SSCL-N-830

KINREL: A Nuclear Data Code for the SSCL LINAC

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August 1993

*Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

Abstract

To predict the outcomes of nuclear reactions within the Radio Frequency Quadrupole (RFQ) of the SSC linac, a program entitled KINREL* was brought to the SSC from Los Alamos. This program uses relativistic kinematics to determine the Q-value of given reactions. By determining the Q of a reaction, KINREL can predict whether that reaction will occur or not. KINREL tests were run for all elements with natural abundances greater than 0.1 %. For beam energies of 2.5 MeV, 147 of 271 possible (p,n) reactions will occur; data concerning these reactions (resultant nuclei, threshold energies, natural abundances, and cross-sections) is listed in Appendix IV. All of the possible (p,γ) reactions will occur; the table of these reactions is found in Appendix V.

* Directions on using KINREL are found in Appendices I, II, and III.

Introduction

The SSC linac is composed of a Linear Accelerator and a Transfer Line; the Linear Accelerator consists of a cascade of three accelerators [Tooker]. A beam of H- ions from the Ion Source enters the Radio Frequency Quadrupole accelerator (RFQ) at an energy of 0.035 MeV. The RFQ then accelerates the beam to an energy of 2.5 MeV [Cutler]. After leaving the RFQ, the H-beam is accelerated to 70 MeV in the Drift Tube Linac, and then to 600 MeV in the Coupled Cavity Linac.

As the beam passes through the RFQ, technicians monitor its behavior with beam position monitors, toroids, and wire scanners [Funk]. Also, a diagnostic cart will monitor longitudinal and transverse emittances of the beam [Funk] to ensure that the stringent RF field control requirements are fulfilled [Cutler]. At energies near 2.5 MeV, however, protons in the H- beam have enough energy to react with target nuclei in the diagnostic equipment. In this case, we are most interested in (p,n) and (p, γ) type ground-state reactions, where a bombarding proton forces out a neutron or a gamma ray, respectively. The ensuing reactions might not only activate (i.e. make radioactive) the diagnostic equipment by changing the nuclear structure of the atoms in the instrumentation, but prompt radiation from these reactions might also pose a potential safety hazard to the people monitoring that equipment.

For these reasons, the elements used to construct diagnostic equipment for the RFQ must either be shown not to react with protons of energies near 2.5 MeV, or a thorough understanding of those reactions must be demonstrated so that the proper precautions can be taken, in order to protect both the diagnostic equipment and the people that maintain that equipment.

To select "safe" construction elements, a FORTRAN program named KINREL was brought from the Los Alamos Meson Physics Laboratory. Using 2-body relativistic kinematics, KINREL can predict whether a given reaction will occur or not, contingent upon the "Q" of that reaction. Using the information provided by KINREL, linac engineers and physicists can establish proper design and safety standards for the RFQ, as well as for other structures in the SSC linac. The KINREL program has been established in a common-user area on SSCVX1 so that any scientist at the lab may have access to this valuable resource.

Theory

The KINREL program predicts the outcome of a situation in which a target nucleus (like those found in the instruments of the RFQ) is bombarded by an incident moving particle (like a proton from the H- beam, moving at 2.5 MeV). The incident particle (A) enters the nucleus of the target molecule (B) and forces out another particle (C), like a gamma ray or a neutron. A resultant nucleus (D) is produced. This type of reaction, represented by B(A,C)D, can be understood by considering the laws of conservation of energy and conservation of linear momentum. [Meyerhof] Throughout this discussion, the following variables will be used:

M_A, M_B, M_C,M_D: The masses of particles A, B, C, D
V_A, V_B, V_C, V_D: The LAB FRAME velocities of A,B, C, D
V_A', V_B', V_C', V_D': The CENTER-OF-MASS FRAME velocities of particles A, B, C, D
T_A, T_B, T_C, T_D: The LAB FRAME energies of A,B, C, D
T_A', T_B', T_C', T_D': The CENTER-OF-MASS FRAME energies of particles A, B, C, D

Other variables will be defined as needed. For sake of brevity, the theoretical basis for this code will be explained in terms of classical mechanics. KINREL actually uses relativistically correct equations which are too complicated for presentation here.

Figure 1 depicts a simple reaction of the type that KINREL analyzes.

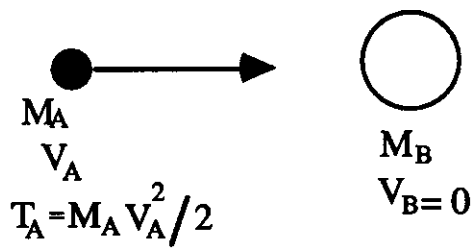

FIGURE 1A: The nuclear reaction in the lab frame, initial situation.

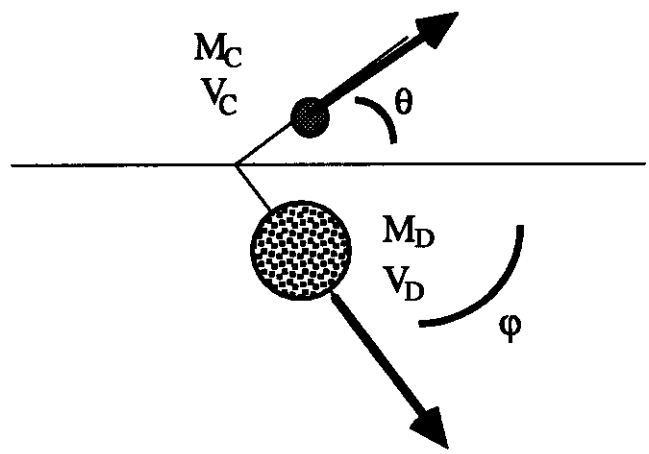

FIGURE 1B: The nuclear reaction in the lab frame, final situation.

A projectile, A, with mass M_A and velocity V_A (in the lab frame), is incident upon a target molecule, B. The kinetic energy (in the lab frame) of particle A is defined as T_A. KINREL calculates and outputs all of these values in the output file. The lab energy T_A is represented by the variable LAB TA; the momentum of particle A is displayed in the field LAB PA. After the reaction, a light particle, C, with velocity V_C and energy T_C, is ejected from the heavy nucleus, D. KINREL also defines the quantities TLC and TLD, the respective lab kinetic energies of resultant particles C and D, and PC, the lab momentum of particle C. (A table explaining all of KINREL's variables and their meanings follows this report in the Appendix.)

