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RECOIL RANGE STUDIES OF REACTION MECHANISMS

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RECOIL RANGE STUDIES OF REACTION MECHANISMS

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Studies of reaction mechanism, made by measuring with solid catchers the recoil ranges of radioactive reaction residues, are reviewed. The experimental information one may obtain by these methods is compared to that one gets by means of gaseous or semiconductor detectors or T O F measurements and one shows that the recoil range measurements offer unique possibilities in the case of heavy residues and/or low residue kinetic energies.

1. INTRODUCTION

Many nuclear reactions lead to production of a single heavy product (the *residue*), together with one or more emitted light particles and/or γ-rays. A natural approach to studying the mechanism of such reactions involves detecting and identifying the residues, and thereby determining the yields of individual residues from a given entrance channel. In fact, this is at present the only way of measuring the cross section for a reaction producing several light ejectiles, since even the most sophisticated detectors developed to date, for detecting multiple ejectiles in coincidence, are unable to deduce the mass and charge of the associated residue with any certainty.

Much more insight into the reaction mechanism can be obtained by measuring, in addition to the residue yields, the angular distribution and/or the energy distribution of the individual recoiling residues; again, this is most likely to be achieved by detecting the residue rather than the associated light ejectiles.

The residue may be identified either by detecting some intrinsic characteristic, such as an emitted *X*-ray or γ-ray or some other decay property, or by determining the way in which it interacts with a stopping medium or with electric and magnetic fields. Several techniques have been developed, based on the latter approach, involving identifying the charge and mass of a heavy residue by measuring its energy loss in a suitable medium, its trajectory in a magnetic and/or electric field, or its time-of-flight (T O F). These techniques will be briefly summarised in Section 3. In general most of these techniques have considerable difficulty in achieving complete mass and charge resolution for heavy residues ($A \geq 100$) with recoil energies below about 1 MeV/Amu. Studies based upon identifying the residue by its prompt γ-ray emissions, or, in the case of radioactive species, by its decay properties are in principle free from such limitations.

Measurement of prompt γ-rays by *in-beam* γ-ray spectroscopy methods allows the identification of both stable and radioactive residues. However, measurements of this kind would miss direct production of the residue

in its ground state, and even in the most favourable cases (measuring the γ-rays from the transition between the first 2^+ excited state and the ground state for an even-even residue) one cannot be sure of detecting all the excited nuclei produced, since it may always be possible that the ground state is directly fed from high lying excited states. Present knowledge of decay schemes at excitation energies exceeding a few MeV is generally insufficient to make precise corrections for this effect. In studying processes with small cross sections, further problems may be caused by interference of γ-rays with essentially the same energy originating from different nuclei. For these reasons, this technique is generally limited to measuring cross sections larger than about 1 mb, and systematic errors up to 20% are expected.

Although in principle one can also measure the angular and/or energy distribution of residues using in-beam γ-ray spectroscopy, by performing a coincidence measurement in which the recoiling heavy residue is detected in coincidence with a prompt γ-ray which serves to identify it, such measurements are in fact almost non-existent (and in many experiments they would be severely limited by the difficulty of placing a detector at a sufficiently forward angle to catch the residues). Rather, in most studies to date, prompt γ-rays have been measured in coincidence with light ejectiles.

For radioactive residues, off line measurements of subsequent decay (sometimes involving chemical separations) allow very small cross sections to be determined with high accuracy. Even without chemical separation, the use of high efficiency, high resolution γ-ray detectors (or, in the case of heavy α-decaying residues, detection of the emitted α-particles) allows cross sections as low as a few tens of microbarns to be determined.

By using catchers of appropriate geometry, the angular and/or range distribution of individual radioactive residues can also be measured by off line techniques. These have the advantage that studies of residues actually recoiling along the beam axis can be made, without the problems of high

count rate and damage to detectors usually associated with measurements at forward angles. Ranges corresponding to kinetic energies down to 100 keV (equivalent to 0.5 10^{-3} MeV/Amu for a heavy nucleus) may be measured [1]. The use of several detectors can greatly reduce the time required for off line measurements, so the only real disadvantage of this technique is that it is only applicable to studying radioactive residues with convenient half lives (from a few minutes up to several years); such residues typically account for only ≈20-30% of the total reaction cross section.

