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KINEMATICS OF NUCLEAR REACTIONS CALCULATED WITH THE IBM-704 COMPUTER

B. D. Williams

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ELECTRONUCLEAR RESEARCH DIVISION

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INTRODUCTION

The program to be described makes it possible to use the IBM-704 computer to calculate certain kinematic quantities for any nonrelativistic reaction of the form

$$i + t \longrightarrow o + r \ .$$

The target particle, t, is assumed to be at rest.

The following are computed for each product particle as a function of center-of-mass angle: laboratory angle, solid angle transformation, laboratory energy, reciprocal of velocity, and magnetic rigidity times atomic charge. Because this code puts out so much data for a small amount of input, care must be exercised in the choice of parameters; otherwise, one will be flooded with sheets and sheets of results.

This program was developed at the request of M. L. Halbert and A. Zucker of the Electronuclear Research Division, ORNL. These calculations can of course be readily performed by hand, but it is usually more convenient and far less expensive to have them computed by machine.

This report is an expanded version of ORNL report CF-58-9-43.

INPUT

The input data are listed in Table 1. One of the product particles is arbitrarily called the "observed" particle, o, while the other is called the "residual" particle, r. These designations are used merely to distinguish the two products. In coincidence experiments both products are detected, and the semantic distinction between "observed" and "residual" loses its significance.

OUTPUT

The quantities listed in Table 2 are calculated and printed out as a function of the parameter θ_{cm}. To identify each problem the program prints out a two-row heading. The first row may be anything the user wishes. The second row consists of Q, E, all mass numbers, and A_o (defined below).

As a check, the machine computes a number proportional to the longitudinal momentum before and after the reaction. It prints a 1 if the results agree within 0.1%; otherwise it prints a zero.

A number of the form −111.11 indicates the computer cannot calculate the value correctly.

The results for $\theta_{cm} = 0°$ are correct only if $A_o = 1$; otherwise they should be ignored. The accuracy of the program at exactly 90° and 180° is questionable.

A sample output sheet for inelastic scattering of N^{14} by C^{12} to the 2.31-Mev excited state of N^{14} is included as Fig. 1.

Table 1. Input Data

Quantity	Definition	Units	Decimals
Q	Energy released by reaction	Mev	2
E	Incident laboratory kinetic energy	Mev	2
M_t	Mass number of target		2
M_o	Mass number of "observed" product		2
M_r	Mass number of "residual" product		2
$\Delta\theta_{cm}$	Angle interval	Degrees	2
N	Number of angles desired; $N \geqq 1$		0
$\theta_{cm}(1)$	Starting angle; $\theta_{cm}(1) \geqq 0$	Degrees	2

Table 2. Output Data

Quantity	Definition	Units	Range	Decimals
θ_{cm}	Center-of-mass angle of particle o	Degrees	0° to 180°	2
θ_o	Laboratory angle of particle o	Degrees	0° to 180°	2
θ_r	Laboratory angle of particle r	Degrees	0° to −180°	2
$d\omega_o/d\omega_{cm}$	Ratio of laboratory solid angle to center-of-mass solid angle for o		−999 to +999	5
$d\omega_r/d\omega_{cm}$	Ratio of laboratory solid angle to center-of-mass solid angle for r		−999 to +999	5
E_o	Laboratory kinematic energy of particle o	Mev	0 to 999	3
E_r	Laboratory kinematic energy of particle r	Mev	0 to 999	3
$1/V_o$	Reciprocal of particle o laboratory velocity	Millimicroseconds/meter	0 to 9999	2
$1/V_r$	Reciprocal of particle r laboratory velocity	Millimicroseconds/meter	0 to 9999	2
$(H\rho z)_o$	Magnetic rigidity times atomic charge for o	Kiloguass-inches	0 to 9999	2
$(H\rho z)_r$	Magnetic rigidity times atomic charge for r	Kilogauss-inches	0 to 9999	2
Check	Conservation of longitudinal momentum		0 or 1	

