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TORINO – A SEMICLASSICAL COUPLED CANNEL CODE FOR HEAVY ION REACTIONS

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A program is presented for the study of collisions between heavy-ions. These include elastic, quasielastic, deep-inelastic and fusion processes. For the internal degrees of freedom of the two ions, we choose in TORINO the collective surface modes treated as dumped harmonic oscillators and incorporate the particle transfer as a statistical process. These degrees of freedom are represented by classical variables and their time evolution is followed by solving a system of first order differential equations. The quantal fluctuations of the dynamical variables are taken into account by following with the classical equations of motion the evolution of the system in phase space with an ensemble of initial conditions which reflect the quantal uncertainties present in the initial state.

PROGRAM SUMMARY

Title of program: TORINO

Catalogue number: ABDB

Program obtainable from: CPC Program Library, Queen's University of Belfast, N. Ireland (see application form in this issue)

Computer: VAX 11/780 and 8650

Operating system: VMS 4.6

Programming language used: FORTRAN 77

High speed storage required: 343 Kbytes

No. of bits in a word: 32

Peripherals used: terminal, line printer, plotter

Number of lines in the program: 2427

Keywords: nuclear reactions, heavy ions, low-energy reactions, elastic scattering, deep-inelastic reactions, quasielastic excitation functions, fusion cross sections

Nature of the physical problem
Collisions between two heavy nuclear systems give rise to a wide variety of phenomena. These include elastic, quasielastic, deep-inelastic and fusion processes. The characteristics of these regimes are determined by an interplay between the relative motion of the two ions and the relevant internal degrees of freedom. Calculations of reaction cross sections with TORINO incorporate the explicit coupling to collective surface modes, which are treated as damped harmonic modes. The statistical exchange of nucleons between the reaction partners is also taken into account.

Method of solution
The different degrees of freedom are represented by classical variables whose evolution is followed by solving a system of first order coupled equations. The quantal character of the surface degrees of freedom is taken into account by constructing semiclassical distributions in phase space from a set of initial conditions which are consistent with the ground state wavefunctions of these modes. For the integration of the equations of motion, use is made of the NAG library Mark 11 [1]. Results of the calculations are displayed in tables and plots which are produced by the CERN-library packages HBOOK and HPLOT Version 3 [2].

Typical running time
Refer to table in long write-up.

References
[1] NAG Library, Numerical Algorithm Group, Mayfield House, 256 Banbury Road, Oxford OX2 7DE, UK.
[2] CERN Computer Center Program Library, Program Library Division DD, CERN, CH-1211 Geneva 23, Switzerland.

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LONG WRITE-UP

1. Introduction

During the past few years considerable effort has been devoted to the study of heavy ion reactions. Particular interest has been centered in the essentially "new" kind of phenomenon that was revealed in the early data, that of the deep-inelastic processes. This name has been applied in the context of heavy ion reactions to describe nuclear collisions where the projectile and target conserve approximately their identity while acquiring extreme excitation energies. Different theoretical approaches have been proposed to describe this class of reactions. TORINO is a reaction code which combines the use of statistical concepts (used to account for the exchange of nucleons between the reaction partners) with nuclear structure information (used to describe deformation of the ions through collective surface excitations). By construction, then, it allows for a smooth transition in the description of a variety of processes ranging from the mild quasielastic collisions down to the more violent deep-inelastic events. Although based on a di-nuclear picture the dynamic calculations can even be used to estimate fusion cross sections.

A rather complete description of the theory as well as a series of examples in which this calculation scheme has been applied exist in the literature [1,2]. Thus, we do not intend to give here a detailed account of the formalism. We include, however, a section 2 where the principal variables of the problem are defined and where the equations of motion solved by the code are listed. Section 3 is devoted to a detailed description of the input. Here the different options available to the user are presented. In section 4 the output of the code is explained through a series of examples that cover the main applications of the code. Finally, section 5 gives a short list of diagnostics which may appear under illegal use of the code's options as well as a simple guide to estimate the computation time required for diverse tasks.

2. Formalism

2.1. Definition of the coordinates

The coordinates specifying the relative motion between the two ions are shown in fig. A. Deformation of the fragments is accounted for by introducing collective variables $\alpha_{n\lambda\mu}$, related to their shape by

$$R(\hat{r}) = R_i^0\left[1 + \sum_{n\lambda\mu} \alpha_{\lambda\mu}(i)\, Y^*_{\lambda\mu}(\hat{r})\right],$$

where R_i^0 is the equilibrium radius. The index $i \equiv$ (a, A) indicates projectile and target, respectively, while the label n is used to distinguish modes of the same multipolarity λ but different frequency $\omega_{n\lambda}$. From now on the label n will be omitted to simplify the notation.

The surface degrees of freedom $\alpha_{\lambda\mu}(i)$ are treated as damped harmonic modes. Through the damping mechanism, deformation energy and angular momentum is dissipated incoherently over the nuclear volumes. Additional damping of the relative motion is associated with the exchange of nucleons between the fragments. This process is treated in the proximity approximation [3].

The restoring force $C_\lambda(i)$ and the mass parameter $D_\lambda(i)$ of the harmonic mode are related to its energy and to its strength through

$$\frac{D_\lambda(i)}{\hbar^2} = \frac{(3+\lambda)^2 A_i^2}{8\pi f_i S(i,\lambda)},$$

$$C_\lambda(i) = \left[\hbar\omega_\lambda(i)\right]^2 D_\lambda(i),$$

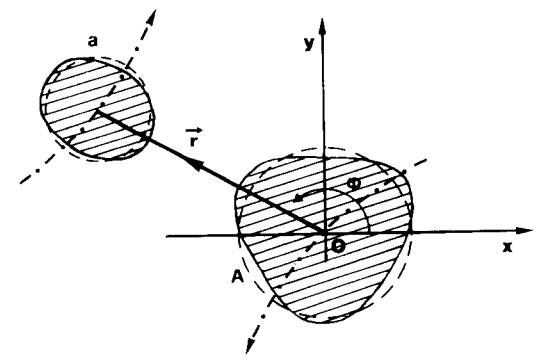


Fig. A.

Table 1
Set of coordinates

	Relative motion	Intrinsic motion
Coordinate	r, ϕ	$\alpha_{\lambda\mu}(i)$ $i \equiv$ (a, A)
Momentum	p_r, p_ϕ	$\Pi_{\lambda\mu}(i)$ $i \equiv$ (a, A)

where $S(i, \lambda)$ indicates the total energy weighted sum rule (EWSR) in MeV spu (spu = single particle unit) for the multipolarity λ and f_i is the fraction of that strength that is exhausted by the mode in question.

Table 1 lists the set of coordinates used in the program, together with their corresponding momenta

$$p_r = m\dot{r}, \quad p_\phi = mr^2\dot{\phi},$$

$$\Pi_{\lambda\mu}(i) = D_\lambda(i)\alpha^*_{\lambda\mu}(i).$$

In these expressions m indicates the reduced mass of the system (a, A). This choice of coordinates is appropriate for trajectories where the initial angular momentum is along the z-axis and which remain in the (x, y)-plane (cf. fig. A).

2.2. Universal response function

During the collision, exchange of particles takes place between the two ions. The response function should thus only represent the average collective strength distribution for nuclei in the neighbourhood of the original projectile and target.

The energy of the modes scales like $A^{-1/3}$ so we introduce a factor α_E so that

$$\hbar\omega_\lambda = \alpha_E A^{-1/3}.$$

Plotting for each multipolarity λ the fraction f_λ of the EWSR exhausted by each state as a function of the parameter α_E, one can see that, for most nuclei, the RPA collective roots concentrate in distinct regions. Taking the centroids of these regions as representative of the states, the *universal response function* shown in table 2 can be constructed. Not very much is known about the systematic of the energy spreading of the states, in particular for the higher multipolarities. Representative values of the width Γ are also listed in table 2. The large numbers used for $\lambda = 4$ and $\lambda = 5$ reflect the fact that for these multipolarities the RPA response is fragmented over several RPA roots.

Table 2
The universal response function

λ	α_E	Γ (MeV)	%EWSR
2^+	0.41	–	20
	1.40	2	80
3^-	0.40	–	25
	2.36	4	50
4^+	1.43	–	25
	3.20	6	60
5^-	0.65	–	12
	2.25	8	50

2.3. The interaction

The interaction potential between the two system is the sum of the Coulomb and the nuclear terms

$$U = U^C + U^N.$$

The Coulomb component U^C consists of the monopole–monopole term and the monopole–multipole terms

$$U^C = \frac{Z_a Z_A e^2}{r} + Z_a e \sum_{\lambda\mu}^{(A)} \frac{3Z_A e (R_A)^\lambda}{2\lambda+1} \frac{Y^*_{\lambda\mu}(\hat{r})}{r^{\lambda+1}} \alpha_{\lambda\mu}(A) + Z_A e \sum_{\lambda\mu}^{(a)} \frac{3Z_a e (R_a)^\lambda}{2\lambda+1} \frac{Y^*_{\lambda\mu}(-\hat{r})}{r^{\lambda+1}} \alpha_{\lambda\mu}(a).$$

For the nuclear interaction the program provides two options: the proximity potential of ref. [4] and the Wood–Saxon empirical potential of ref. [5].

i) Proximity potential. The proximity potential is written in the form

$$U^N(r) = 4\pi\gamma\bar{R}b\Phi(s/b),$$

where γ is the surface tension ($\gamma \approx 1$ MeV/fm^2) and ($b \approx 1$ fm) the surface thickness. The quantity s represents the distance between the surfaces of the two ions. It is approximated to be

$$s = r - \left[R_a(-\hat{r}, \alpha_{\lambda\mu}(a)) + R_A(\hat{r}, \alpha_{\lambda\mu}(A)) + S \right],$$

where R_i are the nuclear radii given above and S is the Sussmann correction [4]. The reduced radius $\overline{R}$ is defined by

$$\overline{R} = \left[\left(C_a^{\parallel} + C_A^{\parallel} \right) \left(C_a^{\perp} + C_A^{\perp} \right) \right]^{-1/2},$$

where the C_i's are the curvatures of the nucleus i in the reaction plane ($\parallel$) and in the perpendicular plane ($\perp$). The equilibrium radii are given by

$$R_i^0 = 1.28 A_i^{1/3} + 0.9 A_i^{-1/3} - 0.76.$$

The function Φ is parametrized as follows

$$\Phi(\xi) = \begin{cases} -3.437 \exp(-\xi/0.75), \\ \quad \xi \geq 1.5, \\ -0.5(\xi - 2.54)^2 - 0.085(\xi - 2.54)^3, \\ \quad \xi \leq 1.5. \end{cases}$$

ii) Wood–Saxon empirical potential. This potential as been obtained with a best fit analysis of existing elastic scattering data. A built in parametrisation is of the form

$$U^N(r) = \frac{-V_0}{1 + \exp[(r - R)/a]},$$

where

$$V_0 = 16\pi a \overline{R}, \quad a = 0.63.$$

At equilibrium the quantity R is given by

$$R = R_a^0 + R_A^0 - 0.29$$

with

$$R_i^0 = 1.233 A_i^{1/3} - 0.978 A_i^{-1/3}.$$

In addition to these two internally generated forms of the nuclear potential an externally given Wood–Saxon function can also be entered.

2.4. Damping of relative motion due to mass transfer

The damping effect in the relative motion due to the exchange of mass between the ions is taken into account by a frictional force. This force is given in the proximity approximation [3] by

$$\boldsymbol{F} = -4\pi n_0 \overline{R} b \left(\boldsymbol{u}_n + \tfrac{1}{2} \boldsymbol{u}_t \right) \Psi(s/b),$$

where $\boldsymbol{u}_n$ and $\boldsymbol{u}_t$ are the radial and tangential components of the relative velocity of the two nuclear surfaces at the point of contact and the function Ψ is parametrized as follows

$$\Psi(\xi) = \begin{cases} 1.4 - \xi, \quad \xi \leq -0.4, \\ 1.6 - 0.6\xi - 0.57 \sin\left(\dfrac{\xi + 0.4}{1.14} \right), \\ \quad -0.4 \leq \xi \geq 3.2, \\ 0, \quad \xi \geq 3.2. \end{cases}$$

The velocity $\boldsymbol{u}$ is evaluated at each instant of time in terms of the relative velocity, the nuclear radii and the rotational frequencies of the two ions and, eventually, in terms also of the deformation variables. It can be written as

$$\begin{aligned} \boldsymbol{u} &= \boldsymbol{v}_a(W) - \boldsymbol{v}_A(W) \\ &= \dot{\boldsymbol{r}} + \boldsymbol{\Omega}_a \times R_a(-\hat{r}) - \boldsymbol{\Omega}_A \times R_A \hat{r} + \boldsymbol{v}^{irr} \end{aligned}$$

with

$$\boldsymbol{v}^{irr} = \boldsymbol{v}_a^{irr} - \boldsymbol{v}_A^{irr}.$$

The angular velocity $\boldsymbol{\Omega}_i$ is calculated from the intrinsic angular momentum $\boldsymbol{I}_i$ using the rigid moment of inertia of nucleus i. With $\boldsymbol{v}_i^{irr}$ we indicate the velocity of the surface of nucleus i due to the vibrational degrees of freedom. Using the irrotational flow approximation [7] we have:

$$\boldsymbol{v}_i^{irr} = \nabla \left[\sum_{\lambda\mu} \frac{R_0^i}{\lambda} \left(\frac{R_W^i}{R_0^i} \right)^{\lambda} \dot{\alpha}_{\lambda\mu}(i) Y_{\lambda\mu}^*(\theta_W, \phi_W) \right],$$

where the label W is used to indicate that these velocities are evaluated at the window.