Very many cross sections, for both light and heavy ion induced reactions, have been mesured by activation techniques, and a great deal of information about reaction mechanisms has been gained in this way, as well as from more detailed studies of recoil ranges which identify with greater certainty the production mechanism for a given residue[2,3]. Section 2 describes the various experimental procedures used in off line radioactive studies, and summarises the results obtained by this technique. In particular, some recent results from α-particle induced reactions and incomplete fusion, in heavy ion processes, will be discussed. The capabilities of this technique compare quite favourably with those of the techniques described in Section 3.

2. RECOIL RANGE TECHNIQUES

The yields of radioactive residues produced in a given reaction can be measured using a thick target in which the residues stop. After irradiation, at times suitably chosen according to the decay constants, the induced γ or α activity is counted and the cross sections for production of the various residues are determined. To measure the excitation function of a given reaction, a stack of targets may be used which also act as degraders for the incident beam. The energy of the beam particles reaching the i-th target

may be evaluated if one knows the total thickness of the preceding targets and the range/energy relation for these ions in the target material. For this purpose the compilations of Northcliffe and Schilling [4] or of Ziegler [5] may be used. Less frequently, to achieve a much better energy resolution, one may use beams of different energies to bombard separate targets thus avoiding the uncertainties of range/energy relationships. In fact, the published range/energy curves are calculated using semi-empirical extrapolations from limited data, and in the case of heavy ions are not necessary expected to be accurate to better than 20%[6,7]. Care must be taken in accurate determination of the target thicknesses, of the total fluence of incident beam and of the detector efficiency; corrections may have to be made to account for straggling of the incident beam and the possible recoil of products from a given target into the next target of the stack (or outside the target if one irradiates a single target).

Although a survey of the published data does not allow one to establish a general rule, cross sections as low as a few tens microbarns can generally be measured with an accuracy of the order or better than 10%.

Measurement of the excitation function of a given reaction is useful as an initial survey of a particular reaction channel, revealing any obvious features which suitably chosen recoil studies can investigate further. The determination of several excitation functions for reactions of different types may also provide a sensible and significant test of a theoretical model describing the interaction of a given projectile with the target nucleus. Examples of investigations of this type are often encountered in the literature (see for instance Refs. 8 and 9).

Additional information may be obtained from measurements of the recoil range distributions of the residues and of their angular distributions.

Most simply, one may measure $\overline{R}_{||}$, the average component of the range R , parallel to the beam axis, or even better both $\overline{R}_{||}$and the per-

pendicular component of R with respect to the beam axis, $\overline{R}_{\perp}$.

The average forward range may be simply obtained using a thick target followed by a thick catcher of suitably chosen material (the most frequently used are plastic sheets like Kapton, Carbon, Al, Al_2O_3, Au; the catcher must be made of a material in which the range of recoiling residues is accurately known and which cannot produce under beam irradiation residues which are also produced in the irradiation of the target). If the target thickness T is greater than the average forward recoil range R_F and x is the fraction of a given product recoiling forward, (1-x) the corresponding fraction recoiling backward, N is the number of nuclei produced in a unit length of the target thickness, and R_B the average backward range, the activities induced in a backward and in a forward catcher and in the target (respectively A_B, A_F, A_T) are given by

$$A_F = xNR_F \tag{1}$$

$$A_B = (1-x)NR_B \tag{2}$$

$$A_T = NT - A_F - A_B. \tag{3}$$

From this it follows that

$$\frac{A_F}{A_F + A_T} = \frac{xR_F}{T - R_B(1-x)} \tag{4}$$

and if, as usually assumed, $x \approx 1$, it follows

$$R_F = \overline{R}_{||} = \frac{TA_F}{A_F + A_T}. \tag{5}$$

A more precise determination of $\overline{R}_{||}$ may be obtained using a thin target and a catcher made of a few foils of a convenient absorber each of thickness much smaller than the expected mean range. After irradiation, the fraction F_t of the total activity that passed through catcher foils of combined

thickness t is plotted against t . The average projected range $\overline{R}_{||}$ is given by the thickness t_o for which $F(t_o)$=0.5. In evaluating t one must take into account the target thickness by assuming that the residue originated in the middle point of the target and converting the half target thickness into its catcher material equivalent [7,10].

In the case of α radioactive residues with kinetic energies varying from ≈70 keV to ≈20 MeV, the mean recoil range may be estimated very precisely by measuring the energy loss, ΔE, of α particles of known energy emerging from a thick catcher foil in which the residues have been stopped. After suitable calibration ΔE can be converted into range units[1]. By this technique one may measure mean recoil ranges of heavy nuclei corresponding to energies as small as about 0.5 10^{-3} MeV/Amu, while, with the methods previously considered, one can measure ranges corresponding to kinetic energies of a few MeV, characteristic of residues from partial fusion of low energy light ions on medium-heavy and heavy target nuclei [6,11,12], or from pre-equilibrium reactions [3], or from quasi-elastic transfer of a few nucleons [7,10].

