgW\UZZYb'k i fXYb"

8]Y:cfgWXib[gghUh]cb:]gh'Y]bY'XYf']gc`]YfhYghYb'UiZ'XYa UbhUf_h]gWXYb'?cbh]bYbh'ibX'VY\YfVYf[h']b'XYf'FY[Y`'XUg'[UbnY \$U\f'ØVYf'&)'K]gqYbqWXUZh`Yf"

8 Yf'\Y]» YghY'C fh'Ui Z'9Ufh\: i fbUWY'7fYY_ž 8 YUh\'J U``Ymž'? U`]Zcfb]Ybž'l G5

'U`h1 Ua Yf]_Ub]gW\Yf'fcUXhf]d'XYUh\'j U``Ym 2 A Ygei]hY': `UW\Y GUbXXØbYb'XYg'8YUh\'J U``Ym

8 Yf B Ua Y 'gU[h'Y][Ybh']W\ 'gW\ cb 'U``Ygž'cXYf3'5a '%) "'\$\`]'%- +& kifXY'\]Yf Y]bY '6cXYbhYa dYfUhif'j cb'-'ž-'...7'[Ya YggYb"'8 Ug]gh'XcW\ '_bUdd'ibhYf'XYa 'G]YXYdib_hž'cXYf3'8]Y'K ÒfhYf' C ZYbibX' HcX 'g]bX'dUggYbXY'B Ua Yb'ZØf'YXYb'Cfhž'XYf'UiW\ 'bifUbb\\YfbX'X]YgY'HYa dYfUhif'YffY]W\ h"

HfchnXYa ']gh'XYf'BUh]cbU'dUf_'\Yi hY'Y]b'Hci f]ghYbn]Y`ž'XUg'Y]b 6Ygi W\YfnYbhfi a 'i bX'nU\`fY]W\Y'K UbXYfk Y[Y'VY\YfVYf[h" K Ybb']W\'VYXYb_Yž'XUgg']W\'j cf'Y]b'dUUf'K cW\Yb'c\bY ?`]a UUb`U[Y'Xcfh'Xi fW\[YZU\fYb'V]b

8 Yf ZYi WX hYghY Cfh Ui Z XYf 9fXYA Uk gmbfUa ž A Y[\U`UmUž =b X]Yb

'U`h1 YI hfYa Y'C fhY'' & 2

 $9\f^]W\f^[YgU[h'_Ubb']W\h'[`UiVYbž'XUgg'Yg'b]W\h'@cbXcb']gh''$ $8\Ug'8\cfZ'A\Uk\gmbfUa\Yf\h'YXcW\f'(*+Nc```fl\%z, *`A\YhYfL$

FY[Yb'dfc'*J\f"'A Uk gmbfUa '`]Y[h']b'*DX]Ybž'UVYf'XUb_'XYf'BÀ\Y
ni 'XYb', VYfgWk Ya a i b[g[YV]YhYb'j cb'6Ub[`UXYgWk'i bX'XYb
@i ZhghfÒa i b[Ybž'X]Y'ØVYf']\bYb'YbX`cg': Yi Wkh][_Y]h'gUa a Y`bž
[Yb]Y*h 'A Uk gmbfUa 'ZUgh'_cbghUbhYb'FY[Yb"'?`]b[h'Y]b
V]ggWkYb'bUWk'@cbXcbž'U``YfX]b[g'a]h'j]Y``k Yb][Yf'9]bk c\bYfb.
%"' '+"

HfcW_YbghYf'Cfh'Ui Z'XYf'9fXY5hUWUa U! K ØghYž'7\]`Yž'DYfi ž'6c`]j]Yb'i bX 5f[Ybh]b]Yb

'U`h1 5hUWUa U!K ØghY.': U_hYb'ØVYf'7\]`Y 25h`Ug'/ '6cchg 5hUWUa U!K ØghYž'XYf'hfcW_YbghY'Cfh'XYf'9fXY