FORMULAS

The following formulas are used for the calculations. Items (1), (2), (5), (6), and (11) follow directly from conservation of energy and momentum. The quantity A_o (or A_r) is the ratio of the speed of the center of mass in the laboratory system to the speed of particle o (or particle r) in the center-of-mass system. Formulas (3) and (4) make use of the relation $d\omega = 2\pi \sin\theta\, d\theta$ plus (1) and (2). The other items were obtained simply by substituting into well-known formulas appropriate factors for the units desired:

$$\left.\begin{aligned} \tan\theta_o &= \frac{\sin\theta_{cm}}{\cos\theta_{cm} + A_o} \\ A_o &= +\left\{\frac{(M_o + M_r - M_t)M_o}{M_t M_r} \times \right. \\ &\quad \left. \times \frac{1}{1 + (Q/E)\,[(M_o + M_r)/M_t]}\right\}^{1/2} \end{aligned}\right\} \quad (1)$$

$$\left.\begin{aligned} \tan\theta_r &= \frac{\sin\theta_{cm}}{\cos\theta_{cm} - A_r} \\ A_r &= \frac{M_r}{M_o} A_o \end{aligned}\right\} \quad (2)$$

$$\frac{d\omega_o}{d\omega_{cm}} = \frac{\sin^3\theta_o}{\sin^3\theta_{cm}} (A_o \cos\theta_{cm} + 1) \quad (3)$$

$$\frac{d\omega_r}{d\omega_{cm}} = \frac{\sin^3\theta_r}{\sin^3\theta_{cm}} (A_r \cos\theta_{cm} - 1) \quad (4)$$

$$E_o = \frac{E + Q}{(M_o \sin^2\theta_o / M_r \sin^2\theta_r) + 1} \quad (5)$$

$$E_r = E + Q - E_o \quad (6)$$

M L HALBERT CASE 1 8-5-58 N(14) C(12) INELASTIC SCATTERING

Q = -2.31 E = 27.90 M(T) = 12.00 M(0) = 14.00 M(R) = 12.00 M(I) = 14.00 A(0) = 1.2879

ANGLES CM	O	R	DWO/DWCM	DWR/DWCM	E(O)	E(R)	1/V(O)	1/V(R)	H(O)	H(R)	C
0.	0.	-90.00	0.	0.	25.590	0.	53.24	-111.11	1072.67	0.	0
2.00	0.87	-18.47	0.19106	-77.16556	25.521	0.069	53.31	948.61	1071.22	51.60	1
4.00	1.75	-33.26	0.19112	-49.20480	25.498	0.092	53.33	821.87	1070.74	59.56	1
6.00	2.62	-43.70	0.19123	-28.25543	25.460	0.130	53.37	690.85	1069.94	70.85	1
8.00	3.50	-50.77	0.19137	-16.06157	25.406	0.184	53.43	581.74	1068.82	84.14	1
10.00	4.37	-55.56	0.19155	-9.33315	25.338	0.252	53.50	496.40	1067.37	98.60	1
12.00	5.24	-58.83	0.19178	-5.56113	25.254	0.336	53.59	430.16	1065.61	113.79	1
14.00	6.11	-61.09	0.19204	-3.36907	25.155	0.435	53.69	378.21	1063.53	129.42	1
16.00	6.99	-62.64	0.19235	-2.04524	25.042	0.548	53.82	336.78	1061.12	145.34	1
18.00	7.86	-63.68	0.19270	-1.21723	24.914	0.676	53.95	303.19	1058.41	161.44	1
20.00	8.73	-64.35	0.19309	-0.68358	24.771	0.819	54.11	275.50	1055.37	177.67	1
22.00	9.60	-64.74	0.19352	-0.33103	24.614	0.976	54.28	252.35	1052.02	193.96	1
24.00	10.47	-64.92	0.19399	-0.09350	24.443	1.147	54.47	232.75	1048.35	210.30	1
26.00	11.34	-64.93	0.19451	0.06895	24.257	1.333	54.68	215.97	1044.37	226.64	1
28.00	12.20	-64.80	0.19506	0.18118	24.058	1.532	54.90	201.45	1040.07	242.98	1
30.00	13.07	-64.56	0.19566	0.25913	23.846	1.744	55.15	188.77	1035.47	259.29	1
32.00	13.93	-64.23	0.19630	0.31327	23.620	1.970	55.41	177.62	1030.55	275.56	1
34.00	14.80	-63.82	0.19698	0.35062	23.381	2.209	55.69	167.75	1025.33	291.79	1
36.00	15.66	-63.36	0.19771	0.37598	23.129	2.461	56.00	158.95	1019.80	307.95	1
38.00	16.52	-62.84	0.19848	0.39268	22.866	2.724	56.32	151.05	1013.97	324.04	1
40.00	17.38	-62.27	0.19929	0.40310	22.590	3.000	56.66	143.94	1007.83	340.06	1
42.00	18.23	-61.67	0.20014	0.40892	22.302	3.288	57.03	137.50	1001.39	355.98	1
44.00	19.09	-61.03	0.20103	0.41136	22.003	3.587	57.41	131.64	994.65	371.82	1
46.00	19.94	-60.36	0.20197	0.41133	21.693	3.897	57.82	126.30	987.62	387.56	1
48.00	20.79	-59.67	0.20295	0.40947	21.372	4.218	58.25	121.40	980.29	403.19	1
50.00	21.64	-58.95	0.20397	0.40630	21.041	4.549	58.71	116.90	972.68	418.70	1