Determination of the mean forward projected range provides useful information for interpreting the mechanism of a given reaction. Just to give one example, Fig. 1, from Ref. 2, shows the excitation functions for production of ^{57}Co and ^{55}Co in ^{6}Li bombardment of iron isotopes, together with the corresponding forward projected ranges of the Co residues. The full line in the lower part of the Figure represents the expected range of these residues, assuming full momentum transfer to the composite (projectile+target) system. It is quite clear that at energies between 20 and 55 MeV a mechanism involving low momentum transfer is acting. The authors of Ref. 2 suggest that, at these energies, transfer of a deuteron from the projectile to the target may substantially contribute to these reactions.

Another beautiful example of the information one may gain from

measuring the forward projected range is provided by Fig. 2, from Ref. 7, which shows the variation of $\overline{R}_{||}$ as a function of incident energy for the reaction $^{209}Bi+^{40}Ca \rightarrow ^{211}At$.

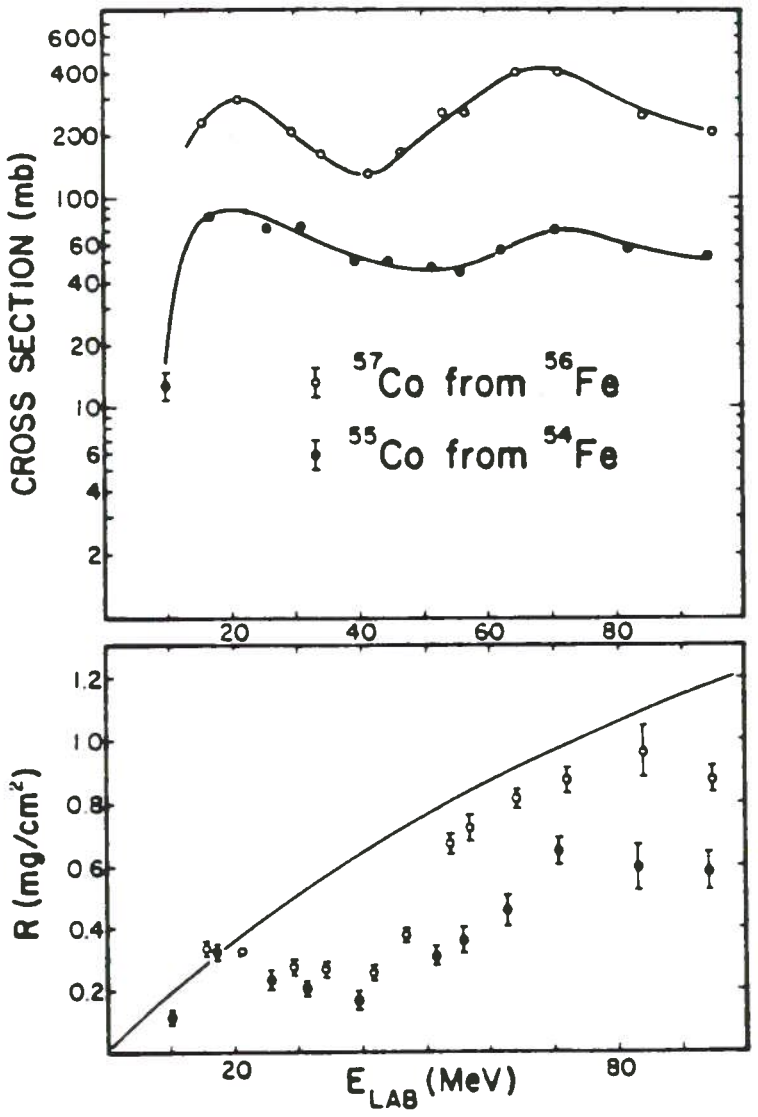

FIGURE 1 - In the upper part of this figure the excitation functions for production of ^{55}Co and ^{57}Co in ^{6}Li bombardment of ^{54}Fe and ^{56}Fe are reported; in the lower part the mean forward recoil ranges of Co residues[2] .

