Title

TABLES OF THE CLEBSCH-GORDAN COEFFICIENTS FOR ODD- AND EVEN-MASS DEFORMED NUCLEI

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LAWRENCE RADIATION LABORATORY
UNIVERSITY of CALIFORNIA BERKELEY

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TABLES OF THE CLEBSCH-GORDAN COEFFICIENTS FOR ODD- AND EVEN-MASS DEFORMED NUCLEI*

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A set of tables has been prepared as a convenient source of the Clebsch-Gordan Coefficients commonly used in the calculation of nuclear transition probabilities for deformed nuclei. Similar, less extensive tables have been prepared by other authors (Si 54, Lu 61, and Ya 66).

The transition probability for a nuclear transition of multipole order L between an initial state I and a final state F is characterized by the reduced transition probability B(L, II → IF).

If the nuclear motion is separated into two modes--rotational and intrinsic--the reduced transition probability can be written as a product of a geometrical factor, depending only on the angular momenta, and a factor involving integrations over the intrinsic wave function of the initial and final states.†

If one compares the reduced transition probability for the emission of a given multipole radiation from a state I to different members F,F' ··· of a rotational family, the factors involving the intrinsic wave functions are the same. One thus obtains a ratio which depends only on the geometrical factors.

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*Available as UCRL-18975 from Lawrence Radiation Laboratory, University of California, Berkeley, California 94720.

†This and most of the following discussion is taken from Ref. Al .

$$\frac{B(L,II \rightarrow IF)}{B(L,II \rightarrow IF')} = \frac{|\langle II\ L\ KI\ KF\text{-}KI | IF\ KF \rangle|^2}{|\langle II\ L\ KI\ KF\text{-}KI | IF'\ KF \rangle|^2}, \tag{1}$$

where $\langle II\ L\ KI\ KF\text{-}KI | IF\ KF \rangle$ is the Clebsch-Gordan Coefficient (Co 35).

II = The spin of the initial state.

IF = The spin of the final state.

KI = The K of the initial state, where K is the projection of the nuclear angular momentum on the nuclear symmetry axis.

KF = The K of the final state

L = The angular momentum carried off by the radiation emitted during the transition from the initial to the final state.

The relation (1) holds when the initial and final states belong to the same or different rotational bands.

In special cases when L $\geqslant$ KI + KF, symmetrization of the wave function may cause the transition matrix elements to become a sum of two products of geometrical and intrinsic factors. The ratio of reduced transition probabilities can then be written in the form.

$$\frac{B(L,II \rightarrow IF)}{B(L,II \rightarrow IF')} = \left[\frac{\langle II\ L\ KI\ KF\text{-}KI | IF\ KF \rangle + b(-)^{IF+KF} \langle II\ L\ KI\ \text{-}KF\text{-}KI | IF\ \text{-}KF \rangle}{\langle II\ L\ KI\ KF\text{-}KI | IF'\ KF \rangle + b(-)^{IF'+KF} \langle II\ L\ KI\ \text{-}KF\text{-}KI | IF'\ \text{-}KF \rangle}\right]^2 \tag{2}$$

where b is a parameter depending on the intrinsic wave function.

The reduced transition probabilities are also important in Coulomb excitation experiments. The cross section for Coulomb excitation of particular states is proportional to B(L,II $\rightarrow$ IF).

THE ARRANGEMENT OF THE TABLES

The compilation is arranged into four tables covering integral and half-integral values of the spin (I) and positive and negative values of KF. The range of the arguments used is shown in the table below.

Table I. Range of Arguments for Clebsch-Gordan Coefficients

Table	KI	KF	II	L	IF
1	1/2 - 31/2	1/2 - 31/2	1/2 - 31/2	0 - 6	1/2 - 43/2
2	1/2 - 11/2	1/2 - (-11/2)	1/2 - 31/2	0 - 6	1/2 - 43/2
3	0 - 16	0 - 16	0 - 16	0 - 6	0 - 22
4	0 - 5	-1 - (-6)	0 - 16	0 - 6	0 - 22

