7ci fgY^{*}Cj Yfj]Yk

`GHJZZ:7cbHJWh:8YHJ]`g`

'7cbj Ybcfg'

B Ua Y	9a U]`	5j U]`UV]`] m	@cWUh]cb	D\cbY
9a YfmGWWi VYfh	Y"gWXi VYfr4 i bgk "YXi "Ui	,	FcVYfh KYVghYf`%\$%	-',) '*, \$,

GW.cc`7cbhJWh′±bZcfa Uh]cb

Fcca " ‰ž"Yj Y`" FcVYfhK YVghYf'6i]`X]b[

7ci fgY 8YHJ] g

7 fYX]hDc]bhg * *

Gi a a UfmcZh\Y 7ci fgY

Gi VYWi5fYU. ? ge[U

H\]g`Wci fgY`Ug_g`ei Ygh]cbg`UVci ha i g]WWc[b]h]cb`UbX`VY\Uj]ci f. < ck `Xc`k Y`dYfWY]j Y`a i g]WB`K \m\WUb Ub`]bghfi a Ybhgci bX`a i g]WB`S < ck `Xc`k Y`fYgdcbX`hc`UbX`dfcWfgchXYgci bX3`K \Uh\UddYbg`k \Yb`k Y UfY`dfYdUf]b[`UbX`dYfZcfa]b[`a i g]WB`K \m\WUb`dYfZcfa Yfg`VYWca Y`XYV]`]hUh]b[`mbYfj ci g3`K \Uh]g`h\Y fY`Uh]cb`VYhk YYb`a i g]WbgYl `UbX`W\YYgYWU_Y3`7 Ub`a i g]Wa U_Y`mci `ga UfhYfz`UbX`k\Uh]g`h\Y`A cnUfh 9ZZYWB`K \mXcYg`h\Uhh bY`[Yhgh W_]b`a m\YUX3`< ck `c`X`a i ghU'dYfgcb`VY`VYZcfY`h\YmWUb`\YUf`UbX UddfYW]UhY`a i g]WB`Mci `k]```UXXfYgg`h\YgY`UbX`fY`UhYX`ei Ygh]cbg`h\fci [\`Yl Ua]bUh]cb`cZh\Y`a i g]W dgmW\c`c[m`]hYfUh fYz`UbX`h\Y`Wf]h]WU``Yj U`i Uh]cb`cZmci f`ck b`a i g]WU``Uhh]h XYgz`VY`]YZg`UbX`VY\Uj]ci fg"

7 ci fgY @YUfb]b[Ci hWca Yg

- %" 91 d`U]b`\ck 'a i g]W]g`XYZ|bYX`Zfca 'U'dgm\%c`c[]WU`'dc]bhcZj]Yk "
- &" ⇒ YbhjZm`\ck a i g]WdgmWkc`c[]ghg`h\]b_`UVci hUbX`UddfcUWk`ei Yghjcbg`WcbWfb]b[`a i g]WdfWYdhjcb`UbX`Wc[b]hjcb"
- ' " 9a d`cmg_]``g`bYYXYX`hc`Z|bXž'UggYgg`UbX`XYg][b`a i g]WfYgYUfW\"

HYUWX]b[GlfUhY[]Yg

H\Y'Wti fgY'k]``VY'dfYgYbhYX'h\fci [\'ZJVW!hc!ZJWW'`YWfi fYg"'Hi hcf]U`g'UfY`\Y'X'cb`]bYž'k\]W\'a YUbg'mci g\ci 'X'YI dYWfihc'XYj chY'i d'hc'cbY'\ci f'dYf'k YY_'fbch]bWi X]b['dfYdUfUh]cb'UbX'UggYgga Ybhih]a YE'hc cb`]bY']bX]j]Xi U``UWfj]hJYg'UbX'Wc``UVcfUh]j Y'UWfj]hJYg'k]h\'ch\Yf'ghi XYbhg"'C h\Yf'UggYgga YbhihUg_g'k]``VY Wta d'YhYX']bXYdYbXYbhmi]b'UXX]hJcb'hc'h\Y'cb`]bY'hi hcf]U``k cf_"'; fci d'`YUfb]b['zWf]hJWU``fYZYWfJcb'UbX'gY`Z UggYgga Ybhik]```VY'XYj Y`cdYX']b'gY'YWhYX'hi hcf]U``HUg_g'hc'YbWti fU[Y'X]j YfgY'a cXYg'cZ`YUfb]b[']b UXX]hJcb'hc'hfUX]hJcb'hc'hfUXJhJcb'hc'hfUXJg"

