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KINEMATICS OF NUCLEAR REACTIONS
CALCULATED WITH THE IBM 704 COMPUTER

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Addendum to Kinematics Program

After using the program for a period of time, it became obvious that certain changes would be desirable. They are listed and are in effect at the time of this notice.

- (1) Page 3, line 9

Replace (± 0.0001) with (0.1%).

- (2) Page 8

Insert this paragraph:

The heading may be changed at any time after the first case. To do this write a non-zero number in the column reserved for M_t and leave the rest of that line blank; then write the new heading on the following line. A line with a non-zero number in M_t and the remainder blank is an indicator and does not change any numbers used in the calculations.

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KINEMATICS OF NUCLEAR REACTIONS
CALCULATED
WITH THE IBM 704 COMPUTER

B. D. Williams

Kinematics of Nuclear Reactions Calculated

With the IBM 704 Computer

B. D. Williams

Oak Ridge National Laboratory

1. Introduction

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

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. 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. Problems may be submitted to the K-25 computing center

and results obtained by mail or by a special messenger service.

2. Input

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. $N \geq 1$.		0
$\theta_{cm}(1)$	Starting angle. $\theta_{cm}(1) \geq 0$.	degrees	2

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.

3. Output

After calculating the quantities listed on the next page, the machine writes the results on magnetic tape. The tape is then read by a separate machine and the results are printed out as a function of the parameter, θ_{cm} . To identify each problem the machine 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_0 (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 ± 0.0001 ; otherwise it prints a zero.

A number of the form -111.11 is to be disregarded.

The results for $\theta_{\text{cm}} = 0^\circ$ are correct only if $A_0 = 1$; otherwise they should be ignored. The accuracy of the program at 90° and 180° is uncertain.

A sample output sheet is reproduced, for inelastic scattering of N^{14} by C^{12} to the 2.31-Mev excited state on N^{14} .

OUTPUT DATA

<u>Quantity</u>	<u>Definition</u>	<u>Units</u>	<u>Range</u>	<u>Decimals</u>
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 cm solid angle for "o"		-999 to +999	5
$d\omega_r/d\omega_{cm}$	Ratio of laboratory solid angle to cm 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	milliμsec/meter	0 to 9999	2
$1/V_r$	Reciprocal of particle "r" laboratory velocity	milliμsec/meter	0 to 9999	2
$(H\rho z)_o$	Magnetic rigidity times atomic charge for "o"	kilogauss-inch	0 to 9999	2
$(H\rho z)_r$	Magnetic rigidity times atomic charge for "r"	kilogauss-inch	0 to 9999	2
check	Conservation of longitudinal momentum		0 or 1	

M. L. HALBERT KINEMATICS 8-5-58

 $N^{14}-C^{12}$ inelastic scatt.

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

CM	ANGLES 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	-18.46	0.19106	-77.16600	25.521	0.069	53.31	948.61	1071.23	51.60	1
4.00	1.75	-33.26	0.19112	-49.20566	25.498	0.092	53.33	821.87	1070.74	59.56	1
6.00	2.62	-43.70	0.19123	-28.25623	25.460	0.130	53.37	690.86	1069.94	70.35	1
8.00	3.50	-50.77	0.19137	-16.06216	25.406	0.184	53.43	581.75	1068.82	84.14	1
10.00	4.37	-55.56	0.19155	-9.33355	25.338	0.252	53.50	496.40	1067.37	98.60	1
12.00	5.24	-58.83	0.19178	-5.56141	25.254	0.336	53.59	430.17	1065.61	113.79	1
14.00	6.11	-61.09	0.19204	-3.36926	25.155	0.435	53.69	378.22	1063.53	129.42	1
16.00	6.99	-62.64	0.19235	-2.04537	25.042	0.548	53.82	336.79	1061.13	145.33	1
18.00	7.86	-63.68	0.19270	-1.21733	24.914	0.676	53.95	303.19	1058.41	161.44	1
20.00	8.73	-64.35	0.19309	-0.68365	24.771	0.819	54.11	275.50	1055.37	177.66	1
22.00	9.60	-64.74	0.19352	-0.33109	24.614	0.976	54.28	252.36	1052.02	193.96	1
24.00	10.47	-64.92	0.19399	-0.09354	24.443	1.147	54.47	232.76	1048.35	210.29	1
26.00	11.34	-64.93	0.19451	0.06892	24.257	1.333	54.68	215.97	1044.37	226.64	1
28.00	12.20	-64.80	0.19506	0.18116	24.058	1.532	54.90	201.45	1040.07	242.98	1
30.00	13.07	-64.56	0.19566	0.25912	23.846	1.744	55.15	188.78	1035.47	259.29	1
32.00	13.93	-64.23	0.19630	0.31326	23.620	1.970	55.41	177.63	1030.55	275.56	1
34.00	14.80	-63.82	0.19698	0.35061	23.381	2.209	55.69	167.75	1025.33	291.78	1
36.00	15.66	-63.36	0.19771	0.37597	23.129	2.461	56.00	158.95	1019.80	307.94	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	340.05	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	994.66	371.81	1
46.00	19.94	-60.36	0.20197	0.41133	21.693	3.897	57.82	126.30	987.62	387.55	1
48.00	20.79	-59.67	0.20295	0.40948	21.372	4.218	58.25	121.40	980.30	403.18	1