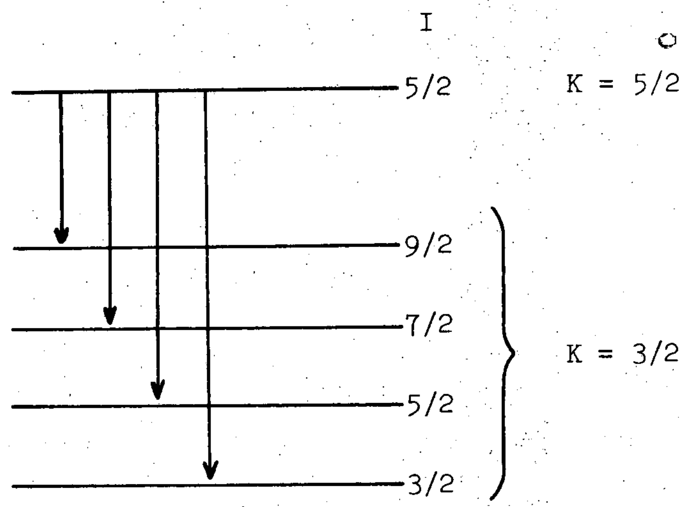
Some sample pages from the tables are reproduced below. The tables are arranged such that the right hand argument IF varies the fastest, followed by L, II, KF, and KI.

KI	KF	II	L	IF	(CLFR)**2	CLFR
1/2	1/2	5/2	0	5/2	1.00000000	1.00000000
1/2	1/2	5/2	1	3/2	.40000000	-.63245553
				5/2	.02857143	.16903085
				7/2	.57142857	.75592895
1/2	1/2	5/2	2	1/2	.20000000	.44721360
				3/2	.05714286	-.23904572
				5/2	.22857143	-.47809144
				7/2	.03809524	.19518001
				9/2	.47619048	.69006556
1/2	1/2	5/2	3	1/2	.14285714	.37796447
				3/2	.11428571	.33806170
				5/2	.07619048	-.27602622
				7/2	.19047619	-.43643578
				9/2	.04329004	.20806259
				11/2	.43290043	.65795169
1/2	1/2	5/2	4	3/2	.19047619	.43643578
				5/2	.09523810	.30860670
				7/2	.08658009	-.29424494
				9/2	.17316017	-.41612519
				11/2	.04662005	.21591676
				13/2	.40792541	.63869039
⋮	⋮	⋮		⋮	⋮	⋮
5/2	3/2	5/2	1	3/2	.66666667	.81649658
				5/2	.28571429	.53452248
				7/2	.04761905	.21821789
5/2	3/2	5/2	2	3/2	.28571429	.53452248
				5/2	.42857143	.65465367
				7/2	.23809524	.48795004
				9/2	.04761905	.21821789
5/2	3/2	5/2	3	3/2	.07142857	.26726124
				5/2	.28571429	.53452248
				7/2	.38095238	.61721340
				9/2	.21645022	.46524211
				11/2	.04545455	.21320072
5/2	3/2	5/2	4	3/2	.00793651	.08908708
				5/2	.09523810	.30860670
				7/2	.28860029	.53721531
				9/2	.36075036	.60062498
				11/2	.20396270	.45162230
				13/2	.04351204	.20859541
⋮	⋮	⋮		⋮	⋮	⋮
1/2	-1/2	3/2	5	7/2	.36363636	-.60302269
				9/2	.04545455	-.21320072
				11/2	.22377622	.47304992
				13/2	.36713287	.60591490
1/2	-1/2	3/2	6	9/2	.36713287	-.60591490
				11/2	.05594406	-.23652496
				13/2	.20769231	.45573272
				15/2	.36923077	.60764362
1/2	-1/2	5/2	1	3/2	.20000000	.44721360
				5/2	.51428571	.71713717
				7/2	.28571429	.53452248
1/2	-1/2	5/2	2	1/2	.13333333	-.36514837
				3/2	.23809524	-.48795004
				5/2	.00000000	.00000000
				7/2	.31111111	.55777335
				9/2	.31746032	.56343617
1/2	-1/2	5/2	3	1/2	.19047619	.43643578
				3/2	.00952381	-.09759001
				5/2	.22857143	-.47809144
				7/2	.01587302	-.12598816
				9/2	.23088023	.48049998
				11/2	.32467532	.56980288

Fig. 1

EXAMPLES OF THE USE OF THE TABLES

A. An E2 transition from a K = 5/2 to a K = 3/2 rotational band.



We can obtain the relative transition probabilities from the spin 5/2 member of the K = 5/2 rotational band to the different rotational members of the K = 3/2 band using formula 1. In this case II = 5/2, KI = 5/2, KF = 3/2, L = 2, and IF = 9/2, 7/2, 5/2 and 3/2.