5ggYgga Ybh

5ggYgga Ybh'HUg_g

5ggYgga Ybh'hUg_	K Y][\h	8iY'8UhY	Gh XYbh@YUfb]b[CihWca Ygʻ5ggYggYX
HYgh	*\$1	Bch5dd`]WUV`Y	%ž&Ž
Ei]n	%\$ı	Bch5dd`]WUV`Y	%ž&Ž
Dcfh7c`]c	' \$1	Bch5dd`]WUV`Y	&Ž

5ggYgga Ybh'8YHJ]`g

cZk YY_`mž'h\fYY!\ci f`cb`]bY`cf`XY`UmYX!cb`]bY`hUg_g"``GYY`a ccX`Y`Zcf`XYhU]`g"``D`YUgY`bchY`h\Uhih\Y UggYgga Ybhk Y][\h'Zcf`h\, ht\si hf\f\f\hU`mk Yc`YUgY`Y`XYV\gYY``b`cfk chk Y\cf`Hchihk fhiY`h\Uhih\Y

5 hm/b XUb WY F Yei]fYa Ybhg

 $\hbox{Ghi XYbhg'UfY'ghfcb[`mYbWci fU[YX'hc'UhhYbX'U```WUggYg'UbX'fYj]Yk ``YWhi fY'fYWcfX]b[g''] } \\$

7ci fgY'GWXYXi `Y

<u>J]Yk "WUgg"hja YHUV"Y</u>

H]a YHJV`Y

8 UHY	HmdY	7 cbhYbh
K YY_'%'%'GYdhYa VYf'! &\$'GYdhYa VYf	@YWhi fY	9jc`ih]cb.''K\UhgYI'UbX'WXYYgYWU_Y'\UjY'hc'Xck]h\'h\Y'cf][]bg'cZaig]W
K YY_'&.'&' 'GYdhYa VYf'! &+'GYdhYa VYf	@YWhifY	9a ch]cb. 'K \m]gʻa i g]Wgcʻdck YfZ `3
K YY_''.'' \$'GYdHYa VYf'! ('C WcVYf	@YWhifY	

FYgci fWfg

DfYgWf]VYX F Ygci fWYg

 $\label{eq:def-energy} D`YUgY`gYY`a~ccX`Y`Zcf`YI~dYWYX`fYgci~fVWg"$

FYWca a YbXYX FYgci fWYg

D`YUgY gYY a ccX`Y Zcf'fYWca a YbXYX fYgci fW/g"

7ci fgY 9j U`i Uh]cb UbX 8Yj Y`cda Ybh

7 ci fgY`ZYYXVUW_`]g`HU_Yb`gYf]ci g`m'UbX`]a d`Ya YbHYX`]b`H\Y`gUa Y`gYa YgHYf`k \YfY`dcgg]V`Y"``H\YfYZcfYž **gh XYbhg`UfY`YbWci fU[Yx**VH[cYdYcjf]}xXkZY[YH\V**U%**LghKYMAYYc`]hYdf]cdjXgYUXW_M]}XXdYkYY<u>f</u>i`%"`'**%A|b**VVXc`H\YY<u>K</u>'J[YYK\ZY[YH\VUW_`]gdV\YVX Gi Va]gg]cb cZ5ggYgga YbhHUg_g

Gi Va]gg]cb cZ5ggYgga YbhHUg_g

Hi fb]h]b Gi Va]gg]cb

Image: Ybwci bhYf'U'dfcV'Ya k \Yb'UhYa dhJb['hc'gi Va]hmci f'Ugg][ba Ybht\fci [\ 'Hi fb]hJbž'd'YUgY