The experimental projected ranges are represented by the black dots with error bars; the excitation function for ^{211}At production is given by the curve labelled $\sigma(^{211}At)$. The straight line R(CN) represents the range calculated assuming a compound nucleus process. B_V and B are two estimates of the interaction barriers between projectile and target. The authors interpret these data as indicating that at incident energies *below* the interaction

barrier the distance of closest approach of the nuclei is limited by Coulomb repulsion so that only head-on collisions can lead to the transfer of two protons from the projectile to the target.

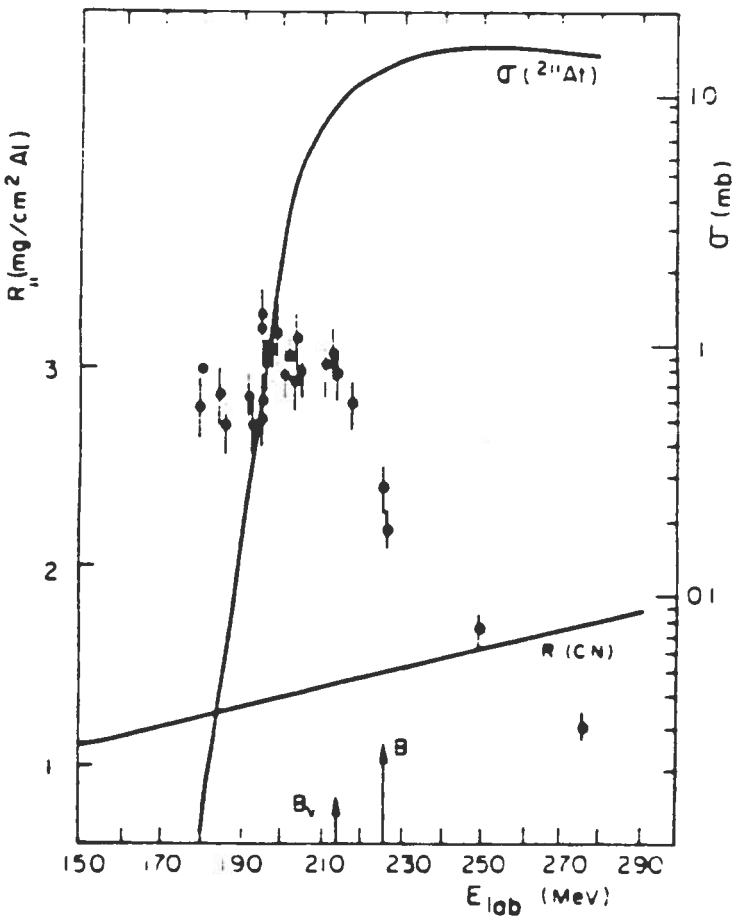

FIGURE 2 - Excitation function for production of ^{211}At in the interaction of ^{40}Ca ions with ^{209}Bi and mean forward ranges of ^{211}At residues (black points with error bars). The projected ranges calculated in the hypothesis of a compound nucleus process are given by the straight line. B_V and B are two estimates of the interaction barriers for ^{40}Ca on ^{209}Bi[7] .

The projectile-like residue is emitted backwards while the target-like residue comes out at a small forward angle (in the Lab system) with a velocity well *above* that corresponding to total momentum transfer. In contrast, at incident energies above the interaction barrier the head-on collisions lead to deeply inelastic reactions. This implies a decrease in the laboratory kinetic energy of the heavy residue, associated with an increase of its emission

angle. Both phenomena lead to a decrease of the projected range of the heavy residue.

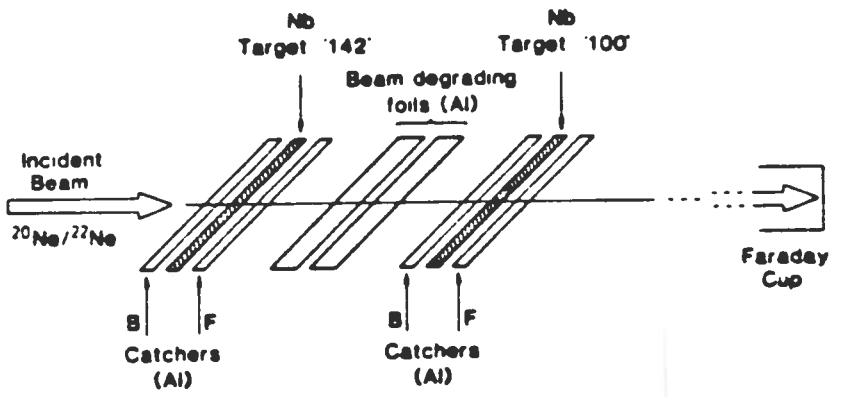

FIGURE 3 - Experimental arrangement for irradiation of foil stacks mounted at 45° to the beam axis. The niobium targets are sandwiched between a forward, F, and a backward catcher, B [13] .