A light particle C and a heavy nucleus D will not always be produced. The reaction will only occur if sufficient energy is injected into the system by the moving particle to overcome a certain threshold. This threshold is determined by the Q of the reaction, the amount of energy absorbed or given off in a reaction. For a reaction to occur, the incoming beam energy

must be enough to make Q positive in the center-of-mass frame of reference. To determine if the reaction will occur, that threshold must be calculated, by considering conservation of energy and conservation of linear momentum.

By considering all masses as atomic masses, and discounting negligible binding energies of a few ev [Meyerhof 175], conservation of energy dictates that, in this situation:

$$M_A c^2 + T_A + M_B c^2 = M_C c^2 + T_C + M_D c^2 + T_D \tag{1}$$

The Q-value of a reaction is defined from equation (1) as the difference between the initial and the final kinetic energies, as viewed from either reference frame:

$$\begin{aligned} Q &= T_C + T_D - T_A = M_A c^2 + M_B c^2 - (M_C c^2 + M_D c^2) \\ Q &= T'_C + T'_D - T'_A - T'_B = M_A c^2 + M_B c^2 - (M_C c^2 + M \end{aligned} \tag{2}$$

This Q-value is very important when considering reactions of this sort. If Q is positive, the reaction is **exoergic**, and the reaction can freely occur. If Q is negative, however, if the reaction is **endoergic**, the reaction cannot occur without external stimulation: the bombarding particle must have a kinetic energy greater than Q [Serway Moses Moyer 393]. From equation (2), recognizing that the final kinetic energies T_C+T_D and T_C',+T_D' must be positive, we can say that

$$\begin{aligned} Q + T_A &\geq 0 \\ Q + T'_A + T'_B &\geq 0 \end{aligned} \tag{3}$$

One must note that T_A does not always = $T'_A + T'_B$. To define Q more precisely, we must observe the reaction in the center-of-mass frame of reference. See Figure 2.

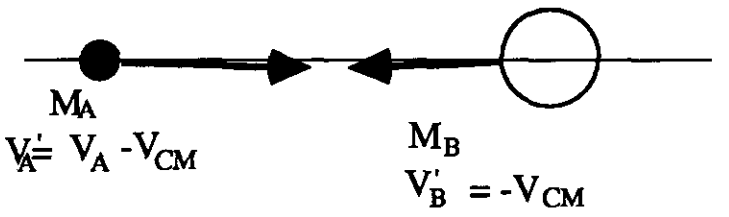

FIGURE 2A: The nuclear reaction in the center-of-mass frame, initial situation.

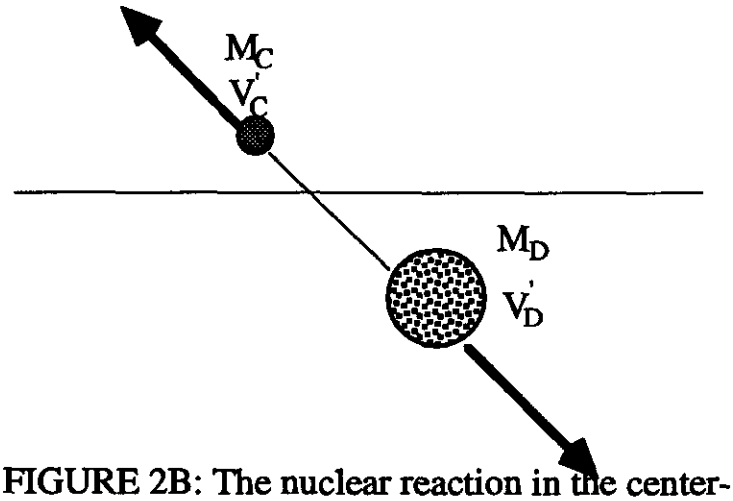

FIGURE 2B: The nuclear reaction in the center-of-mass frame, final situation. Note that the total momentum is zero in this frame: $M_C V'_C = - M_D V'_D$

The kinetic energy of the center-of-mass itself is given by

$$T_{CM} = \frac{1}{2}(M_A + M_B)V^2, \quad V_{CM} = \left(\frac{M_A}{M_A + M_B}\right)V_A \tag{4}$$

where V_{CM} is the speed of the center-of-mass as viewed from the lab frame (found by realizing that total momentum in the center-of-mass frame is zero [Davis]). The TOTAL kinetic energy of the initial particles in the center-of-mass frame, T_o is defined as

$$T_O = T_A - T_{CM}, \quad \text{or} \quad T_O = \frac{1}{2}M_A\left(V_A - V_{CM}\right)^2 + \frac{1}{2}M_B V_{CM}^{\ 2} \tag{5}$$

which simplifies to

$$T_O = \frac{M_B}{M_A + M_B}T_A. \tag{6}$$

Thus, the total energy available for the nuclear reaction is only

$$Q + T_O \tag{7}$$

which is essentially the kinetic energy of the reaction constituents, when viewed in the center-of-mass frame.

$$Q + T_O = \frac{1}{2}M_A\left(V_A - V_{CM}\right)^2 + \frac{1}{2}M_B V_{CM}^{\ 2} \tag{8}$$

Obviously, then, the reaction can only occur if the right-hand side of the equation is positive:

$$Q + T_O \geq 0 \tag{9}$$

This condition can also be expressed, by applying eq. (6), as

$$T_A \geq -Q\frac{\left(M_A + M_B\right)}{M_B} \tag{10}$$

The Q-value for a reaction can also be found by considering conservation of linear momentum. Referring back to Figure 1, looking at the reaction in the lab frame, we can see that

$$\begin{aligned} M_A V_A &= M_D V_D \cos\phi + M_C V_C \cos\theta \\ 0 &= M_D V_D \sin\phi + M_C V_C \sin\theta \end{aligned} \tag{11}$$

Substitution of $MV = \sqrt{2MT}$ gives:

$$\sqrt{M_A T_A} - \sqrt{M_C T_C}\cos\theta = \sqrt{M_D T_D}\cos\phi$$
$$\sqrt{M_C T_C}\sin\theta = \sqrt{M_D T_D}\sin\phi \tag{12}$$

Combining the squares of both equation then produces

$$M_A T_A - 2\sqrt{M_A T_A M_C T_C}\cos\theta + M_C T_C = M_D T_D \tag{13}$$

Finally, by applying equation (2) to eliminate T_D, we arrive at the infamous Q-equation:

$$Q = T_C\left(1 + \frac{M_C}{M_D}\right) - T_A\left(1 - \frac{M_A}{M_D}\right) - \frac{2}{M_D}\sqrt{M_A T_A M_C T_C}\cos\theta \tag{14}$$

As stated earlier, certain reactions will not proceed unless they are boosted past this Q-level with some external energy. This level of energy required is known as the **threshold** energy. KINREL uses the equations and theory, as described above, to calculate the threshold energy for the requested reaction. If the beam energy surpasses the threshold energy, KINREL then calculates lab energies, magnetic bending field values, and other values for the resultant particles C and D, by applying conservation of momentum laws.