2.5. Equations of motion

The codes solves the following system of coupled equations

$$\dot{r} = p_r/m, \qquad \dot{p}_r = \frac{p_\phi^2}{mr^2} - \frac{\partial(U^N + U^C)}{\partial r} + F\dot{r},$$

$$\dot{\phi} = \frac{p_\phi}{mR^2}, \qquad \dot{p}_\phi = -\frac{\partial(U^N + U^C)}{\partial \phi} + M_\phi,$$

$$\dot{\alpha}_{\lambda\mu}(i) = \frac{\Pi^*_{\lambda\mu}(i)}{D_\lambda(i)},$$

$$\dot{\Pi}_{\lambda\mu}(i) = -C_\lambda(i)\alpha^*_{\lambda\mu}(i) - \gamma_\lambda(i)\frac{\Pi_{\lambda\mu}(i)}{D_\lambda(i)} - \frac{\partial(U^N + U^C)}{\partial \alpha_{\lambda\mu}(i)},$$

where M_ϕ stands for the torque associated with the frictional force F. The damping coefficient $\gamma_\lambda(i)$ appearing in the equation for $\Pi_{\lambda\mu}$ is related to the width $\Gamma_\lambda(i)$ of the vibrational mode through the relation

$$\gamma_\lambda(i) = \frac{2}{\hbar}\Gamma_\lambda(i)D_\lambda(i).$$

2.6. Dissipated quantities

The equations of motion written above do not conserve energy and angular momentum because of the presence of dissipative terms. The angular momentum balance can however be written as follows,

$$L_{tot} = p_\phi + L(a) + L(A),$$

$$L(i) = L_{vib}(i) + L_{vib,dis}(i) + L_{trans,dis}(i),$$

where $L_{vib}(i)$ is the angular momentum stored in the surface modes. This can be evaluated from the relations

$$L_{vib}(i) = \sum_\lambda L_{\lambda,vib}(i),$$

$$L_{\lambda,vib}(i) = \sum_\mu \mu\alpha_{\lambda\mu}(i)\Pi_{\lambda\mu}(i).$$

The angular momentum dissipated in each nucleus through the damping of the surface degrees of freedom is evaluated by integrating along the trajectory its rate of change, that is

$$L_{vib,dis}(i) = \int_{-\infty}^{+\infty} dt \sum_\lambda \frac{\gamma_\lambda(i)}{D_\lambda(i)} L_{\lambda,dis}(i).$$

The angular momentum loss in the relative motion due to the dissipative force F is evaluated through

$$L_{trans,dis} = \int_{-\infty}^{+\infty} dt\ (r \times F)_z.$$

This expression provides the total angular momentum loss due to mass transfer. It is divided between the ions according to

$$L_{trans,dis} = L_{trans,dis}(a) + L_{trans,dis}(A),$$

where

$$\dot{L}_{trans,dis}(i) = \frac{R_i(t)}{R_a(t) + R_A(t)}\dot{L}_{trans,dis}(t).$$

In a similar way the energy balance can be written as

$$E_{tot} = E_{rel} + E(a) + E(A) + U^N + U^C,$$

where

$$E_{rel} = \frac{p_r^2}{2m} + \frac{p_\phi^2}{2mr^2},$$

$$E(i) = E_{vib}(i) + E_{trans,dis}(i) + E_{vib,dis}(i),$$

$$E_{vib}(i) = \sum_\lambda E_{\lambda,vib}(i),$$

$$E_{\lambda,vib}(i) = \sum_\mu \frac{1}{2}\left[\frac{|\Pi_{\lambda\mu}(i)|^2}{D_\lambda(i)} + C_\lambda |\alpha_{\lambda\mu}(i)|^2\right],$$

$$E_{vib,dis}(i) = \sum_{\lambda\mu}\int_{-\infty}^{+\infty} dt \frac{\gamma_\lambda(i)}{D_\lambda(i)^2}|\Pi_{\lambda\mu}(i)|^2.$$

The total energy dissipated by the mass transfer is given by

$$E_{trans,dis} = E_{trans,dis}(a) + E_{trans,dis}(A) = \int_{-\infty}^{+\infty} dt\ (r \cdot F).$$

This energy is then divided between the two partners in relation to their masses.

2.7. Fluctuations and zero point motion

The description of the collision process in terms of the average trajectory, would be complete if the fluctuations about the expectation values of the dynamical variables were small. The experimental data, however, show that large fluctuations are present in measured quantities like energy loss, scattering angle, etc.

Inspired by the results of the linear coupling model (cf. ref. [1] and references quoted therein) the fluctuations in the energy loss $E_{\rm loss}$ (excitation energy) can be incorporated in a simple way. Making use of the linear approximation the dispersion around the average energy loss due to the excitation of the surface modes can be written as

$$(\Delta E_{\rm loss})^2_{\rm vib} = \sum_{\lambda} \Big[\langle N_\lambda(\mathrm{a}) \rangle (\hbar\omega_\lambda(\mathrm{a}))^2 + \langle N_\lambda(\mathrm{A}) \rangle (\hbar\omega_\lambda(\mathrm{A}))^2 \Big],$$

where $\langle N_\lambda(i) \rangle$ is the average number of phonons present in the mode λ of the nucleus i, and $\hbar\omega_\lambda$ indicates the corresponding energy of the mode.

Besides the excitation of the surface modes, energy is also dissipated through mass transfer. This is a statistical process, and we can estimate its contribution to the dispersion in energy in terms of the energy loss due to this mechanism $E_{\rm trans.dis}$. The total dispersion in the energy loss is written as

$$(\Delta E)_{\rm loss} = \sqrt{(\Delta E_{\rm loss})^2_{\rm vib} + (\Delta E_{\rm trans.dis})^2}\,.$$

This procedure gives only an idea of the fluctuations present in the excitation energy of the fragments. To take into account the fluctuations in all dynamical variables one follows with the classical equations of motion the evolution of the system in phase space with an ensamble of initial conditions which reflect the quantal uncertainties present in the initial state. Since the relative motion is regarded essentially classical the sampling of initial condition actually covers only the values of the variables $\alpha_{\lambda\mu}(i)$, $\Pi_{\lambda\mu}(i)$. These are given by Gaussian distributions with standard deviations

$$(\Delta\alpha)^2 = \frac{\hbar\omega}{2C}, \quad (\Delta\Pi)^2 = \frac{\hbar\omega D}{2}.$$

2.8. Quasielastic spectra

To construct excitation functions for the quasielastic regime, the code looks for the set of impact parameters which feed a given scattering angle θ. The average occupation number $\langle N_i(\rho) \rangle$ for each mode is given by

$$\langle N_i(\rho) \rangle = E_i(\rho)/\hbar\omega_i,$$

where $E_i(\rho)$ is the excitation energy associated with the mode of energy $\hbar\omega_i$. The probability distribution for having a number ν_i of phonons in the mode is

$$P_{\nu_i} = \frac{\langle N_i(\rho) \rangle^{\nu_i}}{\nu_i!} \exp(-\langle N_i(\rho) \rangle)$$

while the probability for an energy loss E is defined as

$$P(\rho, E) = \sum_{\{\nu_i\}} \delta\Big(E - \sum_i \nu_i \hbar\omega_i\Big) \prod_i P_{\nu_i}(\rho).$$

Here $\{\nu_i\}$ indicates the set of all possible occupation numbers. The double differential cross section is then written as

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}E\,\mathrm{d}\omega} = \sum_{\rho} \frac{\rho\,|\mathrm{d}\rho/\mathrm{d}\theta\,|}{2\pi \sin\theta\,\mathrm{d}E} P(\rho, E) T(\rho),$$

where $T(\rho)$ is a coefficient describing the probability to remain in the initial mass partition (a, A). It is given by

$$T(\rho) = \exp\Big[\frac{2}{\hbar}\int_{-\infty}^{\infty} W_{\rm tr}(r)\,\mathrm{d}t\Big].$$

The function $W_{\rm tr}(r)$ describes the depopulation of the entrance channel due to particle transfer.

3. Input

The information that it is necessary to provide to run the code has been kept to a minimum. Thus, in its simplest form the program can be run supplying very few data records. Of course, this means that quite a few decisions have to be taken by the code itself during execution. These internally generated choices are called *default options*.

It is quite natural to expect that the utilization of the code in specific applications may not be optimal with the default options. Thus, ways to overrule these internal choices have been provided.

Following these remarks we can roughly divide the data records into two groups. There are records that always should be read and other that are only read when a default option is to be overruled. In what follows we shall always indicate one of the records belonging to the second group by means of a diamond (◇).

Record number 1

READ (*) MA,ZA,MB,ZB,ELAB

MA = Mass of the projectile,
ZA = Charge of the projectile,
MB = Mass of the target,
ZB = Charge of the target,
ELAB = Energy of the reaction in the laboratory system.

Record number 2

READ (*) K1,K2,K3,K4,K5,K6,K7,K8,K9,K10

K1 = 0 For average trajectories. The calculations are performed with initial conditions for the surface modes that correspond to the quantal expectation values of the deformation and momentum in the ground state.
= 1 Random initial conditions for the surface modes. The calculations are performed with initial conditions for the surface modes that are generated at random in consistency with the spread in deformation and conjugate momentum corresponding to the ground state. Note that although the initial conditions are provided by a random number generator, the same sequence of numbers would be repeated in another un with identical data records.
= 2 Irreproducible random initial conditions (same as above but generates irreproducible random initial conditions. A call to the clock achieves this result). The advantage of this option becomes obvious if you want to improve the statistics of a given run by adding more trajectories corresponding to the same bombarding conditions.

K2 = 0 Proximity potential of ref. [4] is used for the nuclear ion–ion interaction.
= 1 Empirical potential of ref. [5] is used.
= 2 Externally given Woods–Saxon potential is used. An additional record containing its parameters will be read (see record number 5 (◇)). Note that in this case the depth of the potential is kept constant along the trajectory.

K3 = 0 Surface deformations are taken into account.
= 1 Surface degrees of freedom will be ignored in the actual calculation, even if specified. In this way the nuclei remain spherical throughout the collision.

K4 = 0 The dissipative effect of nucleon exchange between the reacting nuclei is taken into account according to ref. [3].
= 1 The dissipative effect of nucleon exchange between the reacting nuclei ignored. With the choices (K3,K4) = (0,1) or (1,0) one can thus investigate separately the effects of the inelastic and transfer channels. Note, however, that one should not use this type of analysis to draw conclusions concerning the relative importance of these two processes. This is due to the fact that either mechanism strongly affects the dissipation through the other. It follows from these considerations that the choice (K3,K4) = (1,1) can be used to generate elastic deflection functions.

K5 = 1 This generates as special modus operandi which is suited to the study of reaction in the quasielastic regime. Since the contribution to quasielastic events come from a rather narrow range of partial waves close to the rainbow, the program will try to optimize the calculation by selecting those impact parameters. The main objective of this option is to generate the cross sections as a function of energy for a few angles near the rainbow. These are internally chosen. In order to construct absolute cross

section in mb/sr MeV the depopulation in the initial mass partition is taken into account through an absorptive potential $W(r)$ (see ref. [8]). The default values of W_0 are 0, 25, 50 MeV. The angles where the cross section is produced and the values of W_0 can be externally specified (see option keys K7,K8). If the calculation is performed with random initial conditions for the surface modes (K1 = 0) the impact parameter range must be specified externally (see key option K6 = 1).

K6 = 0 Impact parameter range generated internally.

a) For average trajectories (K1 = 0). The calculation will sample the impact parameter range from zero (SMIN) up to a value slightly exceeding the rainbow (SMAX) with a number of trajectories which is specified in record number 3. If this value (NTR) is left zero, the interval for the impact parameter (DS) is set to 0.2 fm.

b) For random initial conditions (K1 = 0). In this case the number of trajectories must be specified. They will be distributed between SMIN and SMAX so that each trajectory carries the same cross section weight. The interval DS is thus a function of S, so that more trajectories are calculated for the larger impact parameters.