Fig. 1. Output Sheet for Inelastic Scattering of N^{14} by C^{12}.

$$\frac{1}{V_o} = 71.9741\left(\frac{M_o}{E_o}\right)^{1/2} \tag{7}$$

$$\frac{1}{V_r} = 71.9741\left(\frac{M_r}{E_r}\right)^{1/2} \tag{8}$$

$$(H\rho z)_o = 56.672\,(M_o E_o)^{1/2} \tag{9}$$

$$(H\rho z)_r = 56.672\,(M_r E_r)^{1/2} \tag{10}$$

$$(M_t E)^{1/2} \stackrel{?}{=} (M_o E_o)^{1/2} \cos\theta_o + (M_r E_r)^{1/2} \cos\theta_r \tag{11}$$

PREPARATION OF COMPUTER INPUT

The input is written on standard IBM 80-column data sheets, of which only the first 64 columns and every other row are used. These 64 columns are divided equally into eight fields, providing eight columns for each input number. The first field is reserved for Q, the next for E, then M_t, M_o, M_r, $\Delta\theta$, N, and $\theta(1)$. Each number must be no more than eight digits, counting the decimal point as one digit. If the decimal point is not written in a number, it will be assumed to lie at the right-hand edge of the field reserved for that number. Each row across the page comprises one IBM card and will be one case for output purposes. As many cases as desired may be run off sequentially. An all-zero (or blank) card is placed at the end to stop the program.

It was thought desirable to include a method of changing Q without changing the other quantities. To change only Q, write the next Q in the proper place in the second row following any full row of data; leave the rest of the row blank. As many different Q's may be used as desired. If the results for $Q = 0$ are required, this Q value must be used first. Otherwise the card $Q = 0$ would be a blank and would stop the calculations.

At the beginning, before the first case is written and on the first row of the first data sheet, a row of heading is written. This will be reproduced on the output sheets and serve as an identification. Capital letters and numbers are allowed, plus the following signs:

= . $ ( ) / * − + ,

The first character of this row must be a 1. It will not be printed but is used as a control character.

The heading may be changed any time after the first case. To do this write a nonzero number in the field reserved for M_t, leave the rest of the line blank, and write the new heading on the following line. The line with a nonzero number in M_t and with blanks elsewhere will not affect the M_t used in the calculations.

A sample input data sheet is reproduced as Fig. 2.