Procedure

In the middle of June, work began to make the KINREL program, as found in John McGill's directory, operational. The program came from Los Alamos, and many of the calls in the program referred to programs on the Los Alamos system. After finding all of these calls, and reformatting some statements, the program was nearly operational. When running on SSCVX1, however, KINREL was writing its integers into memory in a format too large for KINREL to understand later. Once this problem was finally diagnosed and solved, KINREL was fully functional and produced satisfactory output. One modification of the output format was attempted, however, because the output table does not fit onto a SSCVX1 screen and must be printed out to be fully viewed in a readable format. However, because of the complicated nesting of loops in the code, reformatting the output in this manner was not feasible. The output can still be read and understood from a terminal screen, but it is most presentable when printed out.

Test cases were run for various (p,n) and (p,gamma) reactions. The ground-state Q-level for all of these reactions corresponded to values found in Serway, Moses, and Moyer's Modern Physics . Threshold values produced by KINREL also corresponded to those given by Brookhaven National Laboratory Nuclear Data Center.

The most significant data output from KINREL this summer concerns the possible (p,n) reactions within the RFQ, as discussed in the Introduction, above. From the *Table of the Nuclides* in C.M. Lederer and V.S. Shirley's *Table of the Isotopes* , all nuclei with a natural abundancy greater than 0.1% were selected. This selection was to insure that all feasible reactions were considered. There were 271 of these nuclei.

Instead of writing a batch driver code that would direct KINREL to run a large group of reactions at once, it was decided to enter each reaction separately. For a batch driver code to function completely, a file of all the requested reactions would have to be created on SSCVX1, and creating the FORTRAN code involved in building a batch driver would have been more complicated than merely typing each reaction into KINREL directly. (When entering a set of reactions into KINREL, one does not need to constantly re-enter the beam energy and requested angles over and over. A user can set the beam energy at the beginning of a KINREL session; that beam energy will apply to all reactions unless one exits, by pressing <CNTRL>-Z three times. A more detailed instruction guide to KINREL follows in the

Appendix.) Also, KINREL had some unexplained problems with certain reactions. With 168Er(p,n) , for example, it could not calculate the ratio of energies for the resultant particles. Minor, inexplicable problems like this only happened with 6 reactions, but after the first one, I wanted to monitor KINREL directly instead of sifting through the entire output file looking for "****", KINREL's signal for errors. *

Seven different batches of (p,n) reactions, of different sizes, ranging from 10 to 94 reactions per batch were run through KINREL for calculations. (I ran seven batches because I stopped after each error message to examine each error closely.) From this input of 271 possible reactions, KINREL produced 119 reactions that could possibly occur with a beam energy of 2.5 MeV. These reactions, along with their threshold energies, percent abundancy, and cross sectional information are listed in Appendix IV.

KINREL also demonstrated, using the same procedure, that, out of the 271 possible (p,γ) reactions, all of them would occur for beam energies of 2.5 MeV. Appendix V contains a table of all the information for these reactions.

* It has since been determined that this error message indicates that the given value is too large to store in the designated memory space.

Conclusion

The nuclides given in Appendix IV should be avoided when constructing any equipment that will be used in the RFQ in the SSC linac. At H- beam energies of 2.500 MeV, these nuclides have been shown to react with the protons on that beam in such a manner that free neutrons are produced, and other potentially radioactive isotopes are formed. These reactions might not only distort the sensitive digital equipment in place in the RFQ, but also might pose a safety hazard to those working in and around the RFQ.

These reactions were predicted with the KINREL (relativistic kinematics) program, which utilizes conservation of energy and linear momentum laws to predict the outcome of proton bombarding situations. This program is available to any SSC employee on the SSCVX1, and should prove very helpful in predicting other reactions.

Acknowledgments

The author would like to thank Wendy Whittenburg for her invaluable assistance in modifying KINREL for use at the SSCL. Cindy Vandersleen's work in establishing KINREL in a common-user area on SSCVX1 is also greatly appreciated, as is Bill Turner's advice and help in navigating the thoroughfares of the VAX.

I also thank Jim Hurd for his direction and assistance throughout the summer.

Follow-Up

Although KINREL is completely operational and can be used constructively at this date, there remains some room for elaboration:

•a batch driver code, consisting of all elements with abundances greater than 0.1%, could be written. This file would be used to run KINREL tests for different beam energies.

•when the beam energy is entered currently, 5 significant figures are required. Some alteration could be made in KINREL so that a space or a comma could delimit beam energies. A user could then enter "2.5,90,90,0" instead of "2.500 90 90 0".

•an option could be added so that KINREL would only print out reaction that do occur rather than all reactions. Because it is sometimes helpful to have information about reactions that do not occur, however, this feature would have to be optional, and would allow the user to select which type of output he or she desires.

•a wild-card particle could be created that would take the place of partice C in the reaction B(A,C)D. KINREL would then check all possible reactions (i.e. (p,n), (p,γ), and (p,d), etc.) and print out the reactions that will occur.

•KINREL's output format could be modified (again, an optional modification) so that it would only output certain information in a table format. VAX files could then be incorporated into Microsoft Word documents easier.

In addition to these computer science tasks, there is also some physics that can be further explored on KINREL:

•in the output of reactions that do occur, some variables, especially "G" and "DOMEGACM," are not understood fully. If these values were understood, SSC physicists might be able to utilize KINREL to a fuller extent. For example, DOMEGACM is known to refer to some facet of the cross-section of a reaction, but is not fully understood in what way that value can be used to find the cross-section.

•a thorough theoretical discussion of the <u>relativistic</u> kinematics utilized by KINREL could be completed, for reference purposes.

Appendix I: Running KINREL

As of August 13, 1993, KINREL has been set up in a common user area on SSCVX1 for the use by all individuals with accounts on the VAX. To run KINREL from a VAX account, a user must first copy the input file, KINREL.INP, from the common area into his or her own individual account. This may be accomplished by typing SETUP KINREL to initialize certain logical operators, then KINREL_INIT to copy the input file. After these two commands have been entered, the user only needs to enter KINREL to start the program running. The .INP file needs to be copied only once into the user's home directory.