HY'Yd\cbY'9| hYfbU''Gi ddcfhcb'-',) '' ' ' %cf'Ya U] 'h\Ya 'cb'Y! hYfbU'hY'hgi ddcfh4 i bgk "YXi "Ui '"'Gi ddcfh
\ci fg'UfY', .\$\$Ua '-'\\$.\$\$da 'cb'k YY_XUmg'UbX'-.\$\$Ua '-') .\$\$da 'cb'k YY_YbXg'fl *) 'XUmg'U'mYUfŁ" Image:

UfY'i bUV'Y'hc'gi Va]hmci f'Ugg][ba YbhXi Y'hc'U'ZJi 'hk]h\ 'Hi fb]hJb'mci 'a UmUdd'mZcf'Ub'Y! hYbg]cbž'Vi hmci
a i ghfYhJ]b'mci f'hJW_Yhbi a VYf'Zfca '9! hYfbU''Gi ddcfhfU'cb['k]h\ 'Ubmch\Yf'fY'Yj UbhXcW a YbhgŁ'hc
]bWi XY'Ug'Yj]XYbW' 'hc'gi ddcfhmci f'Y! hYbg]cb'Udd']WUh]cb" Image: Ya U]''9! hYfbU''Gi ddcfhmci 'k]''

Ui hca UhJWJ''mfYW'] Y'U'hJW_Yhbi a VYfž'Vi h]Zmci 'hY'Yd\cbY'mci 'k]'''bYYX'hc'gdYWJZWJ''mUg_'Zcf'cbY''

Hi fb]hJb'U'gc'dfcj]XYg'i dXUhYg'cb'h\Y]f'gmghYa 'ghUh' g'cb'Hk]hYf"

; YbYfU``mž'UggYgga YbhiHug_g'a i ghVY'gi Va]hhYX'Y`YVWfcb]\W)``mj]U'Y]h\Yf'Hi fb]hjb'cf'U'A ccX`Y Ugg][ba Ybh'' =b']bgHJb\W'g'k \YfY'h\]g']g'bchdcgg]V`Yž']hk]``'VY'gHJhYX'cb'mci f'\\circ i fgY'g'A ccX`Y'g]hY'k]h\ U`hYfbUhj Y'gi Va]gg]cb'XYHJ]`g''

cfi]bZcfa Uh]cbicbi\ckihcigi Va]hUgg][ba Ybhgicbi]bYij]UiA ccXiY.i\hdg.#gh XYbh'i bgk "YXi "Ui #\ck! qi Va]hUgq][ba Ybha ccXiY

5 WUXYa]W<cbYghmUbX D`U[]Uf]ga

D`U[]Uf]ga i]gii g]b[ih\Yik cfXgicfi]XYUgicZch\YfgiUbXidfYgYbh]b[ih\Ya iUgimci fick b"i±i\WbihU_Yia Ubm Zcfa gžZfca iXYi]VYfUhYiW\YUh]b[ihciU\W]XYbhU`m\Wcdm]b[iZfca iUigci f\Wik]h\ci hiU\w_bck iYX[Ya Ybh'

IBGK [fcidg'd'U[]Uf]ga]bhc'h\Y'Zc``ck]b[WUhY[cf]Yg.

7 cdm]b[.'i g]b['h\Y'gUa Y'cf'j Yfmg]a]`Uf'k cfXg'hc'h\Y'cf][]bU`hYl h'cf']XYU'k]h\ci h'UW_bck `YX[]b['h\Y gci fW'cf'i g]b['ei chUh]cb'a Uf_g"'H\]g'U`gc'Udd`]Yg'hc']a U[Ygž'Ufh'UbX'XYg][b'dfcYWhgž'Ug'k Y``'Ug dfYgYbhUh]cbg'k \YfY'gca YcbY'dfYgYbhg'Ubch\Yf'g']XYUg'cf'k cfXg'k]h\ci h'WfYX]h'