= 1 Impact parameter range is externally given. Extra record is read (see record number 6 (◇)).

K7 = 0 Quasielastic spectra angle range generated internally.

= 1 Quasielastic spectra angle range externally given. Extra record is read (see record number 7 (◇)). Note that this key is relevant only if K5 = 1.

K8 = 0 Strength of imaginary potential generated internally.

= 1 Strength of imaginary potential is externally given. Extra record is read (see record number 8 (◇)). Note that this key is relevant only if K5 = 1.

K9 = 0 The relative velocity $\boldsymbol{u}$ is defined in term of the relative velocity and the rotational frequencies of the two ions only.

= 1 An extra term is added to the velocity $\boldsymbol{u}$, representing the velocity flow associated with the deformation degrees of freedom. Applications seem to indicate that more reasonable results are obtained with K9 = 0. This question is still under investigation and therefore an eventual update of the equations of motion may be needed. Examples in section 4 are all calculated setting K9 = 0, an option which at the moment is recommended.

K10 = 0 The output via HPLOT is not produced. This value is recommended if one does not intend to use this facility, as a considerable amount of computing time is saved.

= 1 The output of HPLOT is saved in unit 29.

Record number 3

READ (*) NMA,NMB,NTR

NMA = number of surface modes for the projectile. The sign of this quantity is used to select different possibilities. If NMA < 0 the specification of the modes is externally given. A set of −NMA records, one for each mode, will be read (see set number 4 (◇)). |NMA| should not exceed 12. If NMA = 0 an average set of surface modes will be internally generated, as a function of the projectile mass WMA (cf. section 2). If NMA > 0 a set of NMA modes is added to the average response function generated internally. NMA extra records are read (see set number 4 (◇)). In this case NMA should not exceed 4.

NMB = number of surface modes for the target. The sign of this quantity is used to select different possibilities. If NMB < 0 the specification of the modes is externally given. A set of −NMB records, one for each mode, will be read (see set number 4 (◇)). |NMB| should be exceed 12. If NMB = 0 an average set of surface modes will be internally generated, as a function of the target mass WMB (cf. section 2). If NMB > 0 a set of NMB modes is added to the average response function generated internally.

NMB extra records are read (see set number 4 (◇)). In this case NMB should not exceed 4.

NTR = number of trajectories to be calculated. For average trajectories (K1 = 0), this number is ignored if the range of impact parameters is given with option K6 = 1. In this case NTR will be equal to (SMAX − SMIN)/DS + 1.

Set number 4 (◇)

We call this a *set* because it may contain more than one data record. Actually it must contain |NMA| + |NMB| records. The information for the surface modes is read first for the projectile and then for the target.

READ (*) L(N),E(N),ST(N),G(N)

L(N) = multipolarity of the mode.

E(N) = energy of the mode in MeV.

ST(N) = percent of the energy-weighted sum-rule carried by the mode.

G(N) = width of the mode in MeV. For the low-lying mode (W(N) > 8 MeV) the code sets a width of 0.2 MeV. When the option for random initial condition is selected (K1 = 0) the program automatically sets the width of the modes to zero even if read.

Record number 5 (◇)

READ (*) V0,A0,R0

V0 = absolute value of the depth of the Woods–Saxon ion–ion potential (V0 > 0).

A0 = diffuseness of the ion–ion potential.

R0 = radius parameter (R = R0 * (WMA * * 0.33 + WMB * * 0.33)).

This record is read only if K2 = 2.

Record number 6 (◇)

READ (*) SMIN,SMAX,DS,TSTEP,FLINE

SMIN = lowest value fo the impact parameter S (in fm).

SMAX = highest value of the impact parameter S (in fm). Note that if SMAX = SMIN just one trajectory will be calculated. Only in this case detailed information is printed along the trajectory.

DS = impact parameter step (in fm).

TSTEP = time interval for the printing of information along the trajectory (in $\hbar$ MeV^{-1}). If left zero, the assumed value is $0.4\hbar$ MeV^{-1}.

FLINE = this parameter allows to scale the plots of the nuclear shapes for different printing paper sizes. It should be chosen so that as the nuclei approach each other, they appear as circles in the output. The default value is 41 which correspond to printers with 8 line/in. For printers with 6 line/in one should use FLINE = 31.

This record is read only if K6 = 1.

Record number 7 (◇)

READ (*) TQMIN,TQMAX,DTQ

TQMIN = lowest value of scattering angle in the center of mass where the quasielastic excitation function is calculated (in degrees).

TQMAX = maximum value of the scattering angle in the center of mass where the quasielastic excitation function is calculated (in degrees).

DTQ = scattering angle interval (in degrees).

This record is read if K7 = 1 but it is only relevant when K5 = 1. Distributions of cross section are displayed in histograms of one MeV bins up to 30 MeV of excitation energy.

Record number 8 (◇)

READ (*) WMIN,WMAX,DW

WMIN = lowest value of the imaginary potential used to generate quasielastic cross sections. All values of the imaginary potential should be entered as positive numbers.

WMAX = highest value of the imaginary potential used to generate quasielastic cross sections.

DW = imaginary potential interval (in MeV).

This record is read if K8 = 1 but it is only relevant when K5 = 1.

4. Output

The results of the calculations are collected in a number of tables which are mostly printed at the end of the run. One should then be careful not to underestimate the specified time limit. An orientation on this matter is given in section 5. Several of the calculated quantities are also plotted in the output. Although the quality of figures produced in a standard line printer is not high, it is hoped that this facility will prove convenient to the users.

All the line printer plots are obtained by using the CERN HBOOK Version 3 package. High quality drawings of the same plots, suitable for talks and publications, can also be obtained using the CERN HPLOT Version 3 package. This is done by selecting the option K10 = 1 (cf. record number 2) that saves in the output of HPLOT in 29. This output file has then to be sent to a high resolution graphic terminal.

In order to explain the output we have prepared a series of examples that cover the most standard applications of the code. In each instance we give an overview of the printout, plus a detailed explanation of tables and figures as they appear for the first time.

We also provide a list of error messages that can appear when problems in the data and/or dimension violations are detected. It is possible, however, that protection may not cover some other inconsistencies.

Example 1: Elastic deflection function

The simplest application of the code is to produce the elastic deflection function for a given reaction. This is a fast and inexpensive run that provides a first idea of the range of scattering angles and impact parameters that are relevant for the case. It is always convenient to start the analysis of a reaction by producing the elastic deflection function. This is especially important if one wants to input the impact parameter range.

As explained in the data set, the way to obtain the elastic deflection function is by the combination (K3,K4) = (1,1). In this case the information for the surface modes (either provided or internally generated) is ignored.

Consider the reactions ^{86}Kr + ^{208}Pb at 610 MeV and ^{16}O + ^{208}Pb at 125 MeV. The simplest data sets for these reactions are

```
≫ 86.0 36.0 208.0 82.0 610.0
≫ 0 0 1 1 0 0 0 0 0 0
≫ 0 0 0
```

for the Kr + Pb case, and

```
≫ 16.0 8.0 208.0 82.0 125.0
≫ 0 0 1 1 0 0 0 0 0 0
≫ 0 0 0
```

for O + Pb.

The printouts appear as shown in fig. 1. The first column corresponds to the Kr + Pb reaction while the second is for O + Pb. Since this is the first example we explain all the elements of the output, tables (A) and (B) and figure (C).

(A) This table will always appear in any run of TORINO. It contains a reminder of the input data plus some useful information pertinent to the reaction under study. The blow-up of this table is in fig. 1(A). We trust that the identification of the different quantities is evident. Since in our data NMA = NMB = 0 the table shows the internally generated response function for the two nuclei. These quantities are ignored in the present case. In the box labelled "reaction information" the conversion factor from impact parameter into angular momentum is given. Estimations of the Coulomb barrier and grazing quantities according to ref. [9] are also printed. The impact parameters quoted in the last box give the actual range where the calculation is performed. The code will normally complete the tables up to $S = 16$ fm, assuming elastic Coulomb trajectories. The lower limit can be cut short in the quasielastic option (K5 = 1).

(B) This table collects the results of the calculated trajectories concerning the relative motion. The scattering angle and the final energy are in the center of mass system. Fig. 1(B) allows to identify the different columns. Here the last two

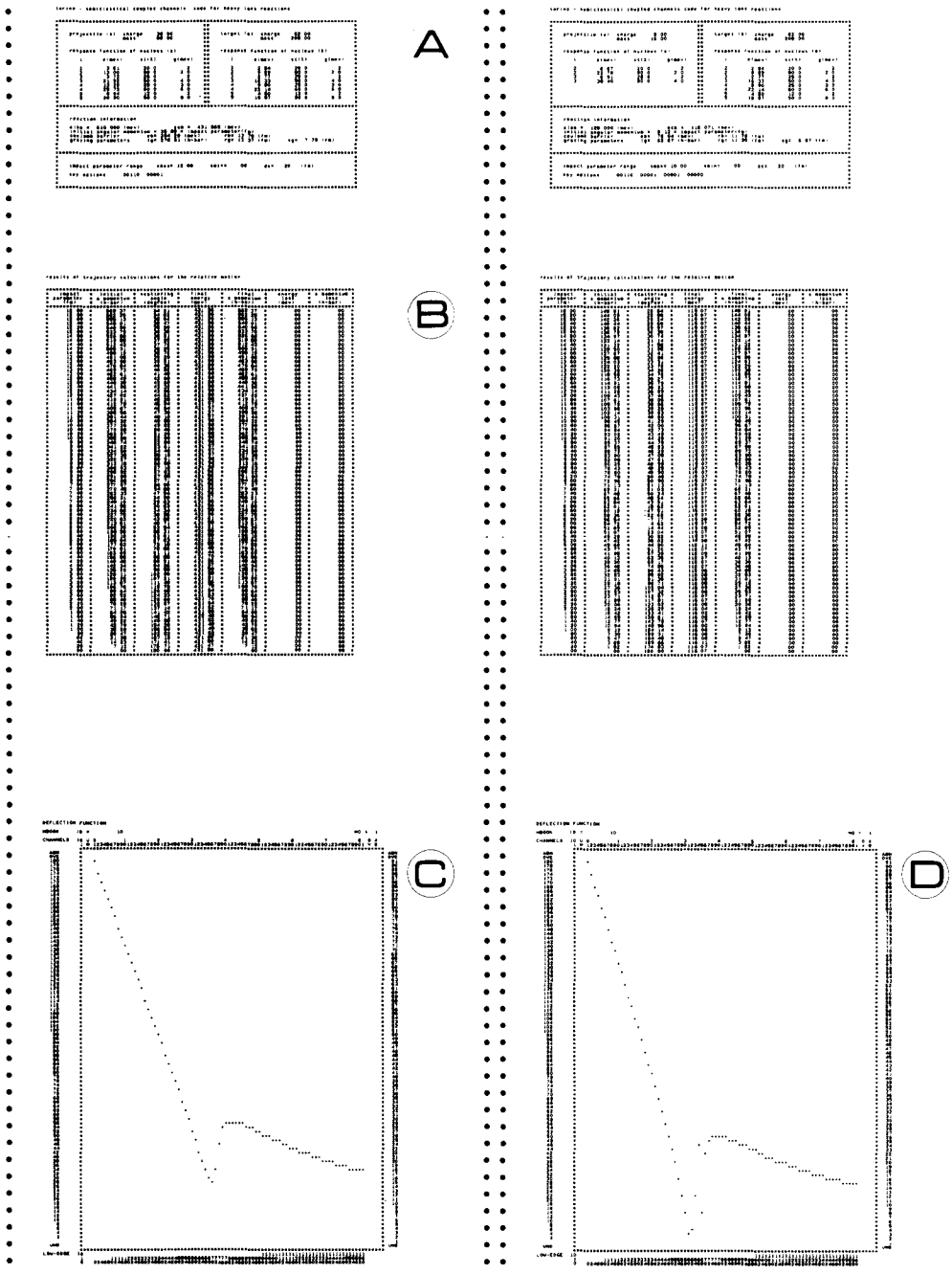


Fig. 1.

```
projectile (a)   charge    36 00          target (b)   charge    82 00
                 mass      86 00                       mass     208 00

response function of nucleus (a)          response function of nucleus (b)
   l       e(mev)      st(%)     g(mev)       l       e(mev)      st(%)     g(mev)
   2        3 81       20 0          2        2        2 84       20 0          2
   2       13 00       80 0        2 0        2        9 69       80 0        2 0
   3        3 72       25 0          2        3        2 77       25 0          2
   3       21 92       50 0        4 0        3       16 33       50 0        4 0
   4       13 28       25 0        3 0        4        9 90       25 0        3 0
   4       29 72       60 0        6 0        4       22 14       60 0        6 0
   5        6 04       12 0        2 0        5        4 50       12 0        2 0
   5       20 90       50 0        8 0        5       15 57       50 0        8 0

reaction information

plab =  610 000 (mev)          ecm =  431 565 (mev)
initial angular momentum = 35 59 * impact parameter(fm)
coulomb barrier       eb= 294 29 (mev)       rb= 13 78 (fm)
grazing parameters    lg= 276 81 (h-bar)     rg= 13 37 (fm)     sg=  7 78 (fm)

impact parameter range    smax= 12 00     smin=    00     ds=   20   (fm)

key options     00110  00001
```