When KINREL begins, it will first ask the user for the beam energy. In the case of the RFQ in the SSC linac, the maximum beam energy will be 2.5 MeV. Because KINREL reads in the first five digits of this entry field as the beam energy, the user must enter 2.500 instead of merely 2.5. (The program will assume units of MeV.) KINREL also asks for the lab angle for which it is calculating this reaction. For example, if the user wants to see the result of a 2.5 MeV beam incident at 90°, the input statement would read:
2.500 90 90 0
with no commas or extra spaces.

The next KINREL statement asks for the reaction itself. It should be given in the form B(A,C)D, where A is the incoming, incident particle, B is the target nucleus, C is the light product, and D is the heavy product. If the residual nucleus, D, is not given, KINREL will find it. The target nucleus should be specified by its mass number and chemical symbol, in the form 27AL or 12C, but not AL27 or C12. (KINREL is not case-sensitive, so either all upper- or all lower-case letters may be used.) The incident particles also have their own symbolic code:

G=gamma	N=neutron	P=proton	D=deutron
T=triton	H+ = 3He+	H++ = 3He++	A+ = 4He+
A++ = 4He++	PI+ = PI+	PI0 = PI0	PI- = PI-
MU+ = MU+	MU- = MU-	E- = electron	E+ = positron
K+ = kaon+	K0 = kaon	K- = kaon-	

If the user wishes to utilize a special, more exotic particle (either as a target nucleus or as an incident particle), KINREL offers the option of designating an "individualized" particle. If an item in the reaction does not correspond

to an entry in KINREL's mass table or this table of special symbols, or is a "-", KINREL will prompt the user for information on that item. The user will need to know the item's atomic mass (in amu), error in that mass (KeV), atomic #IZ, mass #IA, and charge state IQ. When dealing with the residual nucleus, the user will be prompted for the ground state reaction q-value instead of the atomic mass.

At any point in the program, HELP will display a the help statement included with the program. Also, <CNTRL> - Z will stop the program and return the user to the previous input demand, and eventually back to the VAX itself.

Appendix II: KINREL output

KINREL will output all information about a requested reaction to a file, KINREL.OUT, in the main directory of the user. This file can be viewed by using the TYPE KINREL.OUT command, the EDIT KINREL.OUT command, or by printing a hard copy of the data. Because KINREL creates a table of information for reactions that do occur (for the given beam energy), and because that table is wider than the screen, it is advisable to print a hard copy of the output if the user plans on consulting that data table regularly.

The output begins with a listing of the reaction in the typical B(A,C)D format. Immediately under this listing is the same reaction, with the masses of the particles substituted for the chemical symbols. QA and QC, which appear next, represent the charge state of incident particle A and resultant particle C, respectively. QGND is the ground state Q value for the reaction, as given by the user.

The next section of output lists values for the reaction when viewed from the lab frame of reference:

TA:	kinetic energy of particle A (MeV)
PA:	momentum of particle A (GeV/c)
BRHOA:	BxRHO of particle A [the bending field] (kGcm)
BETAA:	β value of particle A [β=v/c]
1/VA:	inverse velocity of particle A (ns/m)

KINREL then lists similar values for the same reaction, when viewed from the center-of-mass frame of reference:

TA:	kinetic energy of particle A (MeV)
PA:	momentum of particle A (GeV/c)
TB:	kinetic energy of particle B (MeV)
T TOTAL:	total kinetic energy in c.m. frame (MeV)
S:	square of the total relativistic energy (GeV^2)

If the requested reaction does not have enough energy to overcome the reaction threshold, KINREL will simply display a message,

"BEAM ENERGY IS BELOW REACTION THRESHOLD="

and then list what that threshold energy is, for whatever ground state the user requested. ("Ground state" refers to the ground state of the resultant nucleus.) If the beam has given enough energy to the incident particle to

overcome the reaction threshold, KINREL will give more information about the results of the reaction:

EX:	excitation energy of the residual nucleus C
RXN THRESHOLD:	reaction threshold energy
DOMEGACM:	Jacobian which converts $d\sigma/d\Omega$ (differential cross section)to $d\sigma/dt$, where $t = 4 \bullet$momentum transfer
CM: PC:	center of mass momentum of particle C
THLC:	lab angle θ for particle C (deg)
THCMC:	center of mass angle θ for particle C (deg)
TLC:	lab kinetic energy of particle C
BRHOC:	BxRHO for particle C (bending field)
PC:	momentum of particle C (lab frame)
BETAC:	β of particle C (β=v/c)
1/VC:	inverse of velocity of particle C
G:	Jacobian connecting lab frame and CM frame
DTC/DTH:	derivative of TC with respect to THLC
THLD:	lab angle θ of particle D (deg)
TLD:	lab kinetic energy of particle D
Q**2:	square of three-momentum transfer
1/LAMBDA:	inverse wavelength of particle D
-T:	negative of square of four-momentum transfer

Appendix III: FORTRAN code for KINREL

KINREL resides in 7 FORTRAN programs, which are all kept together in a common user area on SSCVX1. These programs are KINREL, KINSUB, LOOKUP, MCALL, SPSET, DVM, and MASSER. Each of these subroutines is integral to the functioning of the entire program, and thus must be kept together. If any change is made to any part of the FORTRAN code in any of these files, the entire system must be rebuilt using the @KINREL.BLD command. This command will re-compile each file, create object codes for each file, and link all the object codes together so that the user must only command KINREL to run for the entire program to work. Do not attempt to compile any part of the code separately: the .BLD file also dictates to KINREL the proper size of integers to use when outputting data. The program will not be able to output without the proper size of integers.

Additionally, KINREL will not run without the KINREL.INP file established in the user's home directory. This matter is discussed more extensively in the beginning of Appendix I.