8]YgYf'Cfh'k]fX'fY[Y`a À»]['a]h'XYa 'AUfg'j Yf[`]WXYb"'8]Y'B5G5 k]YXYf\c`hY'gc[Uf'X]Y'HYghgž'X]Y'g]Y'Ui Z'XYa 'AUfg'Xi fWXZØ\fhYbž i bX'YbhXYW_hYž'XUgg'HY]'Y'XYf'5hUWUaU' [Y[Ybk Àfh][Y @YVYbgnY]WXYb']b'6cXYbdfcVYb'ØVYfgU\Yb ž'kUg'g]Y']a KYgYbh`]WXYb'ZfYaXUfh]['aUWXhY"'8]Y'5hUWUaU'YfghfYW_h'g]WX ØVYf'%\$) "\$\$\$ EiUXfUh_]`caYhYf'f('%"\$\$\$ EiUXfUhaY]`YbŁ GØXUaYf]_Ug'i bX'b]aah'HY]`Y'j cb'j]Yf'@ÀbXYfb'Y]b"

8]Y`Xi fW\gW\b]hh`]W\Y`B]YXYfgW\`U[ga Yb[Y`VYhfÀ[h`Yhk U`%)
A]``]a YhYf`f\\$ž) - `Nc``Ł'dfc`¾J\fž`k Ug`VYXYi hYhž`XUgg`Yg`]b`j]Y`Yb
; YV]YhYb`XYf`K ØghY`ZUgh`_Y]bYb`B]YXYfgW\`U[`[]Vh"`9g`ØVYffUgW\h
b]W\hž`XUgg`X]Y`K ØghY`Y]bYg`XYf`Ua `XØbbghYb`VYg]YXY`hYb
; YV]YhY`XYf`9fXY`]gh"

? A`hYghYf'VYk c\bhYf'Cfh'Ui Z'XYf 9fXYCma mU_cbž'Fi gg`UbX

'U`h1 2 fb]`X. 'A UUfhYb 'HU_Ybgž'7fYUh]j Y '7ca a cbgŁ

8]Y') \$\$ 'A YbgW\Ybž'X]Y'\]Yf'`YVYbž'Yf`YVYb'XUb_'XYf'bÒfX`]W\Yb@U[Y'HU[Y'j cb'' 'Ghi bXYb']a '8YnYa VYf'V]g'&%'Ghi bXYb']a '\$|b]" =a '\$U\f'%-'''Z]Y``X]Y'HYa dYfUhi f'Ui Z'!*+ž+'...7'fl-\$'...:\Łž'k Ug'ZØfY]bY'K Y]`Y'ni a 'K YhhVYk YfV'i a 'XYb'_À`hYghYb'Cfh'XYf'9fXY

8 Ugʻ?`]a Uʻ]ghʻVfi hU`i bXʻgW\bY]XYhʻX]YʻGhUXhʻfY[Y`a À»][ʻj ca FYghʻFi gg`UbXgʻUVžʻk UgʻC]a mU_cbʻUi W\ni 'Y]bYa 'XYf UV[Y`Y[YbqhYbʻCfhY`XYfʻ9fXY`a UW\h"

8 Yf'\Y]» YghY'VYk c\bhY'Cfh'Ui Z'XYf 9fXY8 U``c`ž'Ÿh\]cd]Yb

 $"U"h1 YI hfYa Y"CfhY" "Ÿh\]cd]Yb 2$

±b 'Y]bYa 'UbXYfYb 'HY]` 'XYf 'K Y`h'ni 'Y]bYf 'UbXYfYb 'NY]h'k Uf '8 U``c` a Ò[`]WXYfk Y]gY 'Y]b 'VY`]YVhYg 'Hci f]ghYbn]Y`ž'k Ybb 'a Ub 'VYXYb_hž XUgg 'Yg 'nk]gWXYb '%- *\$ 'i bX '%- ** 'Y]bY 'Xi fWX gWX b]hh`]WXY HU[Yg\ÒW ghhYa dYfUhi f'j cb '(½%'...7 'f%\$* ž\$'...: Ł'Ui Zk]Yg"