The average recoil range perpendicular to beam direction, $\overline{R}_{\perp}$, may be measured using thick catchers downstream and upstream of the target, provided both catcher and target are tilted with respect to beam direction [13]. Fig. 3 reports the experimental arrangement used by Hogan *et al.*[13] for studying the recoil products from the interaction of 100 and 142 MeV ^{20,22}Ne ions with ^{93}Nb. These authors show that, using a ***backward catcher–target—forward catcher*** assembly mounted at 45° to the beam axis, average recoil angles $\overline{\theta}_L$, which substantially exceed 45°, and the forward projected range $\overline{R}_{||}$ may be estimated from the fractions of the yield escaping in the forward, f_F, and in the backward catcher, f_B,by means of the relations

$$\overline{R}_{||} = T(f_F - f_B), \tag{6}$$

$$\frac{\pi f_B}{f_F - f_B} = \overline{(tan^2\theta_L - 1)^{1/2} - cos^{-1}(cot\theta_L)}, \tag{7}$$

where T is the target thickness. If the recoil velocity distribution is sufficiently narrow one may assume that

$$\overline{(tan^2\theta_L - 1)^{1/2} - cos^{-1}(cot\theta_L)} \approx (tan^2\overline{\theta}_L - 1)^{1/2} - cos^{-1}(cot\overline{\theta}_L), \tag{8}$$

and the average recoil range perpendicular to beam axis is given by

$$\overline{R}_{\perp} \approx \overline{R}_{||} tan\overline{\theta}_L. \qquad (9)$$

If the angular distribution of the recoiling residues is broad, the value of $\overline{\theta}_L$ from (8) is systematically greater than the true value. Furthermore if the angular distribution extends significantly to angles below 45°, the averaging process is truncated, leading to a further systematic overestimation of $\overline{\theta}_L$. The results obtained in the study of reactions induced by 100 – 142 MeV Ne ions on ^{93}Nb indicate that target like residues with mass between 87 and 96 have large recoil angles with respect to the beam direction, indicative of glancing processes in which a few nucleons are transferred from the projectile to the target or from the target to the projectile. Afterwards the slightly excited target like residues may de-excite by emission of one or two nucleons and γ-rays.

It is relatively easy to measure the angular distribution of radioactive residues using a thin target, a well collimated beam, and a suitable catcher arrangement.

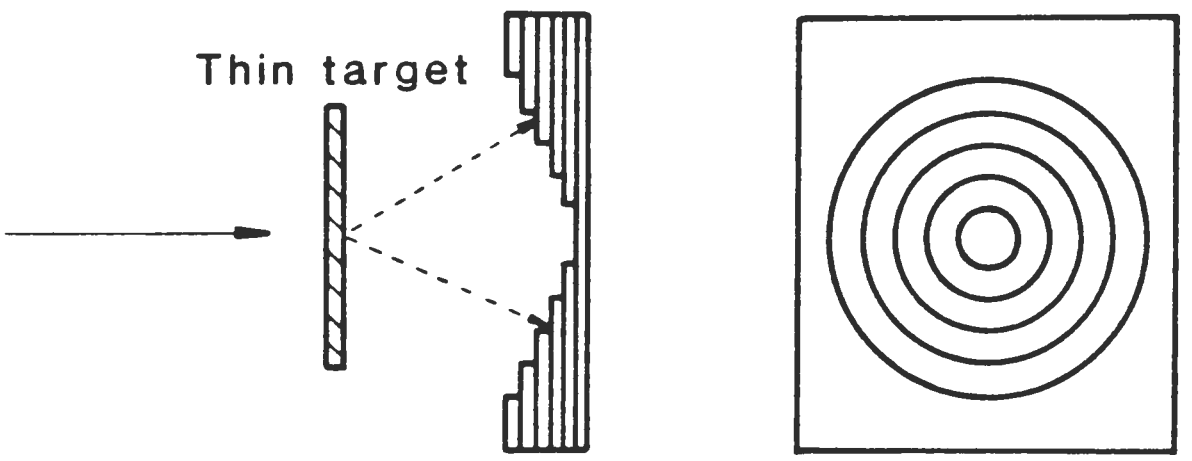

FIGURE 4 - A stack of thick catchers with concentric holes allows one to measure the angular distribution of residues recoiling from the target[14] .