Appendix IV

(p,n) Reactions that Occur for Beam Energies = 2.500 MeV

Reaction	Rxtion Threshold	Natural Abundance
7Li(p,n)7Be	1.880 MeV	92.5%
9Be(p,n)9B	2.057 MeV	100%
40Ar(p,n)40K	2.345 MeV	99.60%
41K(p,n)41Ca	1.233 MeV	6.73%
48Ca(p,n)48Sc	0.520 MeV	0.187%
49Ti(p,n)49V	1.412 MeV	5.4%
50V(p,n)50Cr	-0.262 MeV	0.250%
51V(p,n)51Cr	1.564 MeV	99.750%
53Cr(p,n)53Mn	1.406 MeV	9.50%
54Cr(p,n)54Mn	2.198 MeV	2.36%
55Mn(p,n)55Fe	1.033 MeV	100%
57Fe(p,n)57Co	1.648 MeV	2.15%
59Co(p,n)59Ni	1.887 MeV	100%
64Ni(p,n)64Cu	2.499 MeV	0.91%
65Cu(p,n)65Zn	2.166 MeV	30.8%
67Zn(p,n)67Ga	1.810 MeV	4.10%
70Zn(p,n)70Ga	1.457 MeV	0.62%
71Ga(p,n)71Ge	1.032 MeV	39.9%
73Ge(p,n)73As	1.137 MeV	7.8%
76Ge(p,n)76As	1.731 MeV	7.8%
75As(p,n)75Se	1.669 MeV	100%
77Se(p,n)77Br	2.175 MeV	7.6%
82Se(p,n)82Br	0.877 MeV	9.2%
79Br(p,n)79Kr	2.444 MeV	50.69%
81Br(p,n)81Kr	1.090 MeV	49.31%
83Kr(p,n)83Rb	1.843 MeV	11.5%
86Kr(p,n)86Rb	1.321 MeV	17.3%
85Rb(p,n)85Sr	1.868 MeV	72.17%
87Rb(p,n)87Sr	0.515 MeV	27.83%
91Zr(p,n)91Nb	2.067 MeV	11.2%
94Zr(p,n)94Nb	1.699 MeV	17.4%
96Zr(p,n)96Nb	0.606 MeV	2.80%

93Nb(p,n)93Mo	1.193 MeV	100%
97Mo(p,n)97Tc	1.139 MeV	9.6%
98Mo(p,n)98Tc	2.398 MeV	24.1%
100Mo(p,n)100Tc	1.129 MeV	9.6%
101Ru(p,n)101Rh	1.350 MeV	17.0%
104Ru(p,n)104Rh	1.951 MeV	18.7%
103Rh(p,n)103Pd	1.349 MeV	100%
105Pd(p,n)105Ag	2.138 MeV	22.2%
110Pd(p,n)110Ag	1.682 MeV	11.8%
107Ag(p,n)107Cd	2.220 MeV	51.83%
109Ag(p,n)109Cd	0.974 Mev	48.17%
111Cd(p,n)111In	1.623 MeV	12.8%
113Cd(p,n)113In	0.490 MeV	12.2%
114Cd(p,n)114In	2.232 MeV	28.7%
116Cd(p,n)116In	1.260 MeV	7.5%
113In(p,n)113Sn	1.824 MeV	4.3%
115In(p,n)115Sn	0.299 MeV	95.7%
119Sn(p,n)119Sb	1.373 MeV	8.6%
124Sn(p,n)124Sb	1.409 MeV	5.64%
121Sb(p,n)121Te	1.797 MeV	57.3%
123Sb(p,n)123Te	0.846 MeV	42.7%
123Te(p,n)123I	2.001 MeV	0.89%
125Te(p,n)125I	0.938 MeV	7.0%
128Te(p,n)128I	2.052 MeV	31.7%
130Te(p,n)130I	1.249 MeV	34.5%
127I(p,n)127Xe	1.458 MeV	100%
129Xe(p,n)129Cs	1.901 MeV	26.4%
131Xe(p,n)131Cs	1.146 MeV	21.2%
134Xe(p,n)134Cs	2.015 MeV	10.4%
136Xe(p,n)136Cs	0.856 MeV	8.9%
133Cs(p,n)133Ba	1.307 MeV	100%
135Ba(p,n)135La	1.834 MeV	6.59%
137Ba(p,n)137La	1.296 MeV	11.2%
139La(p,n)139Ce	1.065 MeV	99.911%
142Ce(p,n)142Pr	1.528 MeV	11.1%
143Nd(p,n)143Pm	1.865 MeV	12.2%
145Nd(p,n)145Pm	0.959 MeV	8.3%
146Nd(p,n)146Pm	2.275 MeV	17.2%
148Nd(p,n)148Pm	1.320 MeV	5.7%
150Nd(p,n)150Pm	0.921 MeV	5.6%

149Sm(p,n)149Eu	1.551 MeV	13.9%
154Sm(p,n)154Eu	1.530 MeV	22.6%
151Eu(p,n)151Gd	1.255 MeV	47.9%
153Eu(p,n)153Gd	1.030 MeV	52.1%
155Gd(p,n)155Tb	1.638 MeV	14.8%
157Gd(p,n)157Tb	0.852 MeV	15.7%
158Gd(p,n)158Tb	2.035 MeV	24.8%
160Gd(p,n)160Tb	0.909 MeV	21.8%
159Tb(p,n)159Dy	1.155 MeV	100%
161Dy(p,n)161Ho	1.609 MeV	19.0%
163Dy(p,n)163Ho	0.796 MeV	24.9%
164Dy(p,n)164Ho	1.772 MeV	28.1%
165Ho(p,n)165Er	1.162 MeV	100%
167Er(p,n)167Tm	1.539 MeV	22.9%
168Er(p,n)168Tm	2.495 MeV	27.1%
170Er(p,n)170Tm	1.107 MeV	14.9%
169Tm(p,n)169Yb	1.700 MeV	100%
171Yb(p,n)171Lu	2.192 MeV	14.4%
173Yb(p,n)173Lu	1.481 MeV	16.2%
174Yb(p,n)174Lu	2.166 MeV	31.6%
176Yb(p,n)176Lu	0.903 MeV	12.6%
176Lu(p,n)176Hf	-0.409 MeV	2.61%
175Lu(p,n)175Hf	1.397 MeV	97.39%
177Hf(p,n)177Ta	1.952 MeV	18.6%
179Hf(p,n)179Ta	0.907 MeV	13.7%
180Hf(p,n)180Ta	1.718 MeV	35.2%
181Ta(p,n)181W	0.975 MeV	99.9877%
183W(p,n)183Re	1.346 MeV	14.3%
184W(p,n)184Re	2.403 MeV	30.7%
186W(p,n)186Re	1.384 MeV	28.6%
185Re(p,n)185Os	1.807 MeV	37.40%
187Re(p,n)187Os	0.784 MeV	62.60%
187Os(p,n)187Ir	2.299 MeV	1.6%
189Os(p,n)189Ir	1.291 MeV	16.1%
192Os(p,n)190Ir	1.843 MeV	41.0%
191Ir(p,n)191Pt	1.792 MeV	37.3%
193Ir(p,n)193Pt	0.848 MeV	62.7%
195Pt(p,n)195Au	1.017 MeV	33.8%
196Pt(p,n)196Au	2.276 MeV	25.3%
198Pt(p,n)198Au	1.092 MeV	7.2%

197Au(p,n)187Hg	1.204 MeV	100%
199Hg(p,n)199Tl	2.196 MeV	16.8%
201Hg(p,n)201Tl	1.200 MeV	13.2%
202Hg(p,n)202Tl	2.030 MeV	29.8%
204Hg(p,n)204Tl	1.132 MeV	6.9%
203Tl(p,n)203Pb	1.773 MeV	29.5%
205Tl(p,n)205Pb	0.830 MeV	70.5%

Information on Natural Abundances is from Lederer and Shirley's *Table of Isotopes* , 7th edn., 1978, as published in Kaye and Laby's *Tables of Physical and Chemical Constants* , 15th edition.