TIME ESTIMATE

An estimate of computing time in minutes may be obtained by use of the formula: $t = 1/2 + \Sigma N/200$, where N is the number of angles computed in each case. At a typical charge for computation time a series of problems with $\Delta\theta_{cm} = 2°$ would cost approximately $3 per problem.

PROGRAMMING

The program was written in Fortran and is listed on p 6–8. There are no sense switch tests, and the output is placed on tape 9. Listing of tape 9 is under program control of the off-line printer. Input is on cards following the self-loading program.

650 DATA SHEET

REQUEST 1476 JOB TITLE KINEMATICS WRITTEN BY BDW DATE 8-8-58

Q (1-8)	E (9-16)	M_T (17-24)	M_0 (25-32)	M_R (33-40)	$\Delta\theta$ (41-48)	N (49-56)	$\theta(1)$ (57-64)	(65-72)	(73-80)
1 ML HALBERT		CASE 1	8-5-58	N(14)	C(12)	INELASTIC	SCATTERING		
0	27.9	12	14	12	2.0	91	0.0		
-2.31									
-4.43									
		1							
1 ML HALBERT		CASE 2	8-5-58	N(14)	C(12)	INELASTIC	SCATTERING		
0	24.0	12	14	12	2	91	0		
-2.31									
-4.43									
0		0		0					

WCX-2628 (9-56)