4. 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.

$$(1) \quad \tan \theta_o = \frac{\sin \theta_{cm}}{\cos \theta_{cm} + A_o}$$

$$A_o = + \left[\frac{(M_o + M_r - M_t) M_o}{M_t M_r} \cdot \frac{1}{1 + \frac{Q}{E} \frac{M_o + M_r}{M_t}} \right]^{\frac{1}{2}}$$

$$(2) \quad \tan \theta_r = \frac{\sin \theta_{cm}}{\cos \theta_{cm} - A_r}$$

$$A_r = \frac{M_r}{M_o} A_o$$

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

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

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

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

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

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

$$(9) \quad (H_{pz})_o = 56.672 (M_o E_o)^{\frac{1}{2}}$$

$$(10) \quad (H_{pz})_r = 56.672 (M_r E_r)^{\frac{1}{2}}$$

$$(11) \quad (M_i E)^{\frac{1}{2}} \stackrel{?}{=} (M_o E_o)^{\frac{1}{2}} \cos \theta_o + (M_r E_r)^{\frac{1}{2}} \cos \theta_r$$

5. 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 sections providing eight columns for each input number. The first section 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 righthand edge of the eight columns 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. A blank card is placed at the end to stop the machine.

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 one desires. 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.

A sample input data sheet is reproduced on the next page. Note that each case was to be run with three different Q's.

650 DATA SHEET

REQUEST 0000 JOB TITLE KINEMATICS CODE CODE WRITTEN BY B. D. WILLIAMS DATE AUG. 8, 1958

Q	E	M _T	M ₀	M _R	Δθ	N	θ(1)		
1-8	9-16	17-24	25-32	33-40	41-48	49-56	57-64	65-72	73-80
1	M. L. HALBERT	KINEMATICS	8-5-58						
	0	27.9	12	14	12	2.00	91	0.00	
	-2.31								
	-4.43								
	0	24.0	12	14	12	2.00	91	0.00	
	-2.31								
	-4.43								
One blank card (end of problem)									

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6. Submission of Problems

When the data sheets have been properly prepared, they are sent to the Production Group, 704 Machine Room, K-1002, K-25, (telephone 8625), along with the sender's name, address, telephone number, and a charge number ("request number") if the 704 has been used previously. The job title will always be "Kinematics Code." All further operations, such as punching of cards, running the problem, and obtaining printed results, are carried out by the Production Group.

An estimate of computing time must also be submitted. Use of the following formula where N is the number of center-of-mass angles computed in each parameter set will give an approximate time in minutes. The program is quite fast.

$$t = 1/2 + \frac{\sum N}{200}$$

7. Computing Cost

At present the charge for computing time is \$5.33/minute. Card-punching and printing of results cost a slight additional amount, usually about 15% of the computing-time charge. A series of problems with $\Delta\theta_{cm} = 4$ deg has been calculated for about \$1.60 per problem.

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