These reactions were shown by KINREL to proceed for a beam energy of 2.500 MeV; the reaction threshold in column 2 was predicted by KINREL according to conservation of energy and linear momentum.

Appendix V

(p,γ) Reactions that occur for Beam Energies = 2.500 MeV

Reaction	Rxtion Threshold	% Abundancy
6Li(p,γ)7Be	-6.543 MeV	7.5%
7Li(p,γ)8Be	-19.711 MeV	92.5%
9Be(p,γ)10B	-7.319 MeV	100%
10B(p,γ)11C	-9.562 MeV	19.8%
11B(p,γ)12C	-17.405 MeV	80.2%
12C(p,γ)13N	-2.107 MeV	98.89%
13C(p,γ)14N	-8.133 MeV	1.11%
14N(p,γ)15O	-7.815 MeV	99.63%
15N(p,γ)16O	-12.937 MeV	0.366%
16O(p,γ)17F	-0.639 MeV	99.76%
18O(p,γ)19F	-8.438 MeV	0.202%
19F(p,γ)20Ne	-13.521 MeV	100%
20Ne(p,γ)21Na	-2.553 MeV	90.51%
21Ne(p,γ)22Na	-7.063 MeV	0.27%
22Ne(p,γ)23Na	-9.194 MeV	9.22%
23Na(p,γ)24Mg	-12.201 MeV	100%
24Mg(p,γ)25Al	-2.365 MeV	78.99%
25Mg(p,γ)26Al	-6.560 MeV	10.00%
26Mg(p,γ)27Al	-8.590 MeV	11.01%
27Al(p,γ)28Si	-12.015 MeV	100%
28Si(p,γ)29P	-2.847 MeV	92.23%
29Si(p,γ)30P	-5.794 MeV	4.67%
30Si(p,γ)31P	-7.542 MeV	3.10%
31P(p,γ)32S	-9.151 MeV	100%
32S(p,γ)33Cl	-2.349 MeV	95.02%
33S(p,γ)34Cl	-5.298 MeV	0.75%
34S(p,γ)35Cl	-6.561 MeV	4.21%
35Cl(p,γ)36Ar	-8.751 MeV	75.77%
37Cl(p,γ)38Ar	-10.520 MeV	24.23%
36Ar(p,γ)37K	-1.909 MeV	0.337%
40Ar(p,γ)41K	-8.004 MeV	99.60%
39K(p,γ)40Ca	-8.544 MeV	93.26%

41K(p,γ)42Ca	-10.520 MeV	6.73%
40Ca(p,γ)41Sc	-1.112 MeV	96.94%
42Ca(p,γ)43Sc	-5.048 MeV	0.647%
43Ca(p,γ)44Sc	-6.850 MeV	0.135%
44Ca(p,γ)45Sc	-7.046 MeV	2.09%
48Ca(p,γ)49Sc	-9.820 MeV	0.187%
45Sc(p,γ)46Ti	-10.583 MeV	100%
46Ti(p,γ)47V	-5.281 MeV	8.2%
47Ti(p,γ)48V	-6.976 MeV	7.4%
48Ti(p,γ)49V	-6.901 MeV	73.7%
49Ti(p,γ)50V	-8.112 MeV	5.4%
50Ti(p,γ)51V	-8.215 MeV	5.2%
50V(p,γ)51Cr	-9.710 MeV	0.250%
51V(p,γ)52Cr	-10.713 MeV	99.750%
50Cr(p,γ)51Mn	-5.380 MeV	4.35%
52Cr(p,γ)53Mn	-6.688 MeV	83.79%
53Cr(p,γ)54Mn	-7.706 MeV	9.50%
54Cr(p,γ)55Mn	-8.217 MeV	2.36%
55Mn(p,γ)56Fe	-10.374 MeV	100%
54Fe(p,γ)55Co	-5.144 MeV	5.8%
56Fe(p,γ)57Co	-6.135 MeV	91.8%
57Fe(p,γ)58Co	-7.075 MeV	2.15%
58Fe(p,γ)59Co	-7.497 MeV	0.295
59Co(p,γ)60Ni	-9.695 MeV	100%
58Ni(p,γ)59Cu	-3.477 MeV	68.3%
59Co(p,γ)60Ni	-9.695 MeV	100%
60Ni(p,γ)61Cu	-4.872 MeV	26.1%
61Ni(p,γ)62Cu	-5.964 MeV	1.13%
62Ni(p,γ)63Cu	-6.224 MeV	3.59%
64Ni(p,γ)65Cu	-7.562 MeV	0.91%
63Cu(p,γ)64Zn	-7.831 MeV	69.2%
65Cu(p,γ)66Zn	-9.057 MeV	30.8%
64Zn(p,γ)65Ga	-4.000 MeV	48.6%
66Zn(p,γ)67Ga	-5.351 MeV	27.9%
67Zn(p,γ)68Ga	-6.595 MeV	4.10%
68Zn(p,γ)69Ga	-6.706 MeV	18.8%
70Zn(p,γ)71Ga	-7.981 MeV	0.62%
69Ga(p,γ)70Ge	-8.650 MeV	60.1%
71Ga(p,γ)72Ge	-9.869 MeV	39.9%
70Ge(p,γ)71As	-4.690 MeV	20.5%