Fig. 1(A).

results of trajectory calculations for the relative motion

impact parameter (fm)	initial a momentum (h-bar)	scattering angle (degree)	final energy (mev)	final a momentum (h-bar)	energy loss (mev)	a momentum loss (h-bar)
16 00	569 37	34 21	431 56	569 37	00	00
15 80	562 25	34 62	431 56	562 25	00	00
15 60	555 13	35 04	431 56	555 13	00	00
15 40	548 01	35 47	431 56	548 01	00	00
15 20	540 90	35 90	431 56	540 90	00	00
15 00	533 78	36 35	431 56	533 78	00	00
14 80	526 66	36 81	431 56	526 66	00	00
14 60	519 55	37 28	431 56	519 55	00	00
14 40	512 43	37 76	431 56	512 43	00	00
14 20	505 31	38 25	431 56	505 31	00	00
14 00	498 19	38 76	431 56	498 19	00	00
13 80	491 08	39 28	431 56	491 08	00	00
13 60	483 96	39 81	431 56	483 96	00	00
13 40	476 84	40 36	431 56	476 84	00	00
13 20	469 73	40 92	431 56	469 73	00	00
13 00	462 61	41 49	431 56	462 61	00	00
12 80	455 49	42 09	431 56	455 49	00	00
12 60	448 38	42 69	431 56	448 38	00	00
12 40	441 26	43 32	431 56	441 26	00	00
12 20	434 14	43 96	431 56	434 14	00	00
12 00	427 02	44 62	431 56	427 02	00	00
11 80	419 91	45 29	431 56	419 91	00	00
11 60	412 79	45 94	431 57	412 79	00	00
11 40	405 67	46 64	431 57	405 67	00	00
11 20	398 56	47 36	431 57	398 56	00	00
11 00	391 44	48 10	431 57	391 44	00	00
10 80	384 32	48 85	431 56	384 32	00	00
10 60	377 20	49 62	431 56	377 20	00	00
10 40	370 09	50 40	431 56	370 09	00	00
10 20	362 97	51 20	431 56	362 97	00	00
10 00	355 85	52 00	431 56	355 85	00	00
9 80	348 74	52 80	431 56	348 74	00	00
9 60	341 62	53 61	431 57	341 62	00	00
9 40	334 50	54 40	431 57	334 50	00	00
9 20	327 38	55 18	431 57	327 38	00	00
9 00	320 27	55 91	431 56	320 27	00	00
8 80	313 15	56 59	431 56	313 15	00	00
8 60	306 03	57 18	431 56	306 03	00	00
8 40	298 92	57 63	431 56	298 92	00	00
8 20	291 80	57 85	431 56	291 80	00	00
8 00	284 68	57 71	431 56	284 68	00	00
7 80	277 57	56 90	431 56	277 57	00	00
7 60	270 45	54 68	431 56	270 45	00	00
7 40	263 33	47 94	431 56	263 33	00	00
7 20	256 21	34 99	431 57	256 21	00	00
7 00	249 10	29 63	431 56	249 10	00	00
6 80	241 98	30 63	431 56	241 98	00	00
6 60	234 86	34 34	431 58	234 86	00	00
6 40	227 75	38 95	431 56	227 75	00	00
6 20	220 63	43 82	431 61	220 63	00	00
6 00	213 51	48 71	431 58	213 51	00	00
5 80	206 39	53 54	431 51	206 39	00	00
5 60	199 28	58 31	431 55	199 28	00	00
5 40	192 16	63 01	431 59	192 16	00	00
5 20	185 04	67 63	431 62	185 04	00	00
5 00	177 93	72 18	431 59	177 93	00	00
4 80	170 81	76 66	431 48	170 81	00	00
4 60	163 69	81 11	431 44	163 69	00	00
4 40	156 58	85 55	431 70	156 58	00	00
4 20	149 46	89 91	431 56	149 46	00	00
4 00	142 34	94 26	431 57	142 34	00	00
3 80	135 22	98 59	431 59	135 22	00	00
3 60	128 11	102 90	431 55	128 11	00	00
3 40	120 99	107 21	431 81	120 99	00	00
3 20	113 87	111 49	431 56	113 87	00	00
3 00	106 76	115 78	431 75	106 76	00	00
2 80	99 64	120 05	431 54	99 64	00	00
2 60	92 52	124 33	431 63	92 52	00	00
2 40	85 40	128 60	431 70	85 40	00	00
2 20	78 29	132 87	431 64	78 29	00	00
2 00	71 17	137 14	431 62	71 17	00	00
1 80	64 05	141 42	431 58	64 05	00	00
1 60	56 94	145 71	432 45	56 94	00	00
1 40	49 82	149 98	431 52	49 82	00	00
1 20	42 70	154 26	431 49	42 70	00	00
1 00	35 59	158 54	431 49	35 59	00	00
80	28 47	162 83	431 62	28 47	00	00
60	21 35	167 12	431 55	21 35	00	00
40	14 23	171 41	431 50	14 23	00	00
20	7 12	175 71	431 47	7 12	00	00
00	00	180 00	431 56	00	00	00

Fig. 1(B).

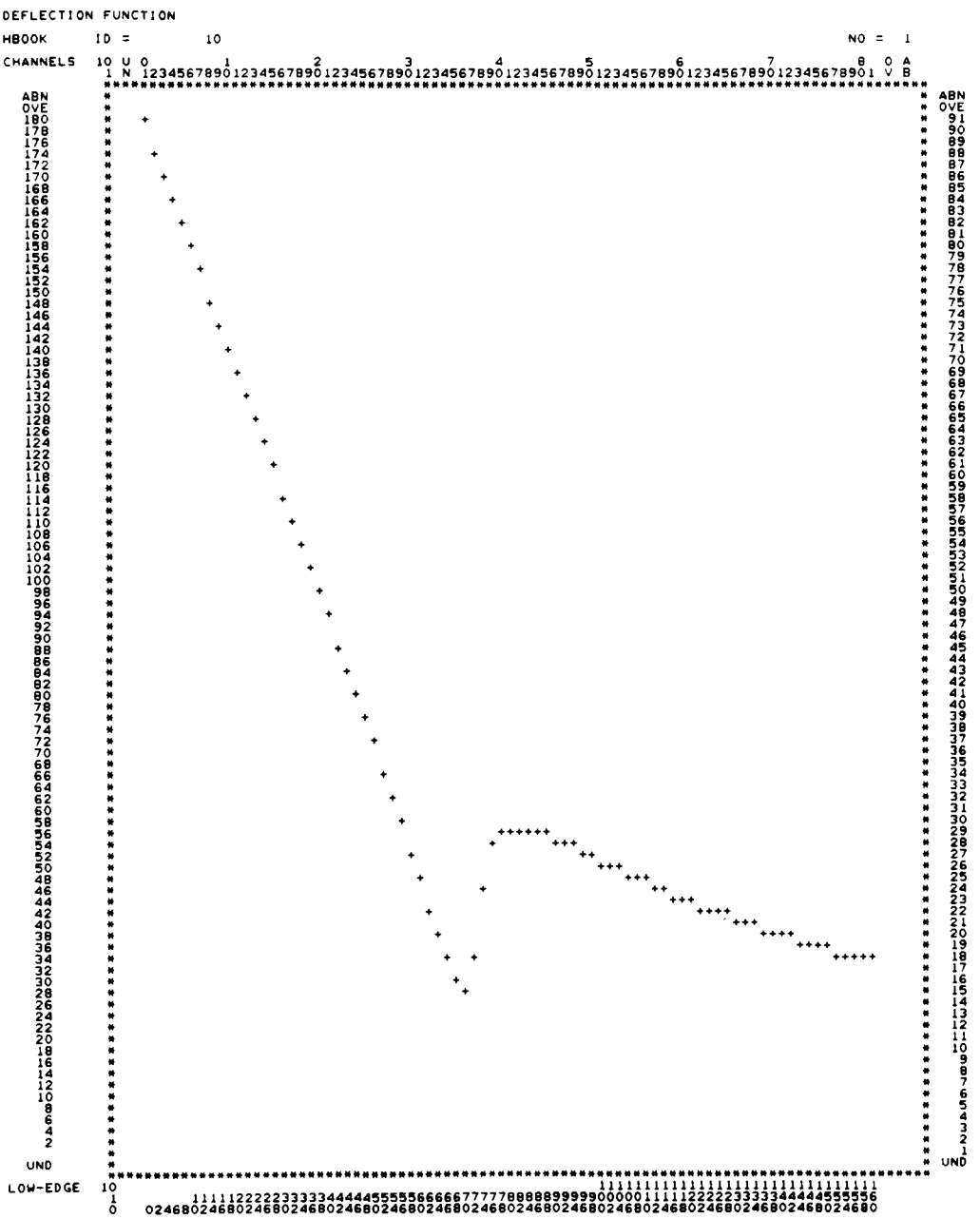


Fig. 1(C).

columns contain zeros, as we have an elastic process for all impact parameters.

(C) This figure displays the content of the first and third columns of table (B). Although the scattering angle is printed there with a negative sign when the trajectory bends past the beam direction, in all plots the scattering angle is displayed with positive sign. An enlargement of this plot is shown in fig. 1(C). The example of O + Pb has been chosen to illustrate this point, as shown

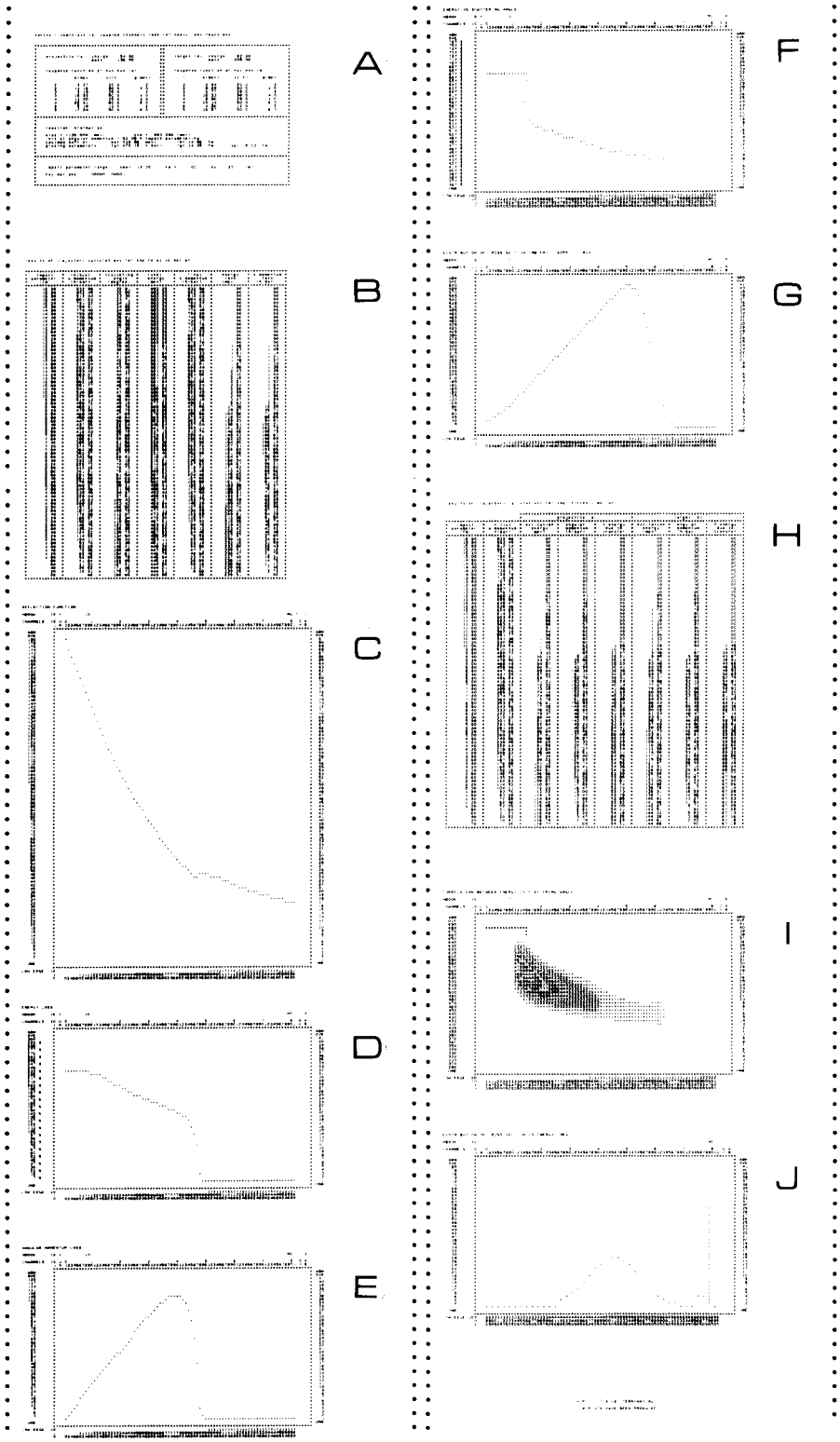


Fig. 2.