@Y]XYf'\Y`ZYb`gc`WXY`HYa dYfUhi fYb`Y]bYa `@UbX`b]WXhž`XUg`i bhYf i b\Y]`VUfYb`8 ØffYb`i bX`<i b[YfgbOhYb``Y]XYh"`9g`[]Vh`_Y]bY GWXAhni b[`ZØf`X]Y``c_U`Y`6Yj O`_Yfi b[`\]Yfž`k Ug`Ui Z[fi bX`gY]bYf 5V[YgWX]YXYb\Y]h`i bX`Ui WX`XYf`HUhgUWXYž`XUgg`Yg`%' \$`a `f!('\$ZhŁ`i bhYf`XYa `A YYfYggd]Y[Y```]Y[hž`ni `Yfk UfhYb`]gh"

; fò» hYf'fY]b'j Yfh]_U`Yf'5VZU``'Ui Z 9Ufh\A ci bh'H\cfž'5i mi]hhi e'BUh]cbU`'DUf_ž 6UZZ]b'=g`UbXž'Bi bUj i hž'? UbUXU

'U`h1 YI hfYa Y`CfhY`A h"`H\cf 2 DUi `;]YfgnYk g_]#7fYUh]j Y
7ca a cbg'f6]`X.`DUi `;]YfgnYk g_]ž'7fYUh]j Y`7ca a cbgŁ

9g'k ØfXY'i b[YZÀ\f'' * 'GY_i bXYb'XUi Yfbž'V]g'Y]bY'++'_['gWk YfY DYfgcb'X]Y'%''&) \$ 'a 'f(''%\$%'ZhŁ'j cb'XYf'?`]ddY'(\$\$'A YhYf'i bhYf XYa ';]dZY`'XYg'A ci bh'H\cf'ghØfnh''8]Y'ØVYf\Àb[YbXY'?`]ddY'ZÀ``h]b'Y]bYa 'Xi fWkgWkb]hh`]WkYb'K]b_Y`'j cb'%) '; fUX'ni f'GYb_fYWkhYb UVž'k Ug'VYXYi hYhž'XUgg'G]Yž'k Ybb'G]Y'XUg'DYWk'\UhhYbž'ni ghØfnYbž'b]Wkhg'hfYZZYb'k ØfXYbž'V]g'G]Y'XYb'; fi bX'YffY]WkYb''

 $\ddot{Y} \ \dot{z} [i h3"HfchnXYa"]gh"Yg"]a a Yf"bcW\"Y]b"VY`]YVhYf"Cfh"ni a$

8Yf'[YZÀ\f`]WXghY'Cfh'XYf'9fXY

 $5b[Yg]Wkhg'U``XYf'jYfgWk]YXYbYb': U_hcfYb']gh'X]Yg'Y]bY'gWkkYfni'a YggYbXY' 5i gnY]Wkbi b["'5``YfX]b[g'kifXYb'5Z[\Ub]ghUb ibX'Gmf]Yb'`Uih'XYa '6Yf]Wkh'XYg'; `cVU``DYUWY'<math>\pm$ 0XYI'f| D \pm k]YXYf\c`h'U`g'X]Y'[YZÀ\f`]WkghYb'@ÀbXYf'XYf'KY'h'VYnY]WkbYh''

8 UfØVYf`\]bUi g`[]`h`X]Y`GhUXh`GUb`DYXfc`Gi`U`]b`< cbXi fUgʻa]h %"' %- '9fa cfXYhYb`]a '\\f`&\\$%('i bX`Y]bYf`A cfXfUhY`j cb`%+\%\\\$\\$ A cfXYb`dfc`\%\\$\"\\$\\$\\$)bk c\bYf`U`g`X]Y`[YZÀ\f`]W\ghY`GhUXh`XYf K Y`h"