72Ge(p,γ)73As	-5.742 MeV	27.4%
73Ge(p,γ)74As	-6.949 MeV	7.8%
74Ge(p,γ)75As	-6.990 MeV	36.5%
76Ge(p,γ)77As	-8.100 MeV	7.8%
75As(p,γ)76Se	-9.641 MeV	100%
74Se(p,γ)75Br	-4.289 MeV	0.87%
76Se(p,γ)77Br	-5.341 MeV	9.0%
77Se(p,γ)78Br	-6.221 MeV	7.6%
78Se(p,γ)79Br	-6.418 MeV	23.5%
80Se(p,γ)81Br	-7.600 MeV	49.8%
82se(p,γ)83Br	-8.827 MeV	9.2%
79Br(p,γ)80Kr	-9.227 MeV	50.69%
81Br(p,γ)82Kr	-10.029 MeV	49.31%
78Kr(p,γ)79Rb	-4.115 MeV	0.356%
80Kr(p,γ)81Rb	-4.874 MeV	2.27%
82Kr(p,γ)83Rb	-5.716 MeV	11.6%
83Kr(p,γ)84Rb	-7.141 MeV	11.5%
84Kr(p,γ)85Rb	-7.100 MeV	57.0%
86Kr(p,γ)87Rb	-8.721 MeV	17.3%
85Rb(p,γ)86Sr	-9.753 MeV	72.17%
87Rb(p,γ)88Sr	-10.726 MeV	27.83%
84Sr(p,γ)85Y	-4.539 MeV	0.56%
86Sr(p,γ)87Y	-5.831 MeV	9.8%
87Sr(p,γ)88Y	-6.790 MeV	7.0%
88Sr(p,γ)89Y	-7.148 MeV	82.6%
89Y(p,γ)90Zr	-8.461 MeV	100%
90Zr(p,γ)91Nb	-5.216 MeV	51.5%
91Zr(p,γ)92Nb	-5.913 MeV	11.2%
92Zr(p,γ)93Nb	-6.105 MeV	17.1%
94Zr(p,γ)95Nb	-6.887 MeV	17.4%
96Zr(p,γ)97Nb	-7.546 MeV	2.80%
93Nb(p,γ)94Mo	-8.584 MeV	100%
92Mo(p,γ)93Tc	-4.149 MeV	14.8%
94Mo(p,γ)95Tc	-4.944 MeV	9.3%
95Mo(p,γ)96Tc	-5.593 MeV	15.9%
96Mo(p,γ)97Tc	-5.748 MeV	16.7%
97Mo(p,γ)98Tc	-6.334 MeV	9.6%
98Mo(p,γ)99Tc	-6.573 MeV	24.1%
100Mo(p,γ)101Tc	-7.504 MeV	9.6%
96Ru(p,γ)97Rh	-3.806 MeV	5.5%

98Ru(p,γ)99Rh	-4.682 MeV	1.86%
99Ru(p,γ)100Rh	-5.314 MeV	12.7%
100Ru(p,γ)101Rh	-5.524 MeV	12.6%
101Ru(p,γ)102Rh	-6.172 MeV	17.0%
102Ru(p,γ)103Rh	-6.266 MeV	31.6%
104Ru(p,γ)105Rh	-7.110 MeV	18.7%
102Pd(p,γ)103Ag	-4.183 MeV	1.0%
104Pd(p,γ)105Ag	-5.004 MeV	11.0%
105Pd(p,γ)106Ag	-5.860 MeV	22.2%
106Pd(p,γ)107Ag	-5.850 MeV	27.3%
108Pd(p,γ)109Ag	-6.545 MeV	26.7%
110Pd(p,γ)111Ag	-7.239 MeV	11.8%
107Ag(p,γ)108Cd	-8.206 MeV	51.83%
109Ag(p,γ)110Cd	-8.996 MeV	48.17%
106Cd(p,γ)107In	-3.694 MeV	1.25%
108Cd(p,γ)109In	-4.604 MeV	0.89%
110Cd(p,γ)111In	-5.418 MeV	12.5%
111Cd(p,γ)112In	-6.081 MeV	12.8%
112Cd(p,γ)113In	-6.109 MeV	24.1%
113Cd(p,γ)114In	-6.889 MeV	12.2%
114Cd(p,γ)115In	-6.876 MeV	28.7%
116Cd(p,γ)117In	-7.568 MeV	7.5%
113In(p,γ)114Sn	-8.588 MeV	4.3%
115In(p,γ)116Sn	-9.351 MeV	95.7%
112Sn(p,γ)113Sb	-3.088 MeV	1.01%
114Sn(p,γ)115Sb	-3.754 MeV	0.67%
115Sn(p,γ)116Sb	-4.320 MeV	0.38%
116Sn(p,γ)117Sb	-4.446 MeV	14.8%
117Sn(p,γ)118Sb	-4.891 MeV	7.75%
118Sn(p,γ)119Sb	-5.186 MeV	24.3%
119Sn(p,γ)120Sb	-5.689 MeV	8.6%
120Sn(p,γ)121Sb	-5.833 MeV	32.4%
122Sn(p,γ)123Sb	-6.627 MeV	4.56%
124Sn(p,γ)125Sb	-7.382 MeV	5.64%
121Sb(p,γ)122Te	-8.070 MeV	57.3%
123Sb(p,γ)124Te	-8.654 MeV	42.7%
122Te(p,γ)123I	-4.986 MeV	2.5%
123Te(p,γ)124I	-5.526 MeV	0.89%
124Te(p,γ)125I	-5.700 MeV	4.6%
125Te(p,γ)126I	-6.226 MeV	7.0%

126Te(p,γ)127I	-6.255 MeV	18.7%
128Te(p,γ)129I	-6.857 MeV	31.7%
130Te(p,γ)131I	-7.444 MeV	34.5%
127I(p,γ)128Xe	-8.232 MeV	100%
128Xe(p,γ)129Cs	-5.059 MeV	1.92%
129Xe(p,γ)130Cs	-5.495 MeV	26.4%
130Xe(p,γ)131Cs	-5.510 MeV	4.1%
131Xe(p,γ)132Cs	-6.101 MeV	21.2%
132Xe(p,γ)133Cs	-6.144 MeV	26.9%
134Xe(p,γ)135Cs	-6.876 MeV	10.4%
136Xe(p,γ)137Cs	-7.482 MeV	8.9%

130Ba(p,γ)131La	-3.781 MeV	0.106%
132Ba(p,γ)133La	-4.543 MeV	0.101%
134Ba(p,γ)135La	-5.193 MeV	2.42%
135Ba(p,γ)136La	-5.492 MeV	6.59%
136Ba(p,γ)137La	-5.657 MeV	7.85%
137Ba(p,γ)138La	-6.080 MeV	11.2%
138Ba(p,γ)139La	-6.246 MeV	71.7%
139La(p,γ)140Ce	-8.204 MeV	99.911%
136Ce(p,γ)137Pr	-4.138 MeV	0.190%
138Ce(p,γ)139Pr	-4.585 MeV	0.254%
140Ce(p,γ)141Pr	-5.265 MeV	88.5%
142Ce(p,γ)143Pr	-5.882 MeV	11.1%
141Pr(p,γ)142Nd	-7.277 MeV	100%
142Nd(p,γ)143Pm	-4.305 MeV	27.2%
143Nd(p,γ)144Pm	-4.692 MeV	12.2%
145Nd(p,γ)146Pm	-5.343 MeV	8.3%
146Nd(p,γ)147Pm	-5.451 MeV	17.2%
148Nd(p,γ)149Pm	-5.995 MeV	5.7%