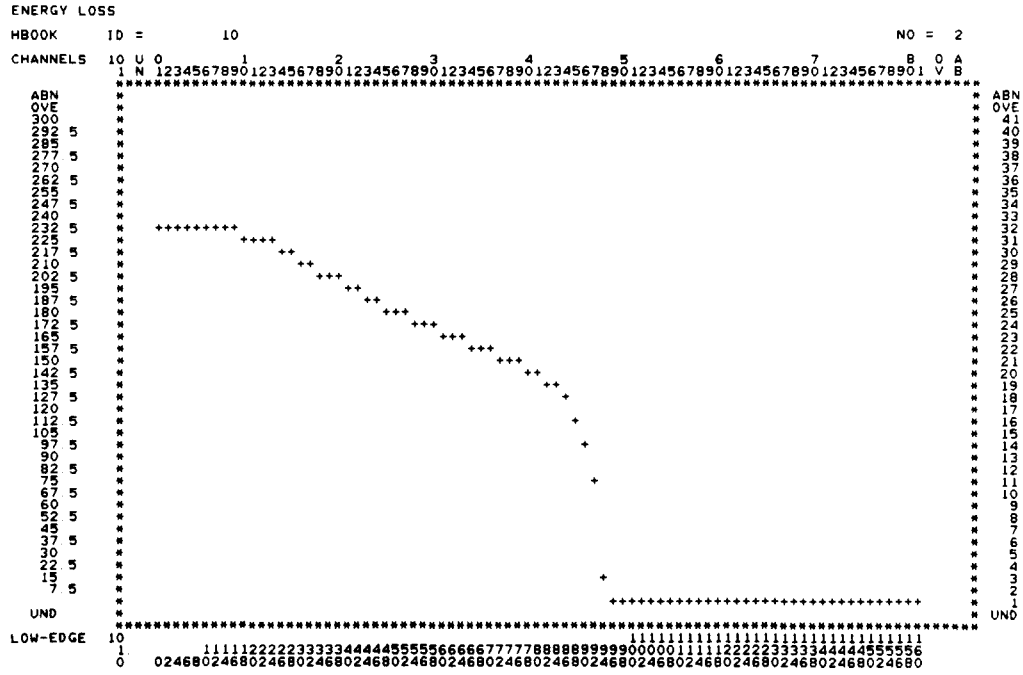

ENERGY LOSS
HBOOK ID = 10
NO = 2
CHANNELS
ABN
OVE
UND
LOW-EDGE

Fig. 2(D).

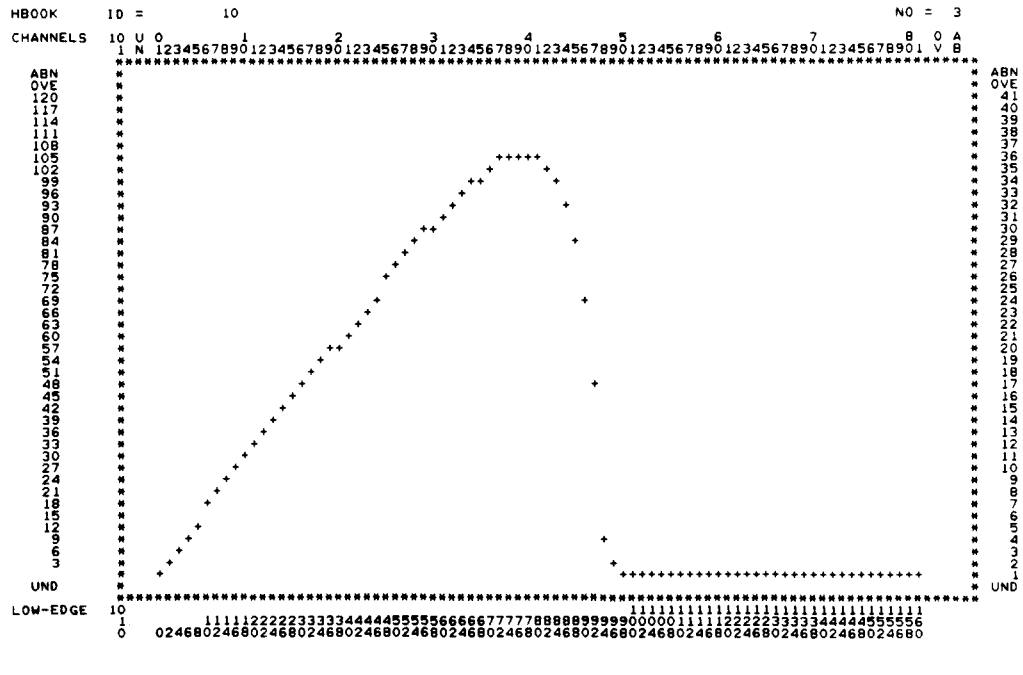

ANGULAR MOMENTUM LOSS
HBOOK ID = 10
NO = 3
CHANNELS
ABN
OVE
UND
LOW-EDGE

Fig. 2(E).

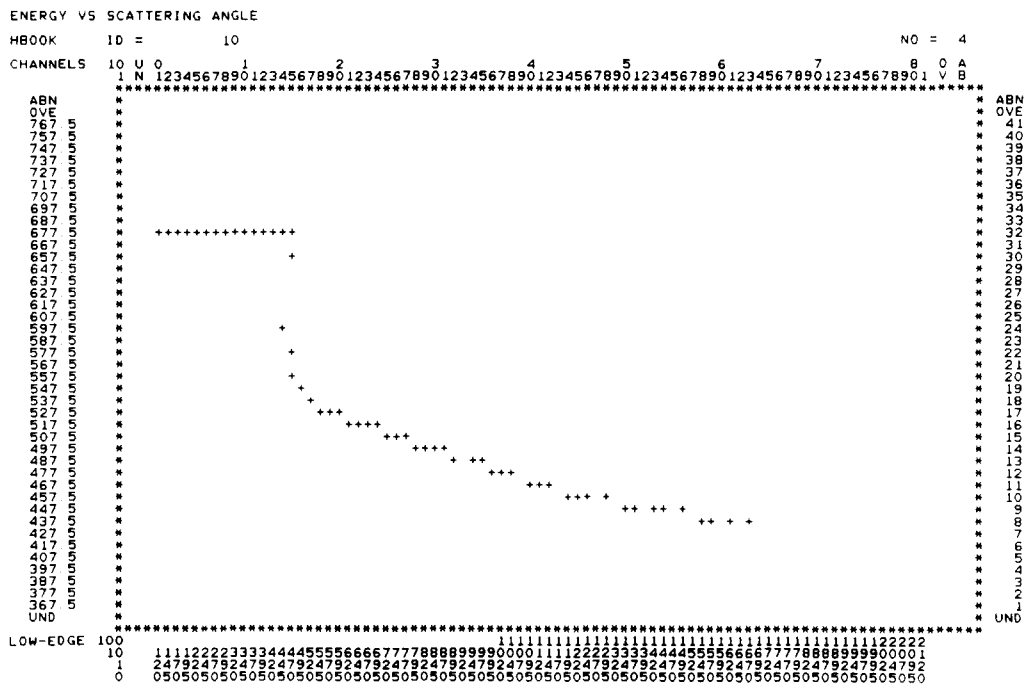

ENERGY VS SCATTERING ANGLE
HBOOK ID = 10
NO = 4
CHANNELS
ABN OVE
UND
LOW-EDGE

Fig. 2(F).

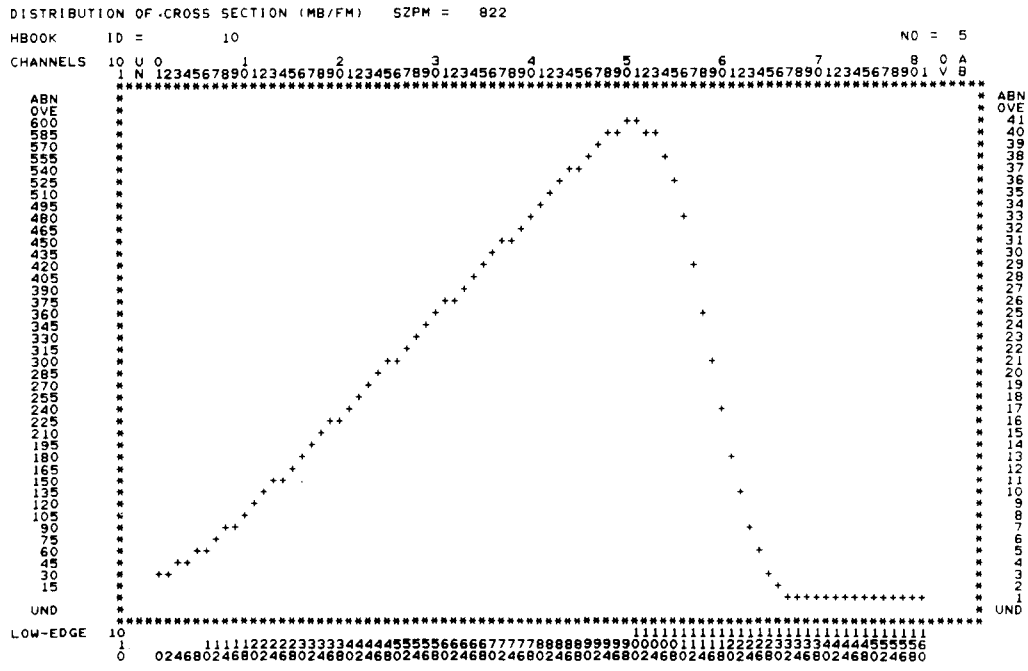

DISTRIBUTION OF CROSS SECTION (MB/FM) SZPM = 822
HBOOK ID = 10
NO = 5
CHANNELS
ABN OVE
UND
LOW-EDGE

Fig. 2(G).