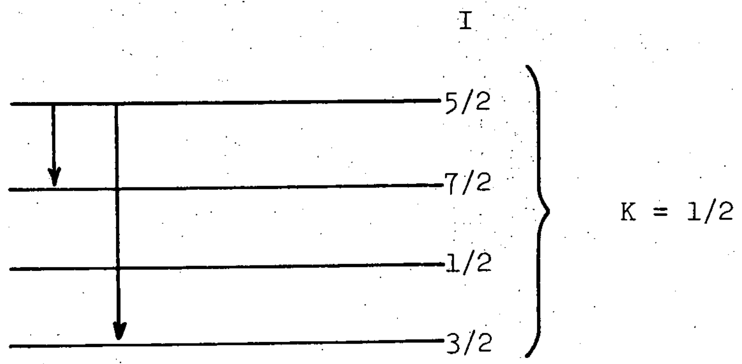
$$B(2,5/2 \rightarrow 3/2)\ \alpha\ |\langle 5/2\ 2\ 5/2\ {-1}|3/2\ 3/2\rangle|^2 = 0.28571429$$

$$B(2,5/2 \rightarrow 5/2)\ \alpha\ |\langle 5/2\ 2\ 5/2\ {-1}|5/2\ 3/2\rangle|^2 = 0.42857143$$

$$B(2,5/2 \rightarrow 7/2)\ \alpha\ |\langle 5/2\ 2\ 5/2\ {-1}|7/2\ 3/2\rangle|^2 = 0.23809524$$

$$B(2,5/2 \rightarrow 9/2)\ \alpha\ |\langle 5/2\ 2\ 5/2\ {-1}|9/2\ 3/2\rangle|^2 = 0.04761905$$

B. An M1 transition within a K = 1/2 rotational band with a decoupling constant (a) of -1.5.



In this case, to find the relative transition probabilities for the transitions from the 5/2 to the 7/2 and 3/2 members of the K = 1/2 band we must use formula 2. Here we have II = 5/2, KI = KF = 1/2, L = 1, and IF = 7/2 and 3/2.

$$B(1,5/2 \rightarrow 7/2) \; \alpha \; [\langle 5/2 \; 1 \; 1/2 \; 0 | 7/2 \; 1/2 \rangle + b \langle 5/2 \; 1 \; 1/2 \; 0 | 7/2 \; -1/2 \rangle]^2$$

$$= [0.75592895 + b \; (0.53452248)]^2$$

$$B(1,5/2 \rightarrow 3/2) \; \alpha \; [\langle 5/2 \; 1 \; 1/2 \; 0 | 3/2 \; 1/2 \rangle + b \langle 5/2 \; 1 \; 1/2 \; 0 | 3/2 \; -1/2 \rangle]^2$$

$$= [-0.63245553 + b \; (0.44721360]^2$$

THE COMPUTER PROGRAM

The computer program consists of a main program, which is slightly different for each of the four tables, and a subroutine CLEB which remains the same. The program is written in Chippewa Fortran for the CDC 6600.