Fig. 2. Input Data Sheet for Inelastic Scattering of N^{14} by C^{12}.

```
1010 FORMAT(72H/
    1                    )
1011 FORMAT(1H1)
1012  READ 1010
1013 FORMAT(0P8F8.0)
1014  READ 1013,(QA1,EI1,AMT1,AMO1,AMR1,DTHE1,
    1SUM1,THEO1)
     IF(EI1)1025,1017,1025
1017 IF(QA1)1022,1018,1022
1018 IF(AMT1)1012,1019,1012
1019  STOP
1022 QA2=QA1
     DTHE1=DTHE2*57.2958
     THEO1=THEO2*57.2958
     GOTO1050
1025 THEO2=THEO1/57.2958
     DTHE2=DTHE1/57.2958
     QA2=QA1
     EI2=EI1
     AMT2=AMT1
     AMO2=AMO1
     AMR2=AMR1
     NUM2=SUM1+0.001
     AMI2=AMO2+AMR2-AMT2
     T1=SINF(THEO2)
     T2=COSF(THEO2)
     T3=SINF(DTHE2)
     T4=COSF(DTHE2)
1050 AO=SQRTF((AMI2*AMO2/(AMT2*AMR2))*(
    1(AMT2*EI2)/((AMT2*EI2)+(QA2*(AMI2+AMT2)))))
     AR=AMR2*AO/AMO2
     WRITEOUTPUTTAPE9,1010
1055 FORMAT(5H0Q = 1F8.2,7H    E = 1F8.2,
    110H    M(T) = 1F8.2,10H    M(O) = 1F8.2,
    210H    M(R) = 1F8.2,10H    M(I) = 1F8.2,
    39H  A(O) = 1F10.4)
     WRITEOUTPUTTAPE9,1055,QA2,EI2,AMT2,
    1AMO2,AMR2,AMI2,AO
1060 FORMAT(16H0          ANGLES)
     WRITEOUTPUTTAPE9,1060
1062 FORMAT(120H    CM        O        R        DWO/DWCM   DWR/DWCM
    1     E(O)       E(R)       1/V(O)     1/V(R)     H(O) H(R)      C)
     WRITEOUTPUTTAPE9,1062
     MAGE=0
     OO=THEO1
     SINC=T1
     COSC=T2
     DO1170J=1,NUM2
     IF(SINC)1068,1073,1068
1068 BAD=COSC+AO
     IF(BAD)1080,1070,1080
1070 O1=1.570796
```

```
      GOTO1083
1073  O2=-1.570796
      O1=0.0
      O3=0.0
      O4=0.0
      O5=EI2+QA2
      GOTO1122
1080  BAD=SINC/BAD
      IFQUOTIENTOVERFLOW1070,1082
1082  O1=ATANF(BAD)
      IF(O1)1201,1083,1083
1201  O1=O1+3.141592
1083  BAD=COSC-AR
      IF(BAD)1084,1086,1084
1084  BAD=SINC/BAD
      IFQUOTIENTOVERFLOW1086,1088
1086  O2=-1.570796
      GOTO1090
1088  O2=ATANF(BAD)
      IF(O2)1090,1202,1202
1202  O2=O2-3.141592
1090  SINO1=SINF(O1)
      COSO1=COSF(O1)
      SINR1=SINF(O2)
      COSR1=COSF(O2)
      SINO2=SINO1*SINO1
      SINO3=SINO2*SINO1
      SINR2=SINR1*SINR1
      SINR3=SINR2*SINR1
      SINC2=SINC*SINC
      SINC3=SINC2*SINC
      O3=SINO3*(AO*COSC+1.0)/SINC3
1102  IFQUOTIENTOVERFLOW1103,1104
1103  O3=-111.111
1104  O4=SINR3*(AR*COSC-1.0)/SINC3
       IFQUOTIENTOVERFLOW1106,1107
1106  O4=-111.111
1107  BAD=1.0+AMO2*SINO2/(AMR2*SINR2)
      IF(BAD)1109,1110,1109
1109  IFQUOTIENTOVERFLOW1110,1120
1110  O5=-111.111
      O6=-111.111
      O7=0.0
      O8=0.0
      O9=-111.111
      O10=-111.111
      GOTO1145
1120  O5=(EI2+QA2)/BAD
      IFQUOTIENTOVERFLOW1110,1122
1122  O6=EI2+QA2-O5
      IF(O5)1124,1124,1130
1124  O5=0.0
```

```
      O9=0.0
1126  O7=-111.111
      GOTO1132
1130  O9=56.672*(SQRTF(AMO2*O5))
1131  O7=71.9741*(SQRTF(AMO2/O5))
      IFQUOTIENTOVERFLOW1126,1132
1132  IF(O6)1133,1133,1140
1133  O6=0.0
      O10=0.0
1135  O8=-111.111
      GOTO1145
1140  O10=56.672*(SQRTF(AMR2*O6))
      O8=71.9741*(SQRTF(AMR2/O6))
      IFQUOTIENTOVERFLOW1135,1145
1145  IF(O5)1150,1150,1146
1146  IF(O6)1150,1150,1148
1148  BAD=(SQRTF(AMI2*EI2)-(SQRTF(AMO2*O5))*
     1COSO1-((SQRTF(AMR2*O6))*COSR1))/SQRTF(AMI2*
     2EI2)
      IF(0.001-ABSF(BAD))1150,1152,1152
1150  MEAN=0
      GOTO1155
1152  MEAN=1
1154  FORMAT(1H01F7.2,2H  1F7.2,2H  1F7.2,3H   1F11.5,
     13H   1F11.5,2H  1F9.3,2H  1F9.3,2H  1F8.2,2H  1F8.2,
     22H  1F8.2,2H  1F8.2,3H   1I1)
1155  MAGE=MAGE+1
      IF(MAGE-26)1172,1172,1157
1157  WRITEOUTPUTTAPE9,1010
      WRITEOUTPUTTAPE9,1055,QA2,EI2,AMT2,
     1AMO2,AMR2,AMI2,AO
      WRITEOUTPUTTAPE9,1060
      WRITEOUTPUTTAPE9,1062
      MAGE=0
1172  O1=O1*57.2958
      O2=O2*57.2958
      WRITEOUTPUTTAPE9,1154,(OO,O1,O2,O3,O4,O5,
     1O6,O7,O8,O9,O10,MEAN)
1163  OO=OO+DTHE1
      BAD=SINC*T4+COSC*T3
      COSC=COSC*T4-SINC*T3
1170  SINC=BAD
      GOTO1014
      END(0,1,0,0,1)
```

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