8Yfg]WXYfghYCfhXYf9fXY

'U`h1 YI hfYa Y'C fhY' 'A cbcWc 2

5a 'UbXYfYb'9bXY'XYg'GdY_hfi a g'VYZ]bXYb'g]W\'X]Y'g]W\YfghYbCfhY'XYf'9fXYž'X]Y'kYb]['ØVYffUgW\YbX'Ui W\'ni 'XYb'hYi YfghYb[Y\ÒfYb"'AcbUWc'i bX'@]YW\hYbghY]b'flVY]XY']b'9i fcdUŁ'\UVYbVY]XY']b'XYb''YhnhYb'\J\\fYb'_Y]bY'AcfXfUhYb'j YfnY]W\bYh"

6Y]XY'g]bX'Ybhk]W_Y`hY'@ÀbXYf'a]h'ghUf_Yb'; Ygi bX\Y]hg!'i bX
A YX]n]bgmghYa Yb'i bX'_Y]bYg'j cb'VY]XYb']gh'i ba]hhY`VUf'j cb
B Uhi f_UhUghfcd\Yb'VYXfc\h": Øf'a UbW\Y']b'CfXbi b[z'cXYf3'I bX
a]h'Y]b][Yb'a Y]bY']W\':]`a ghUfgz'D`UmVcmg'i bX': cfa Y`!%!: U\fYf"

5bXYfY'YI hfYa Y'CfhY'Ui Z'XYf'9fXY

 $H]YZghY'<\mathring{O}\ Y'XYf'9fXY'JcfcbmU!<\mathring{O}\ Y\check{z}'5fUV]_U!AUgg]j\ \check{z}';\ Ycf[\]U\check{z}'''-1'a''fH'''-1':i > k$

 $H]YZghY`YffY]W\&hY`cnYUb]gW\&Y`H]YZY`7 \&U``Yb[Yf`8YYdž\\AUf]UbYb[fUVYb`YffY]W\&hY`%$"-+%`a`fl)"--(`ZhŁ$

$$\label{eq:helicity} \begin{split} H]YZghYg^{\cdot}9]g^{\cdot}XYf^{\cdot}9fXY6Ybh^{\cdot}Ym^{\cdot}Gi\ V\ [\ `UW]U^{\cdot}HfYbW\ \check{z}^{\cdot}5bhUf_h]g^{\cdot}Ui\ Z\\ !\&")\)\)\ a\ `fl\ ,\ "'\ ,\ '\ ZhŁ \end{split}$$

 $B \ Of X^{*}W \ ghY \ f^{*}Di \ b_h^{*}Ub^{*} \ @Ub \ X^{*}? \ UZZY_{i} \ VVY \ b^{*} = g^{*}Ub^{*}X \ Z^{*}Ogh^{*}W \ j \ cb^{*}$ $f \ Ob^{*}Ub^{*}X$

 $GØX^{D}W$ ghY f'Di b_h'Ub'@Ub X'8 Y f'[Yc[fUZ]gWX Y'GØX dc'ž'5 b hUf_h]g

< OWX ghY f'C fh'Ui Z'XY f'9fXYA ci bh'9j Y fYghž'; fYbnY'nk]gWX Yb'7\]bU i bX'BYdU`'Ui Z', ", (, 'a 'f&- "\$&- 'ZhŁ

B]YXf][ghYf'Cfh'Ui Z'XYf'9fXY?ØghY'XYg'HchYb'A YYfYgž'=gfUY`ž K Ygh'cfXUb`UbXž'xfXUb]Yb'VY]'!(&('a'fl'%'' - %'ZhŁ'i bhYf'XYa A YYfYggd]Y[Y`

'U`h1 2

Ni gÀhn`]W\Y': chc[fUZ]Y. HfUi a nY]h

8 YhU]`g

6Ygi WXYb G]Y i bg Ui Z Y]bY!fY]gY "XY