results of trajectory calculations for the intrinsic motion

impact parameter (fm)	initial a momentum (h-bar)	projectile (a) excitation energy (mev)	projectile (a) angular momentum (h-bar)	projectile (a) % energy due to transfer	target (b) excitation energy (mev)	target (b) angular momentum (h-bar)	target (b) % energy due to transfer
16.00	832.86	.00	.00	.00	.00	.00	.00
15.80	822.45	.00	.00	.00	.00	.00	.00
15.60	812.04	.00	.00	.00	.00	.00	.00
15.40	801.63	.00	.00	.00	.00	.00	.00
15.20	791.22	.00	.00	.00	.00	.00	.00
15.00	780.81	.00	.00	.00	.00	.00	.00
14.80	770.40	.00	.00	.00	.00	.00	.00
14.60	759.99	.00	.00	.00	.00	.00	.00
14.40	749.58	.00	.00	.00	.00	.00	.00
14.20	739.17	.00	.00	.00	.00	.00	.00
14.00	728.76	.00	.00	.00	.00	.00	.00
13.80	718.35	.00	.00	.00	.00	.00	.00
13.60	707.93	.00	.00	.00	.00	.00	.00
13.40	697.52	.00	.00	.00	.00	.00	.00
13.20	687.11	.00	.00	.00	.00	.00	.00
13.00	676.70	.00	.00	.00	.00	.00	.00
12.80	666.29	.63	-.41	.00	.85	-.62	.00
12.60	655.88	.67	-.43	.00	.90	-.65	.00
12.40	645.47	.70	-.46	.00	.94	-.69	.00
12.20	635.06	.74	-.48	.00	.99	-.72	.00
12.00	624.65	.78	-.51	.00	1.04	-.76	.00
11.80	614.24	.82	-.53	.00	1.10	-.80	.00
11.60	603.83	.86	-.56	.00	1.15	-.83	.00
11.40	593.42	.85	-.55	.00	1.15	-.84	.00
11.20	583.01	.88	-.57	.00	1.20	-.87	.00
11.00	572.59	.91	-.59	.00	1.24	-.90	.00
10.80	562.18	.94	-.60	.00	1.27	-.92	.00
10.60	551.77	.96	-.60	.00	1.30	-.94	.00
10.40	541.36	1.00	-.60	.00	1.33	-.94	.00
10.20	530.95	1.06	-.60	.01	1.37	-.93	.01
10.00	520.54	1.22	-.62	1.98	1.49	-.94	2.48
9.80	510.13	1.73	-.83	10.78	1.94	-1.11	14.68
9.60	499.72	3.33	-1.65	23.27	3.48	-1.87	34.03
9.40	489.31	10.14	-5.16	28.21	9.95	-5.08	43.87
9.20	478.90	43.27	-25.86	25.14	41.51	-23.85	39.91
9.00	468.49	54.57	-37.15	28.23	53.45	-34.84	43.68
8.80	458.08	60.91	-43.99	30.41	60.55	-41.65	46.28
8.60	447.66	65.04	-48.38	32.38	65.58	-46.13	48.53
8.40	437.25	67.83	-51.14	34.34	69.37	-49.08	50.69
8.20	426.84	69.77	-52.76	36.31	72.37	-50.96	52.79
8.00	416.43	71.21	-53.61	38.24	74.88	-52.12	54.81
7.80	406.02	72.33	-53.88	40.14	77.07	-52.73	56.74
7.60	395.61	73.29	-53.74	41.96	79.09	-52.95	58.53
7.40	385.20	74.14	-53.28	43.69	80.99	-52.86	60.20
7.20	374.79	74.95	-52.57	45.32	82.83	-52.52	61.72
7.00	364.38	75.76	-51.66	46.85	84.63	-51.99	63.09
6.80	353.97	76.61	-50.59	48.24	86.44	-51.29	64.31
6.60	343.56	77.49	-49.40	49.51	88.25	-50.45	65.39
6.40	333.15	78.43	-48.09	50.65	90.09	-49.49	66.33
6.20	322.73	79.37	-46.74	51.69	91.93	-48.47	67.14
6.00	312.32	80.44	-45.28	52.57	93.81	-47.32	67.82
5.80	301.91	81.60	-43.77	53.31	95.73	-46.09	68.38
5.60	291.50	82.84	-42.22	53.92	97.69	-44.80	68.81
5.40	281.09	84.14	-40.64	54.41	99.69	-43.45	69.15
5.20	270.68	85.54	-39.05	54.78	101.73	-42.05	69.38
5.00	260.27	87.01	-37.45	55.05	103.81	-40.61	69.53
4.80	249.86	88.66	-35.87	55.22	105.99	-39.14	69.60
4.60	239.45	90.20	-34.30	55.29	108.12	-37.65	69.58
4.40	229.04	91.92	-32.77	55.29	110.35	-36.15	69.50
4.20	218.63	93.64	-31.27	55.24	112.58	-34.63	69.38
4.00	208.22	95.48	-29.81	55.11	114.90	-33.11	69.20
3.80	197.81	97.34	-28.40	54.95	117.23	-31.59	68.99
3.60	187.39	99.23	-27.03	54.76	119.59	-30.08	68.75
3.40	176.98	101.13	-25.71	54.55	121.99	-28.59	68.49
3.20	166.57	102.99	-24.41	54.35	124.31	-27.10	68.24
3.00	156.16	104.81	-23.13	54.16	126.63	-25.62	68.00
2.80	145.75	106.56	-21.85	53.99	128.88	-24.14	67.77
2.60	135.34	108.20	-20.55	53.85	131.04	-22.67	67.56
2.40	124.93	109.57	-19.25	53.81	133.05	-21.23	67.40
2.20	114.52	110.97	-17.89	53.74	134.98	-19.72	67.26
2.00	104.11	112.23	-16.47	53.70	136.93	-18.17	67.14
1.80	93.70	113.22	-15.00	53.73	138.31	-16.59	67.08
1.60	83.29	114.10	-13.47	53.78	139.71	-14.96	67.04
1.40	72.88	114.84	-11.89	53.85	140.93	-13.27	67.03
1.20	62.46	115.42	-10.27	53.93	141.96	-11.52	67.04
1.00	52.05	115.95	-8.60	54.00	142.87	-9.71	67.05
.80	41.64	116.24	-6.91	54.11	143.51	-7.84	67.09
.60	31.23	116.49	-5.20	54.19	144.03	-5.93	67.13
.40	20.82	116.64	-3.47	54.25	144.39	-3.98	67.16
.20	10.41	116.74	-1.74	54.29	144.61	-2.00	67.18
.00	.00	116.77	.00	54.31	144.68	.00	67.18

Fig. 2(H).

in (D). The left and lower scales correspond to the actual value of the quantities plotted (scattering angle vs. impact parameter in this case). The upper and right "channel" labels may be ignored.

Example 2: Full calculation with average trajectories

A natural extension of the previous example is to consider a case where the coupling of the inelastic and mass transfer degrees of freedom to the relative motion is taken into account. Consider the reaction $^{136}Xe + ^{208}Pb$ at 1150 MeV. The simplest data set is:

```
≫ 136.0 54.0 208.0 82.0 1150.0
≫ 0 0 0 0 0 0 0 0 0 0 0
≫ 0 0 0
```

where we make use of all the default options.

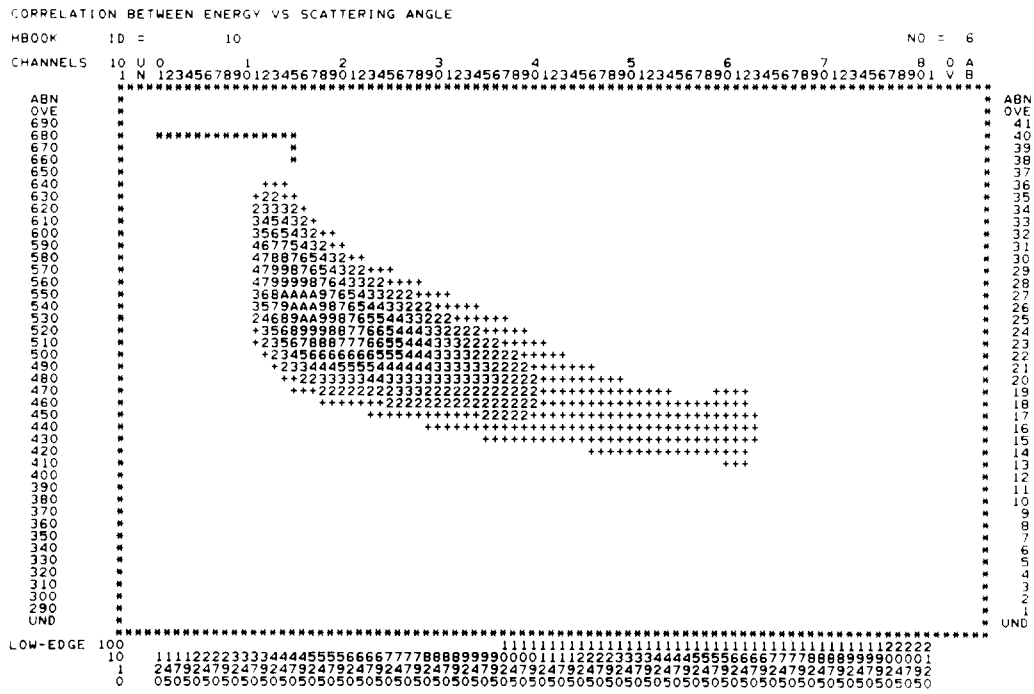

CORRELATION BETWEEN ENERGY VS SCATTERING ANGLE
HBOOK ID = 10
NO = 6
CHANNELS 10 U 0 1 2 3 4 5 6 7 8 0 A
1 N 1234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901 V B
ABN
OVE
UND
LOW-EDGE 100
10
1

Fig. 2(I).

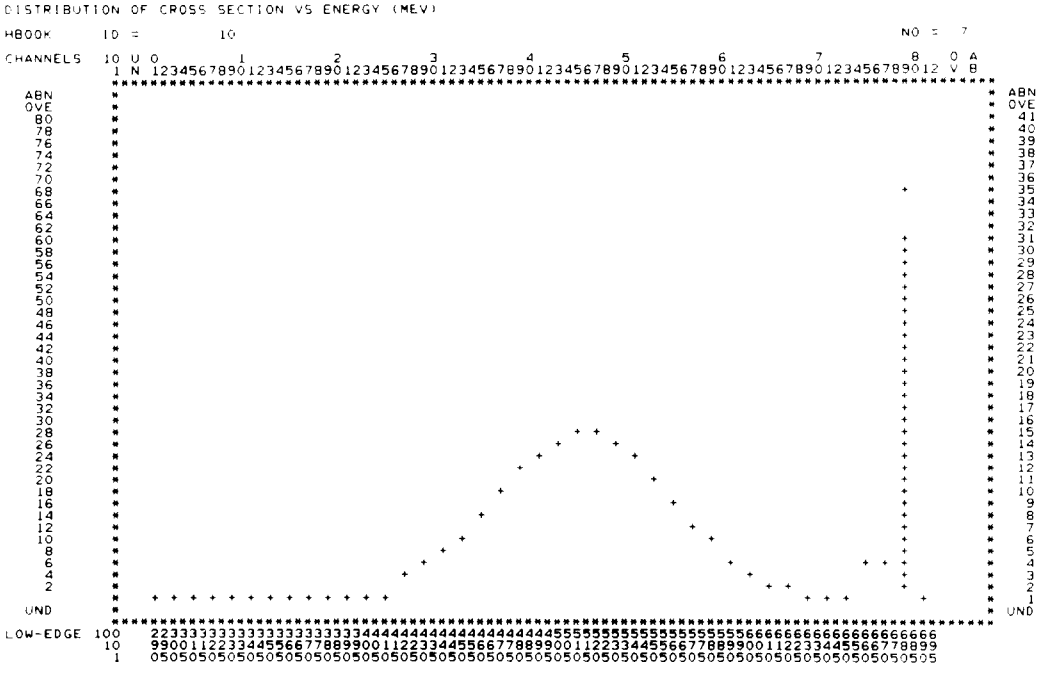

DISTRIBUTION OF CROSS SECTION VS ENERGY (MEV)
HBOOK ID = 10
NO = 7
CHANNELS 10 U 0 1 2 3 4 5 6 7 8 0 A
1 N 1234567890123456789012345678901234567890123456789012345678901234567890123456789012 V B
ABN
OVE
UND
LOW-EDGE 100
10
1

Fig. 2(J).

The output of the code is displayed in fig. 2. Its elements are labelled by the letters (A) to (J).

(A) See example 1(A).

(B) See example 1(B). Note that in this coupled situation the last two columns Contain now numbers which differ from zero. Since the equations of motion listed in section 2 do not strictly conserve energy some of these quantities could in principle be negative (cf. example 5 below).

(C) See example 1(C).

(D) This figure displays the energy loss in the relative motion as a function of the impact parameter, i.e. columns 6 and 1 of table (B). A blow up of this figure is shown in fig. 2(D).

(E) This figure displays the angular momentum loss in the relative motion as a function of the impact parameter, i.e. columns 7 and 1 of table (B), cf. also fig. 2(E).

(F) This figure displays the final energy of relative motion as A function of the scattering angle in the center of mass system, i.e. columns 4 and 3 of table (B), cf. also to fig. 2(F).

(G) This figure gives an indication of the distribution of the reaction cross section as a function of the impact parameter. It excludes the events which led to the formation of a composite system (fusion). In this example, which involves very heavy systems, there are no trajectories leading to capture. In a lighter combination of projectile and target, such as $^{18}O + ^{58}Ni$ at 100 MeV, the distribution would display a "bell-shape" centered at the last partial wave leading to an emerging trajectory. The area under the curve corresponds to quasielastic events. The edges of the function are smooth even though the calculation involves average trajectories because a folding is performed using the quantity σ = SZPM (cf. section 2).

(H) This table collects the results of the calculated trajectories which concern the status of the outgoing fragments. As a function of the impact parameter (partial wave) the excitation energy and angular momentum in the projectile and target are listed (see fig. 2(H)). Columns 5 and 8 give the percentage of the excitation energy due to particle transfer for the projectile and target, respectively. Note that the sum of the excitation energies does not match the energy loss in the relative motion due to the lack of energy conservation (cf. (B) above).

(I) This figure displays contours of the double differential cross section $d^2\sigma/dE\, d\Omega$. The plot incorporates the fluctuations in the final energy of relative motion and scattering angle as explained in section 2 (cf. fig. 2(I)).