The main program for calculating the coefficients for half-integral values of I and negative KF is reproduced below.

```
                PROGRAM IDA(INPUT,OUTPUT,TAPE2=INPUT,TAPE3=OUTPUT)
          C
          C     THIS PROGRAM CALCULATES CLEBSCH GORDON COEFFICIENTS FOR
          C     HALF-INTEGRAL ARGUMENTS
          C     AND NEGATIVE VALUES OF KF
          C
          C     X(1) = II
          C     X(2) = L
          C     X(3) = IF
          C     X(4) = KI
          C     X(5) = KF - KI
          C     X(6) = KF
          C
000043          DATA LINE /0/
000043          DATA CUT/0.00000001/
000043          DIMENSION X(6),M(6)
000043          DIMENSION FMT(5)
000043          DATA NPAGE/1/
000043          FMT(1) = 10H(1H1,5X,*-
000045          FMT(3) = 10H0X,*UCRL-1
000046          FMT(4) = 10H8975*)
000050          DIGIT1 = 10H*,I1,*-*,5
000051          DIGIT2 = 10H*,I2,*-*,5
000053          DIGIT3 = 10H*,I3,*-*,5
000054          DIGIT4 = 10H*,I4,*-*,5
000056          PRINT 1
000061        1 FORMAT(6H1*CVE*)
000061          ICOUNT = 0
000062          IF(NPAGE.LE.9999) FMT(2) = DIGIT4
000067          IF(NPAGE.LE.999) FMT(2) = DIGIT3
000073          IF(NPAGE.LE.99) FMT(2) = DIGIT2
000077          IF(NPAGE.LE.9) FMT(2) = DIGIT1
000103          WRITE(3,FMT) NPAGE
000111          NPAGE = NPAGE + 1
000113          WRITE(3,3003)
000116          WRITE(3,3000)
000121          WRITE(3,3010)
000124          ICOUNT = ICOUNT + 5
000126          DO 80 I4 = 1,11,2
000127          X(4) = FLOAT(I4)/2.
000131          PMAX = (6. - X(4))*2.
000133          KMAX = IFIX(PMAX)
000135          DO 60 I6 = 1,KMAX,2
000136          X(6) = -FLOAT(I6)/2.
000140          X(5) = X(6) - X(4)
000142          DO 50 I1 = I4,31,2
000144          X(1) = FLOAT(I1)/2.
000146          DO 40 I2 = 1,7
000147          LINE = 0
000150          X(2) = FLOAT(I2) - 1.
000152          IF(ABS(X(5)).GT.X(2)) GO TO 40
000157          JMIN = ABS(X(1) - X(2)) * 2
000163          JMAX = ABS(X(1) + X(2)) * 2
000167          KMIN = ABS(X(6)) * 2
000172          IF(JMIN.LT.KMIN) JMIN = KMIN
000174          DO 30 I3 = JMIN,JMAX,2
000176          X(3) = FLOAT(I3)/2.
000200          Y = CLEB(X)
000202          IF(ABS(Y).EQ.0) Y=CUT
000205          Z = Y**2
000207          LINE = LINE + 1
000210          M(1) = 2 * X(1)
000213          M(2) = X(2)
000215          M(3) = 2 * X(3)
000220          M(4) = 2 * X(4)
000223          M(5) = X(5)
000224          M(6) = 2 * X(6)
000227          IF(LINE.GT.1) GO TO 20
000232          WRITE(3,3001) M(4),M(6),M(1),M(2),M(3),Z,Y
000253          ICOUNT = ICOUNT + 2
000255          IF(ICOUNT.GE.60) GO TO 100
000257          GO TO 30
000257       20 WRITE(3,3002) M(3),Z,Y
000270          ICOUNT = ICOUNT + 1
000272          IF(ICOUNT.GE.60) GO TO 100
000274       30 CONTINUE
000277       40 CONTINUE
000301       50 CONTINUE
000303       60 CONTINUE
000306       80 CONTINUE
000310          CALL EXIT
000311      100 ICOUNT = 0
000312          IF(NPAGE.LE.9999) FMT(2) = DIGIT4
000317          IF(NPAGE.LE.999) FMT(2) = DIGIT3
000323          IF(NPAGE.LE.99) FMT(2) = DIGIT2
000327          IF(NPAGE.LE.9) FMT(2) = DIGIT1
000333          WRITE(3,FMT) NPAGE
000341          NPAGE = NPAGE + 1
000343          WRITE(3,3003)
000346          WRITE(3,3000)
000351          WRITE(3,3010)
000354          ICOUNT = ICOUNT + 5
000356          LINE = 0
000357          GO TO 30
000357     3010 FORMAT(1H0)
000357     3000 FORMAT(1H0,7X,2HKI,6X,2HKF,6X,2HII,6X,1HL,6X,2HIF,7X,9H(CLEB)**2,
               110X,4HCLEB)
000357     3001 FORMAT(1H0,5X,I3,2H/2,3X,I3,2H/2,3X,I3,2H/2,3X,I3,4X,I3,2H/2,3X,
               1F12.8,5X,F12.8)
000357     3002 FORMAT(1H ,36X,I3,2H/2,3X,F12.8,5X,F12.8)
000357     3003 FORMAT(1H )
000357          END
```