150Nd(p,γ)151Pm	-7.039 MeV	5.6%
144Sm(p,γ)145Eu	-3.284 MeV	3.1%
147Sm(p,γ)148Eu	-4.287 MeV	15.1%
148Sm(p,γ)149Eu	-4.362 MeV	11.3%
149Sm(p,γ)150Eu	-4.923 MeV	13.9%
150Sm(p,γ)151Eu	-4.918 MeV	7.4%
152Sm(p,γ)153Eu	-5.926 MeV	26.6%
154Sm(p,γ)155Eu	-6.700 MeV	22.6%
151Eu(p,γ)152Gd	-7.400 MeV	47.9%

153Eu(p,γ)154Gd	-7.683 MeV	52.1%
152Gd(p,γ)153Tb	-3.934 MeV	0.20%
154Gd(p,γ)155Tb	-4.850 MeV	2.1%
155Gd(p,γ)156Tb	-5.480 MeV	14.8%
156Gd(p,γ)157Tb	-5.558 MeV	20.6%
157Gd(p,γ)158Tb	-5.946 MeV	15.7%
158Gd(p,γ)159Tb	-6.151 MeV	24.8%
160Gd(p,γ)161Tb	-6.843 MeV	21.8%
159Tb(p,γ)160Dy	-7.481 MeV	100%
158Dy(p,γ)159Ho	-4.373 MeV	0.100%
160Dy(p,γ)161Ho	-4.882 MeV	2.3%
161Dy(p,γ)162Ho	-5.276 MeV	19.0%
162Dy(p,γ)163Ho	-5.514 MeV	25.5%
163Dy(p,γ)164Ho	-5.930 MeV	24.9%
164Dy(p,γ)165Ho	-6.266 MeV	28.1%
165Ho(p,γ)166Er	-7.365 MeV	100%
162Er (p,γ)163Tm	-3.730 MeV	0.14%
164Er (p,γ)165Tm	-4.334 MeV	1.56%
166Er (p,γ)167Tm	-4.936 MeV	33.4%
167Er (p,γ)168Tm	-5.323 MeV	22.9%
168Er (p,γ)169Tm	-5.606 MeV	27.1%
170Er (p,γ)171Tm	-6.426 MeV	14.9%
169Tm(p,γ)170Yb	-6.820 MeV	100%
168Yb(p,γ)169Lu	-3.837 MeV	0.135%
170Yb(p,γ)171Lu	-4.464 MeV	3.1%
171Yb(p,γ)172Lu	-4.770 MeV	14.4%
172Yb(p,γ)173Lu	-4.924 MeV	21.9%
173Yb(p,g)174Lu	-5.347 MeV	16.2%
174Yb(p,g)175Lu	-5.537 MeV	31.6%
176Yb(p,g)177Lu	-6.210 MeV	12.6%
175Lu(p,g)176Hf	-6.738 MeV	97.39%
176Lu(p,g)177Hf	-6.826 MeV	2.61%
174Hf (p,g)175Ta	-3.892 MeV	0.16%
176Hf (p,g)177Ta	-4.466 MeV	5.2%
177Hf (p,g)178Ta	-4.959 MeV	18.6%
178Hf (p,g)179Ta	-5.228 MeV	27.1%
179Hf (p,g)180Ta	-5.711 MeV	13.7%
180Hf (p,g)181Ta	-5.968 MeV	35.2%
181Ta(p,g)182W	-7.125 MeV	99.9877%
180W(p,g)181Re	-4.092 MeV	0.13%

182W(p,g)183Re	-4.879 MeV	26.3%
183W(p,g)184Re	-5.050 MeV	14.3%
184W(p,g)185Re	-5.426 MeV	30.7%
186W(p,g)187Re	-6.028 MeV	28.6%
185Re(p,g)186Os	-6.508 MeV	37.40%
187Re(p,g)188Os	-7.248 MeV	62.60%
186Os (p,g)187Ir	-4.033 MeV	1.6%
187Os (p,g)188Ir	-4.397 MeV	1.6%
188Os (p,g)189Ir	-4.663 MeV	13.3%
189Os (p,g)190Ir	-4.984 MeV	16.1%
190Os (p,g)191Ir	-5.315 MeV	26.4%
192Os (p,g)193Ir	-5.969 MeV	41.0%
191Ir (p,g)192Pt	-6.909 MeV	37.3%
193Ir (p,g)194Pt	-7.562 MeV	62.7%
192Pt(p,g)193Au	-4.497 MeV	0.78%
194Pt(p,g)195Au	-5.140 MeV	32.9%
195Pt(p,g)196Au	-5.685 MeV	33.8%
196Pt(p,g)197Au	-5.845 MeV	25.3%
198Pt(p,g)199Au	-6.515 MeV	7.2%
197Au(p,g)198Hg	-7.139 MeV	100%
196Hg(p,g)197Tl	-3.822 MeV	0.15%
198Hg(p,g)199Tl	-4.487 MeV	10.0%
199Hg(p,g)200Tl	-4.816 MeV	16.8%
200Hg(p,g)201Tl	-5.056 MeV	23.1%
201Hg(p,g)202Tl	-5.765 MeV	13.2%
202Hg(p,g)203Tl	-5.730 MeV	29.8%
204Hg(p,g)205Tl	-6.446 MeV	6.9%
203Tl(p,g)204Pb	-6.669 MeV	29.5%
205Tl(p,g)206Pb	-7.291 MeV	70.5%
204Pb(p,g)205Bi	-3.264 MeV	1.42%
206Pb(p,g)207Bi	-3.571 MeV	24.1%
207Pb(p,g)208Bi	-3.736 MeV	22.1%
208Pb(p,g)209Bi	-3.822 MeV	52.3%
209Bi(p,g)210Po	-5.000 MeV	100%

Information on Natural Abundances is from Lederer and Shirley's *Table of Isotopes* , 7th edn., 1978, as published in Kaye and Laby's *Tables of Physical and Chemical Constants* , 15th edition.

These reactions were shown by KINREL to proceed for a beam energy of 2.500 MeV; the reaction threshold in column 2 was predicted by KINREL according to conservation of energy and linear momentum.

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