(J) This figure gives the distribution of final energies of relative motion for all impact parameters, (cf. fig. 2(J)).

Example 3: Information along a trajectory

As explained in section 3 one can calculate a single trajectory using the key option K6 = 1 and specifying the impact parameter S by entering SMIN = SMAX = S (DS $\neq$ 0). If only one trajectory is calculated, it is assumed that the user is interested in following the evolution of the collision as a function of time. Thus, only in this case information along the trajectory is printed. The time interval for this intermediate output is TSTEP = $0.4\hbar$ MeV^{-1} unless specified different from zero in record number 6 ($\diamond$).

Consider the collision $^{208}Pb + ^{208}Pb$ at 1600 MeV with an impact parameter of 3 fm. If we use the average response function, the data set is the following:

≫ 208.0 82.0 208.0 82.0 1600.0
≫ 0 0 0 0 0 1 0 0 0 0
≫ 0 0 0
≫ 3.0 3.0 1.0

The printout is shown in fig. 3. The letters (A) to (E) indicate the different elements of the output.

(A) See example 1(A).

(B) In these tables detailed information on the relative and intrinsic motion as a function of time is given. The time quoted as the top of the page is measured from the moment the integration of the equations of motion starts. Therefore, it is only meaningful to define time intervals. Fig. 3(B) allows to identify the different quantities. All relative motion variables are referred to the center of mass system. The information about the projectile and target modes that appears at the bottom of

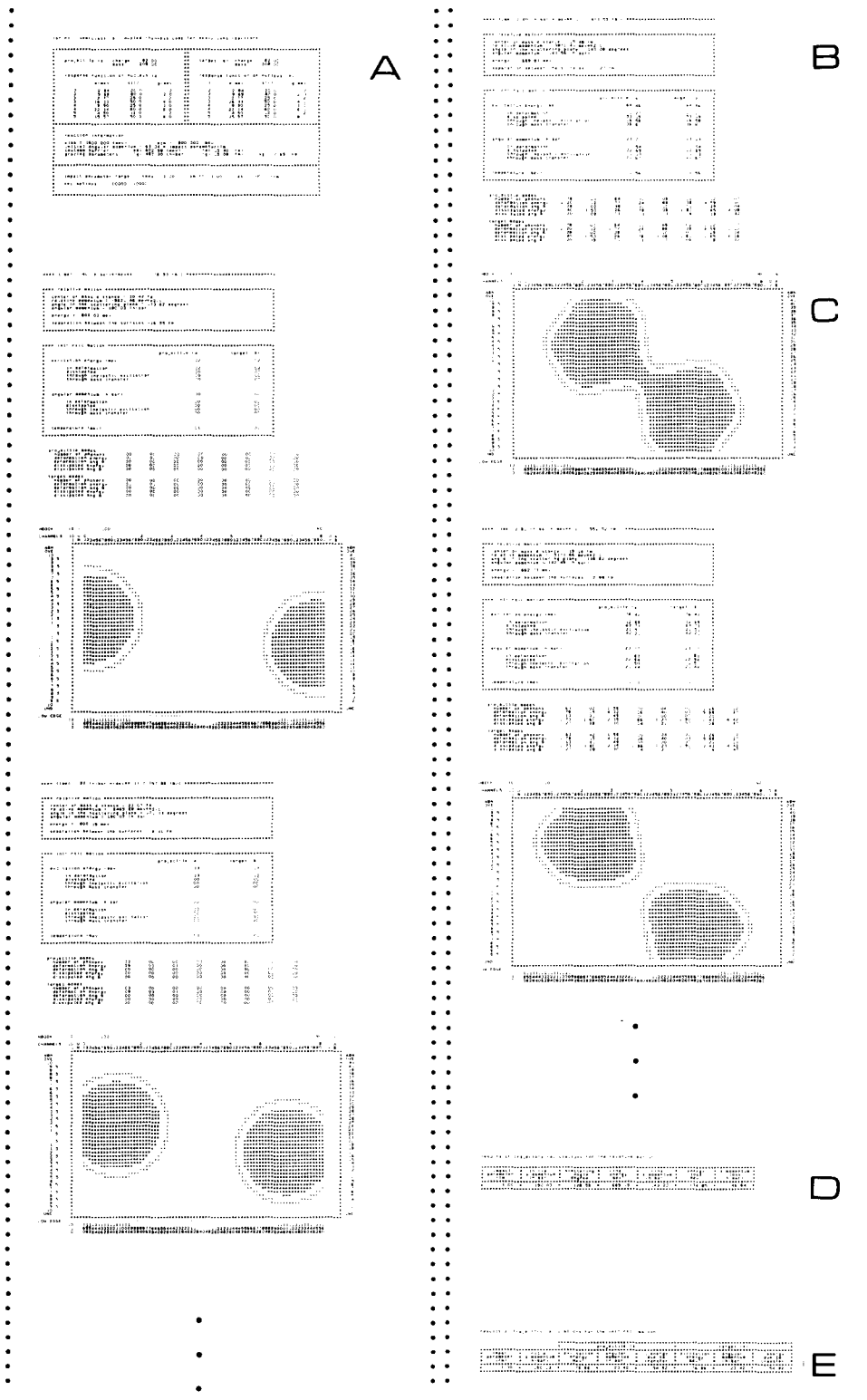


Fig. 3.

```
**** time= 2.40 (h-bar)*(mev**-1) = 473.59 fm/c ****************************

**** relative motion ***************************************************
*                                                                        *
*   center of mass distance = 15.48 fm                                   *
*   relative momentum =  3870.41 mev**2/c                                *
*   angle in the scattering plane = 143.08 degrees                       *
*   angular momentum = 143.56 (h-bar)                                    *
*                                                                        *
*   energy =  689.81 mev                                                 *
*                                                                        *
*   separation between the surfaces =  .27 fm                            *
*                                                                        *
**************************************************************************

**** intrinsic motion **************************************************
*                                                                        *
*                                    projectile (a)      target (b)      *
*                                                                        *
*   excitation energy (mev)                64.46              64.46    *
*                                                                        *
*        in deformation                    11.27              11.27     *
*        dissipated                        53.19              53.19     *
*        through inelastic excitation      16.58              16.58     *
*        through mass transfer             36.61              36.61     *
*                                                                        *
*                                                                        *
*                                                                        *
*   angular momentum (h-bar)              -23.23             -23.23     *
*                                                                        *
*        in deformation                     -.54               -.54     *
*        dissipated                       -22.69             -22.69     *
*        through inelastic excitation      -1.03              -1.03     *
*        through mass transfer            -21.67             -21.67     *
*                                                                        *
*                                                                        *
*                                                                        *
*   temperature (mev)                      1.56               1.56     *
*                                                                        *
**************************************************************************


 projectile modes
   number of phonons      .78     .01     .64     .01     .09     .02    1.02     .07
   deformation energy    2.20     .12    1.77     .24     .88     .38    4.59    1.10
   deformation ang.m.    -.28    -.02    -.38    -.01    -.10     .00     .29    -.04
   dissipated energy      .40    3.53     .26    1.78    3.08    1.80    1.65    4.08
   dissipated ang.m.     -.20    -.09    -.01    -.03    -.13    -.06    -.18    -.32

 target modes
   number of phonons      .78     .01     .64     .01     .09     .02    1.02     .07
   deformation energy    2.20     .12    1.77     .24     .88     .38    4.59    1.10
   deformation ang.m.    -.28    -.02    -.38    -.01    -.10     .00     .29    -.04
   dissipated energy      .40    3.53     .26    1.78    3.08    1.80    1.65    4.08
   dissipated ang.m.     -.20    -.09    -.01    -.03    -.13    -.06    -.18    -.32
```

Fig. 3(B).

the page is printed so that each column corresponds in order to the modes as listed in table (A).

(C) If the distance between the surfaces of the nuclei is smaller than 25 fm, a supplementary figure to table (B) is printed in the next page of the output. This figure displays in a schematic way the density profiles of the reacting nuclei. The crosses indicate the position of the half-density radius for the combined system.

(D) See examples 1(B) and 2(B).

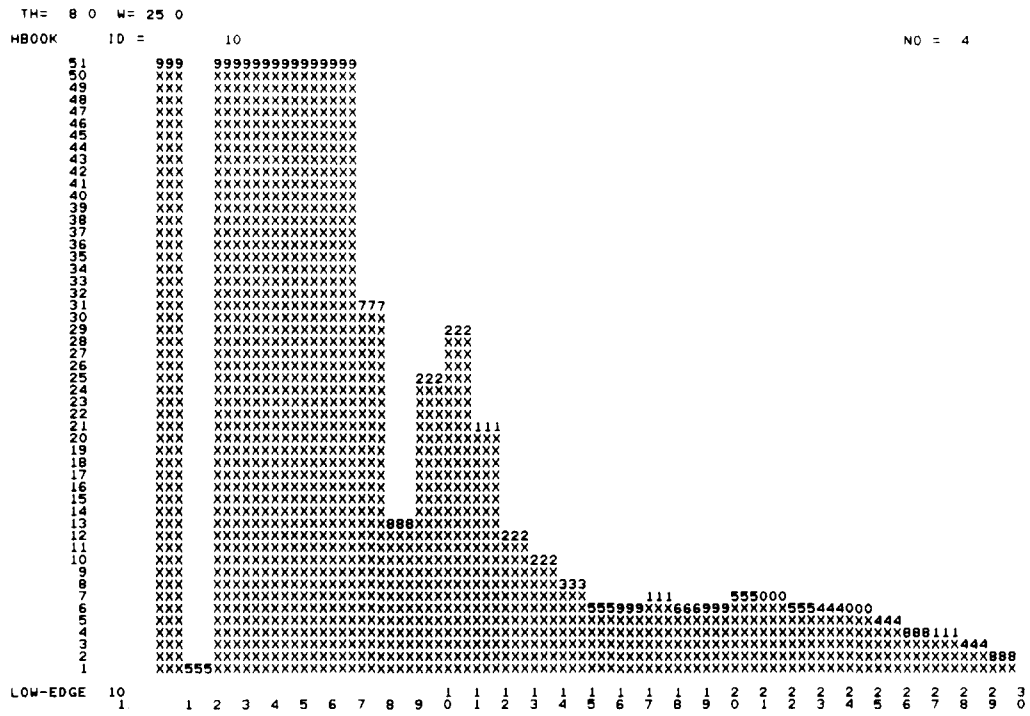
(E) See example 2(H).

Example 4: Quasielastic regime

A quite unique feature of TORINO is the ability of the code to produce excitation functions for angles near the grazing. In this case, the average energy and angular momentum loss in the relative motion is small and a considerable fraction of the cross section goes into single excitation of the individual surface modes. Thus, the analysis of the quasielastic regime provides a way to check and adjust the response function of the reacting nuclei.

The code produces the distribution of cross section for the event where only inelastic excitation of the two nuclei takes place. Of course, these are not the only processes where the mass of the detected fragment coincides with the one of the projectile. Processes where either exchange of particles or particle transfer followed by evaporation takes place also contribute to the cross section. These events constitute a sort of "background" over which the distributions calculated by the code are superimposed. The absolute value of the inelastic cross sections is fixed taking into account the depopulation due to transfer channels by means of an imaginary potential (cf. section 2).

In the quasielastic regime it is important to represent accurately the nuclear response function in the initial mass partition. Thus, it is convenient to use this example to illustrate how the information about the surface modes can be entered exter-


TH= 8 0 W= 25 0
HBOOK ID = 10
NO = 4
LOW-EDGE 10
1 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0

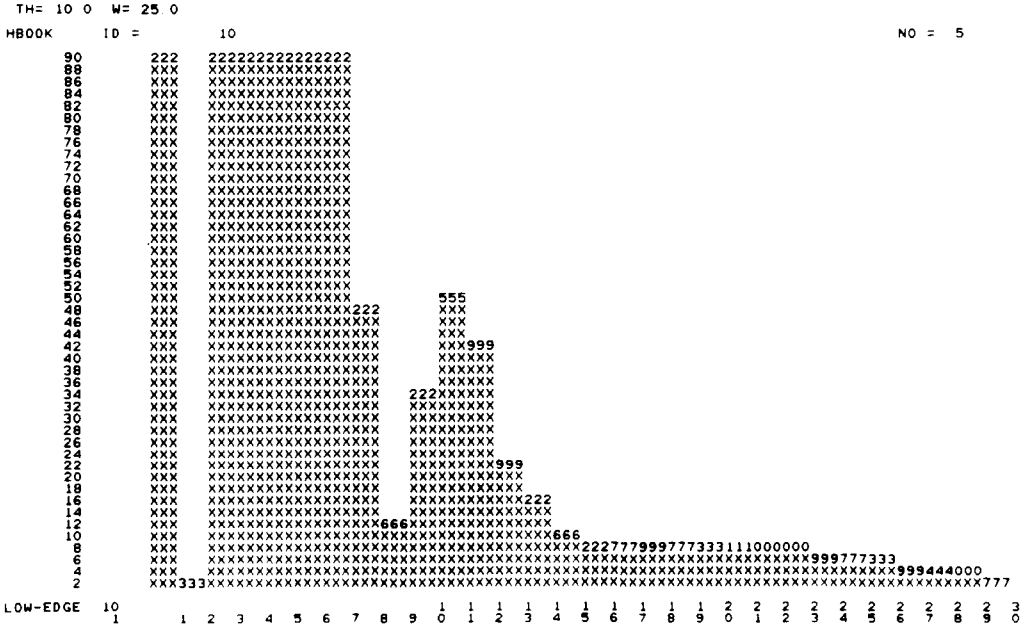

TH= 10 0 W= 25 0
HBOOK ID = 10
NO = 5
LOW-EDGE 10
1 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0

Fig. 4.