Fig. 2

```
              FUNCTION CLEB(X)
000535        DIMENSION X(6)
000535        DIMENSION FACT(101)
000535        DATA EPS/10.E-5/
000535        DATA(FACT(I),I=1,30)/
             X 1.0000000000000E+00, 1.0000000000000E+00,
             X 1.4142135623734E+00, 2.4494897427837E+00,
             X 4.8989794855685E+00, 1.0954451150109E+01,
             X 2.6832815730008E+01, 7.0992957397224E+01,
             X 2.0079840636830E+02, 6.0239521910488E+02,
             X 1.9049409439676E+03, 6.3179743589259E+03,
             X 2.1886105181153E+04, 7.8911474450845E+04,
             X 2.9525970128021E+05, 1.1435359058643E+06,
             X 4.5741436234582E+06, 1.8859677306263E+07,
             X 8.0014834285495E+07, 3.4877657663456E+08,
             X 1.5597762686289E+09, 7.1477928181875E+09,
             X 3.3526120082376E+10, 1.6078562354542E+11,
             X 7.8768547132295E+11, 3.9384273566145E+12,
             X 2.0082117944242E+13, 1.0434974580904E+14,
             X 5.5216695356705E+14, 2.9735100460114E+15/
000535        DATA(FACT(I),I=31,60)/
             X 1.6286535271686E+16, 9.0679869067864E+16,
             X 5.1296280268011E+17, 2.9467469553193E+18,
             X 1.7182339742861E+19, 1.0165209277908E+20,
             X 6.0991255667435E+20, 3.7099532464959E+21,
             X 2.2869687743061E+22, 1.4282115417938E+23,
             X 9.0328029052168E+23, 5.7838159214356E+24,
             X 3.7483411234140E+25, 2.4579516484904E+26,
             X 1.6304206741755E+27, 1.0937194378131E+28,
             X 7.4179661362065E+28, 5.0855013667297E+29,
             X 3.5233386996539E+30, 2.4663370897572E+31,
             X 1.7439636808587E+32, 1.2454391808831E+33,
             X 8.9809896542910E+33, 6.5387591597708E+34,
             X 4.9046196742539E+35, 3.5632012798664E+36,
             X 2.6664556771113E+37, 2.0131298911718E+38,
             X 1.5331540468144E+39, 1.1776379687513E+40/
000535        DATA(FACT(I),I=61,90)/
             X 9.1219444816679E+40, 7.1244663931547E+41,
             X 5.6098104477824E+42, 4.4526490041116E+43,
             X 3.5621192032893E+44, 2.8718723147084E+45,
             X 2.3331200977901E+46, 1.9097411059554E+47,
             X 1.5748128594871E+48, 1.3081378078240E+49,
             X 1.0944666130046E+50, 9.2221396029145E+50,
             X 7.8252449403204E+51, 6.6858922078091E+52,
             X 5.7514219471935E+53, 4.9408775141508E+54,
             X 4.3422283468652E+55, 3.8102899105672E+56,
             X 3.3651569321494E+57, 2.9910169057701E+58,
             X 2.6752448492622E+59, 2.4077221643361E+60,
             X 2.1802851503668E+61, 1.9863343046009E+62,
             X 1.8205054612618E+63, 1.6784231034848E+64,
             X 1.5565055535741E+65, 1.4518117296403E+66,
             X 1.3619201234003E+67, 1.2848328747528E+68/
000535        DATA(FACT(I),I=91,101)/
             X 1.2188996890630E+69, 1.1627560052041E+70,
             X 1.1152763807350E+71, 1.0755335917789E+72,
             X 1.0427685057677E+73, 1.0163650174951E+74,
             X 9.9583027411083E+74, 9.8077907644317E+75,
             X 9.7092175011827E+76, 9.6605494378090E+77,
             X 9.6605494377984E+78/
000535        CLEB=0.
000536        NA=2.*X(1)+EPS
000541        NB=2.*X(2)+EPS
000543        NC=2.*X(3)+EPS
000546        ND=SIGN(ABS(2.*X(4))+EPS,X(4))
000553        NE=SIGN(ABS(2.*X(5))+EPS,X(5))
000561        NF=-SIGN(ABS(2.*X(6))+EPS,X(6))
000567        IF(ABS(X(4)+X(5)-X(6)) .GT. EPS) RETURN
000576        L3=X(2)+X(5)+EPS
000602        L8=X(1)+X(4)+EPS
000605        L10=X(3)-X(6)+EPS
000610        IF(ABS(X(2)+X(5)-FLOAT(L3)) .GT. EPS) RETURN
000617        IF(ABS(X(1)+X(4)-FLOAT(L8)).GT. EPS) RETURN
000626        IF(ABS(X(3)-X(6)-FLOAT(L10)) .GT. EPS) RETURN
000636        L0=L3+L8+L10
000641        IF(L0 .GT. 99) GO TO 2
000644        IF(IABS(ND) .GT. NA  .OR.
             X   IABS(NE) .GT. NB  .OR.
             X     IABS(NF) .GT. NC) RETURN
000663        L1=L0-NC
000665        L2=L8-ND
000667        L9=L3-NF
000671        L11=L10-NF
000673        L6=L0-NB
000675        L7=L0-NA
000677        L4=L6-L2
000701        L5=L7-L3
000703        L20=NC+1
000705        KMIN=MAX0(0,-L4,-L5)
000712        KMAX=MIN0(L1,L2,L3)
000720        IF(KMAX .LT. KMIN)RETURN
000724        C01=FACT(L1+1)*FACT(L6+1)*FACT(L7+1)*FACT(L8+1)
             X      *FACT(L2+1)*FACT(L3+1)
             X*FACT(L9+1)*FACT(L10+1)*FACT(L11+1)/FACT(L0+2)
             X  *FACT(L20+1)/FACT(L20)
000747        SGN=1.
000751        DO 1 K=KMIN,KMAX
000763        L12=L1-K+1
000765        L13=L2-K+1
000767        L14=L3-K+1
000770        L15=L4+K+1
000771        L16=L5+K+1
000773        DEN=FACT(K+1)*FACT(L12)*FACT(L13)*FACT(L14)*FACT(L15)*FACT(L16)
001002        CLEB=CLEB+SGN*C01/DEN**2
001006        SGN=-SGN
001006      1 CONTINUE
001016        IF(MOD(KMIN,2) .NE. 0) CLEB=-CLEB
001022        RETURN
001024      2 CLEB=0./0.
001026        RETURN
001027        END
```