⇒ Uddfcdf]UhY 'dUfUd\fUg]b[. '7\Ub[]b['U'ZYk'k cfXg'UbX'd\fUgYg'k\]Y 'a cghmfYhU]b]b['h\Y'cf][]bU`ghi Wh fY 'UbX#cf'dfc[fYgg]cb'cZ]XYUg'cZh\Y'cf][]bU`žUbX']bZcfa Uh]cb'k]h\ci hUW_bck`YX[Ya Ybh'H\]g'U`gc Udd`]Yg']b'dfYgYbhUh]cbg'k\YfY'gca YcbY'dUfUd\fUgYg'Ubch\Yf'g']XYUg'cf'k cfXg'k]h\ci h'WfYX]h'UbX'hc d]YW]b['hc[Yh\Yf'ei chYg'UbX'dUfUd\fUgYg']bhc'U'bYk'k\c`Yžk]h\ci h'Uddfcdf]UhY'fYZYfYbW]b['"

7 c``i g]cb.'k cf_jb['k]h\ch\Yfg'Vi hdUgg]b['cZZh\Y'k cf_'Ug'U'dYfgcb'g']bX]j]Xi U``k cf_"'7 c``i g]cb'U`gc]bWi XYg'dfcj]X]b['mci f'k cf_'hc'Ubch\Yf'ghi XYbhVYZcfY'h\Y'Xi Y'XUhYžcf'Zcf'h\Y'di fdcgY'cZh\Ya d`U[]Uf]g]b['UhiUbmh]a Yž'dUm]b['Ubch\Yf'dYfgcb'hc'dYfZcfa 'Ub'UWUXYa]WhUg_ž'ghYU']b['cf'UWei]f]b[Ubch\Yf'dYfgcb'g'UWUXYa]Wk cf_'UbX'Wcdm]b[']hz'cZYf]b['hc'Wca d'YhY'Ubch\Yf'dYfgcb'g'k cf_'cf'gYY_]b[dUma YbhZcf'Wca d'Yh]b['UWUXYa]Wk cf_"

±bUddfcdf]UhY`W]hUh]cb.`7]h]b[`gcifWrg`k\]W\`\UjY`bchVYYb`fYUXžk]h\cihUW_bck`YX[]b[`h\Y`´gYWcbXUfm´gcifWrZfca`k\]W\`_bck`YX[Y`cZh\Ya`\Ug`VYYb`cVhU]bYX"

8 i d`]\WUh]cb`ffgY`Zd`U[]\Uf]ga "Ł gi Va]\h]b[`mci f`ck b`k cf_ž]b`k \c`Y`cf`]b`dUfhžk \YfY`]h\Ug`dfYj]ci g`m VYYb`dfYdUfYX`cf`gi Va]\hYX`Zcf`Ubch\Yf`UggYgga Ybhcf\Wci fgY`UhI BGK `cf`Ubch\Yf`i b]j Yfg]\m'

7 cffYWnfYZYfYbWlb['dfUWnWyg.

• DUfUd\fug]b[z'gi a a Uf]q]b[z'YggUmk f]hb['UbX'ha Y'a UbU[Ya Ybh

5 WUXYa]W = b Zcfa Uh cb.

: cf`YggYbhJU``gh XYbh`]bZcfa UhJcb`fY`UhJb['hc.

- fYei Yghg Zcf Yl hYbg]cb/
- `UhY 'gi Va]gg]cbg'[i]XY`]bYg/
- fYj]Yk 'cZa Uf_g/
- I BGK '< YU`h\ 'UbX'GUZYhm'dc`]W[Yg/
- YI Ua]bUhcb dfcWXi fYg/
- gdYWJU``Wcbg]XYfUHjcb`]b`H\Y`Yj YbhcZ]``bYgg`cf`a]gUXj Ybhi fY/
- gh XYbhYei]mUbX X]gUV]`]m/
- UbX'ch\Yf'YggYbhJU`'UWUXYa]W]bZcfa UhJcbž'gYY

\hdg.#k k k "Uffg"i bgk "YXi "Ui #W ffYbhgh XYbhg#UWJXYa]W]bZcfa Uf]cb#dfchcWc`g![i]XY`]bYg#

a U[Y'7fYX]h

Gc`c'DYfZcfa UbWY'A U_]b['&\$%

7F = 7CG

7F = 7CG Dfcj]XYf 7cXY. \$\$\$-,;