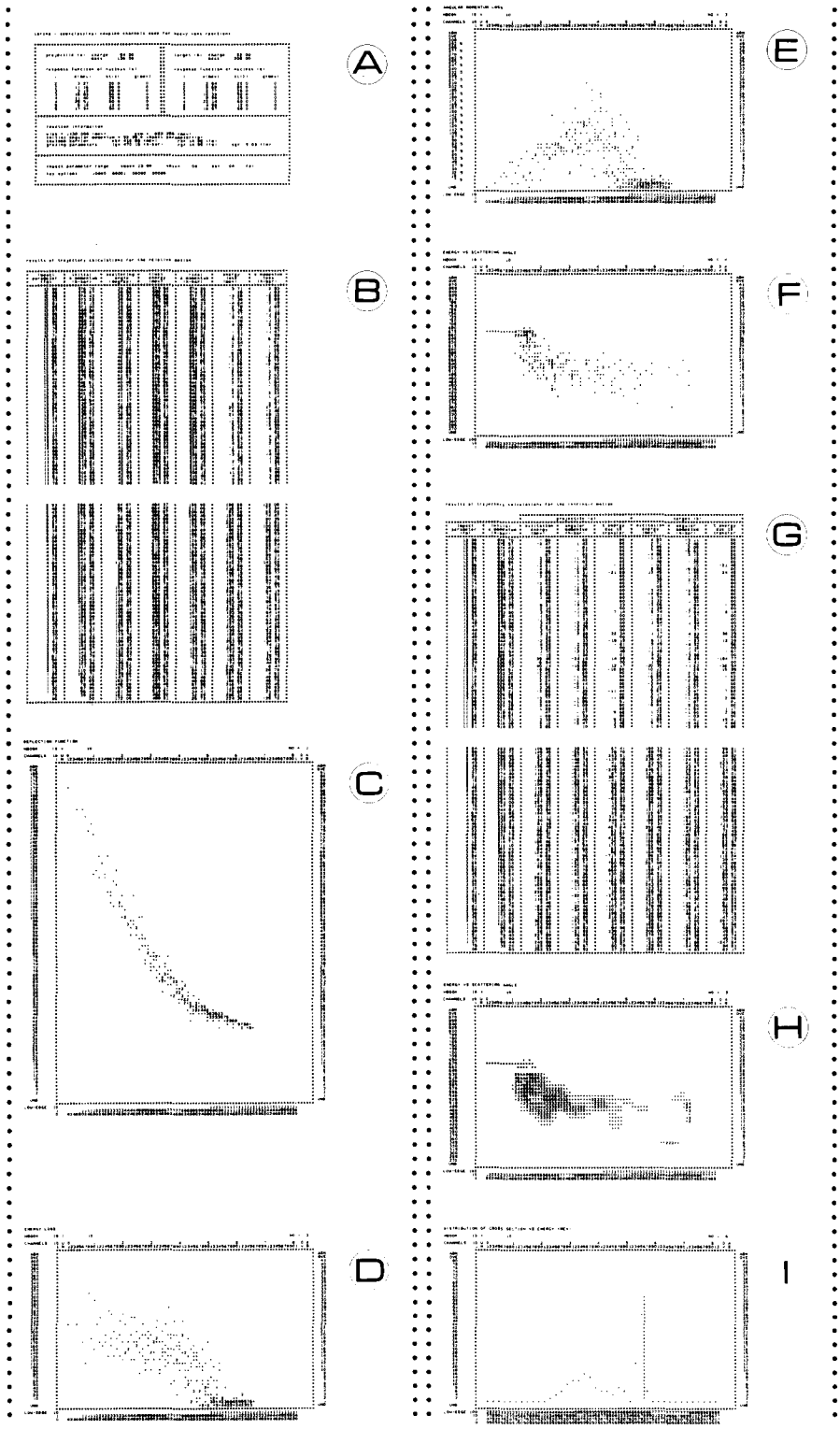


Fig. 5.

nally. Consider the reaction $^{16}O + ^{208}Pb$ at 400 MeV. We use the following input data:

≫ 16.0 8.0 208.0 82.0 400.0
≫ 0 0 0 1 1 1 1 0 0 0
≫ −4 −9 0
≫ 2.0 6.9 8.0 0.0
≫ 2.0 23.0 90.0 6.0
≫ 3.0 6.1 9.0 0.0
≫ 4.0 23.0 25.0 6.0
≫ 2.0 4.1 16.0 0
≫ 2.0 10.8 82.0 2.7
≫ 3.0 2.6 17.0 0.0
≫ 3.0 17.0 80.0 5.0
≫ 4.0 4.3 6.0 0.0
≫ 4.0 10.9 23.0 2.5
≫ 4.0 24.0 71.0 7.0
≫ 5.0 3.3 4.0 0.0
≫ 5.0 20.0 40.0 9.0
≫ 0.0 13.0 0.1
≫ 8.0 10.0 2.0

Notice that by setting K7 = 1 one can enter externally the values of the scattering angle where the excitation function is to be calculated. In this example we have selected 8° and 10°.

The output contains, in this case. the same elements as in example two plus a series of histograms representing the excitation function. Since we have used the default option K8 = 0 three sets are constructed corresponding to the values W_0 = 0, 25 and 50 MeV. For each value of W_0, the set contains the distribution of cross section as a function of excitation energy for all the specified angle. In fig. 4 we show the histograms corresponding to W_0 = 25 MeV. At the top of the figure we list the value of the center of mass scattering angle in degrees the strength of the imaginary potential in MeV. The abscissa (as indicated) goes from zero to 30 MeV in bins of 1 MeV. The ordinate gives the value of the cross section in mb/MeV sr.

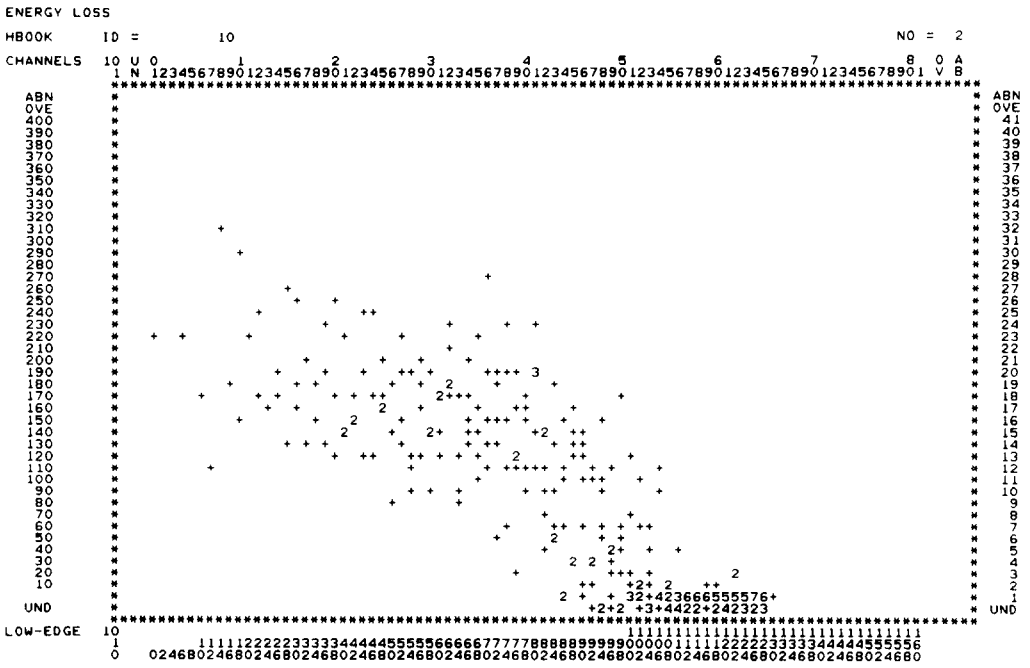


Fig. 5(D).

Example 5: Calculation with random initial conditions

As has been mentioned in section 2, one can take into account the effects of quantal fluctuations beyond the linear approximation by a formalism based in the use of Wigner transforms. This is implemented by calculating a set of trajectories where the initial conditions for the surface variables are chosen at random but consistently with the ground state uncertainty in coordinate and momenta. Here we illustrate the use of this option (K1 = 0) for the reaction $^{136}Xe + ^{208}Pb$ at 1150 MeV, previously used in example 2. The data set is:

≫ 136.0 54.0 208.0 82.0 1150.0
≫ 1 0 0 0 0 0 0 0 0 0
≫ 0 0 299

In these records we have taken K1 = 1 which makes the output reproducible, as has been explained in section 3 (cf. record number 1) and we have set the number of trajectories to be NTR = 299. They will be distributed in the impact parameter range (here internally generated) so that each one accounts for the same cross section.

The output of the calculation is shown if fig. 5. It contains essentially the same elements as explained in connection with example 2. The main difference being that TORINO shifts to a counter-display whenever there is more than one trajectory filling the corresponding box in the x–y grid. Thus, for example, if a number 2 appears in the printout it indicates that two of the trajectories have led to final values of the variables which belong to the same bin (cf. fig. 5(D)). Latin characters in alphabetic order are used if the number of trajectories exceeds 9.

A magnification of the energy-loss distribution as a function of the impact parameter is shown in fig. 5(D).

5. Time estimation and diagnostics

It is difficult to work out a formula which would reliably estimate the computation time for all the different applications of TORINO. We therefore give here only a small table that collects the CPU times used to produce the examples contained in this manual (table 3).

Execution of TORINO is aborted by several conditions. Most often they are due to illegal choice of key options and to vector variables exceeding allotted dimensions. They can also result from a choice of bombarding conditions which are not compatible with the numerical set-up used to integrate the trajectories.

Following is a list of the messages that may appear followed by a short explanation of its meaning and possible corrective steps.

Message: -NTR- too small for ZPM option

If the option K1 = 0 has been used a minimum of trajectories is expected in order to carry out the administration task required by the random initial conditions option. Increase the parameter NTR in record number 3.

Message: number of modes exceeds 24

The total number of modes for projectile and target (either read or internally generated) cannot be larger than 24. This number is defined through a parameter instruction.

Message: -ECM- is below estimated Coulomb barrier

When the center of mass energy is below the estimated Coulomb barrier the code stops automatically since it is not meant to calculate Coulomb excitation alone.

Message: number of equations too large – max 500

This indicates that the number of coupled linear equations n_{eq} to be integrated numerically

Table 3
CPU times

	VAX 8650	VAX 11/780
Example 1	0.12	1.10
Example 2	10.42	52.07
Example 3	1.09	5.50
Example 4	3.52	20.17
Example 5	1.05.00	5.53.00

exceeds the maximum allowed, which is 500. This number can be estimated as follows

$$n_{eq} \sim \sum_m 2(\lambda_m + 1) + 2N + 16,$$

where m goes over all the N modes included in the calculation and λ_m is the corresponding multipolarity. This number is defined through a parameter instruction.

Message: -SMAX- too large for the given energy

The numerical integration is carried out only within a certain distance in the coordinate of relative motion. Outside this prescribed range the trajectories are supposed to be Coulomb-like. If the larger impact parameters are such that the distance of closest approach in a Coulomb orbit is larger than the integration range TORINO stops.

Message: -NTR- larger than 300

Indicates that the number of requested trajectories exceeds the maximum allowed. This number depends on the memory capacity of the system. At the moment we set it to 300. This number is defined through a parameter instruction.

Message: illegal use of quasielastic option

The quasielastic option (K5 = 1) cannot be used with random initial conditions. Resubmit setting K1 = 0.

Message: multipolarity of a mode exceeds 8

The code does not accept modes with multipolarity $\lambda > 8$.

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