Fig. 2

To calculate the coefficients for positive values of KF, the following changes should be made.

```
DO 80 I4 = 1,11,2           becomes      DO 80 I4 = 1,31,2
PMAX     = (6. - X(4))* 2.  becomes      PMAX     = (X(4) + 6.)* 2.
X(6)     = -FLOAT(I6)/2.    becomes      X(6)     = FLOAT(I6)/2.
```

The variable NPAGE which is set in a data statement gives the initial page number. This enables one to calculate the four tables successively and keep consecutive page numbers.

The statements [PRINT 1 / 1 FORMAT(6H1*OVF*)] suppress the automatic skip to a new page on the printer.

For calculating the coefficients with integral arguments and negative KF, the lines from 000126 through 000224 should be replaced by the following sequence.

```
000126          DO 80 I4 = 0,6
000127          X(4) = FLOAT(I4)
000130          PMAX = (6. - X(4))
000132          KMAX = IFIX(PMAX)
000133          DO 60 I6 = 1,KMAX
000135          X(6) = -FLOAT(I6)
000136          X(5) = X(6) - X(4)
000140          DO 50 I1 = I4,I6
000142          X(1) = FLOAT(I1)
000143          DO 40 I2 = 0,6
000145          LINE = 0
000146          X(2) = FLOAT(I2)
000147          IF(ABS(X(5)).GT.X(2)) GO TO 40
000154          JMIN = ABS(X(1) - X(2))
000157          JMAX = ABS(X(1) + X(2))
000162          KMIN = ABS(X(6))
000164          IF(JMIN.LT.KMIN) JMIN = KMIN
000166          DO 30 I3 = JMIN,JMAX
000170          X(3) = FLOAT(I3)
000171          Y = CLEB(X)
000174          IF(ABS(Y).EQ.0) Y = CUT
000177          Z = Y**2
000201          LINE = LINE + 1
000202          DO 10 J = 1,6
000207       10 W(J) = X(J)
```

Fig. 3

For positive KF and integral arguments make the following substitutions.

```
DO 80 I4 = 0,6          becomes     DO 80 I4 = 0,16
PMAX     = 6. - X(4)    becomes     PMAX     = X(4) + 6.
DO 60 I6 = 1,KMAX       becomes     DO 60 I6 = 0,KMAX
X(6)     = -FLOAT(I6)   becomes     X(6)     = FLOAT(I6)
```

The subroutine CLEB was written by Marjory Simmons of the Math and Computing division at LRL Berkeley.

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