A very simple arrangement consisting of a catcher made up of a stack of thick plates with concentric holes of different diameter is shown in Fig.

4^{14}; each plate catches recoils in a different angular interval. Other arrangements may be found in the literature[7,10,15]. In most of cases, one measures

$$\frac{d\sigma}{d\theta_L} = \frac{d\sigma}{d\Omega} 2\pi sin(\theta_L). \tag{10}$$

The measured angular distributions include all residual nuclei of a given charge and mass that were produced with excitation energy between 0 and the minimum excitation energy for particle emission (which in most cases coincides with the binding energy of the last bound neutron B_n). This is also true for any other detection systems, since even residues with kinetic energy up to 100 MeV/Amu need $\approx 10^{-10}$ s to travel 1 cm so that all the excited states of these residues (with the exception of isomeric states) decay to the ground state before reaching the detector.

The Orsay group has made much use of angular distribution measurements in studying quasi-elastic and deep-inelastic reactions (see, for instance Ref. 7). From the laboratory angular distributions and the ranges measured at all angles θ_L for one residue, adopting the hypothesis that the initial interaction produced only two residues which further decayed by evaporation of particles or by emitting γ rays, one may deduce the approximate angular and kinetic energy distribution of these products in the C M system[16]. However the inverse procedure, i.e. the calculation of the expected laboratory system distributions starting from the theoretical estimates of the angular and kinetic energy distributions may prove to be more precise. Other interesting results are reported by Kratz *et al.*[10] who measured the isotopic distribution of residues from deep–inelastic and quasi–elastic interactions of 900 MeV ^{132}Xe ions with ^{197}Au. The perfect mass and charge resolution obtained with the radiochemical methods allowed these authors to resolve the isotope distribution resulting from quasi-elastic processes from that resulting from deep inelastic events.

Certainly the most detailed information one can get from recoil range studies is obtained by measuring the recoil range distributions of the residues as a function of θ_L. More often the range distribution of all forward recoils for a given residue is measured, and this also proves to be extremely useful.

References to experimental results prior to 1967 may be found in the survey by Alexander[17]. Most of the recoil range distributions have been measured using stacks of very thin metallic foils. The thinnest catchers used so far have been made of Al_2O_3 with thickness of 70 $\mu g/cm^2$ [18] and aluminium with thickness of $\approx$100 $\mu g/cm^2$ [3,6,11,12]. To investigate the partial fusion of light ions (A$\leq$20) [6,11,12] or reactions induced by α-particles up to 85 MeV[3] Parker *et al.* use stacks of about 25 evaporated aluminum catcher foils, with thicknesses in the range 50-200 $\mu g/cm^2$, mounted immediately behind the target with an angular acceptance of 2π. The thickness of each catcher can be measured with an accuracy varying from 5 to 10%. Target and catcher foils are mounted inside an electrically suppressed Faraday cup and the incident beam is collimated to a spot diameter of $\approx$5 mm.

A further improvement of this technique has been discussed by Parker [19]. A cylindrical stack of thin Al catchers ($\approx$100$\mu g/cm^2$) with a diameter of about 50 mm is mounted 25 mm downstream of the target. After irradiation, each foil is cut into a series of concentric rings, so that each ring corresponds to a definite angular interval as well as to a definite interval of ranges. By this procedure it is possible to measure not only the distributions of the residue projected ranges in the forward direction, but the residue recoil distribution at different recoil angles. A typical result is shown in Fig. 5 which shows the recoil distributions for three products from the interaction of 72 MeV ^{12}C ions on ^{51}V. The numbers denote the relative yields in the different annuli of the different catchers; contours have been drawn to guide the eye. From data of this kind one may immediately

appreciate that *different reaction mechanisms* lead to production of ^{58,56}Co isotopes and ^{54}Mn. In the case of the residue ^{54}Mn, the contributions due to complete fusion and incomplete fusion with escape of ^{8}Be, can be easily distinguished (the first gives rise to the peak at about the mean range characterising the ^{56}Co and ^{58}Co distributions, the second to the distribution centered around a much smaller recoil range extending from about 4° to more than 40°). Even in the case of ^{56}Co which is formed principally by complete fusion, the results are interesting, since one can clearly see the effect of the evaporation of one α-particle in perturbing the recoil velocity from the compound nucleus value.

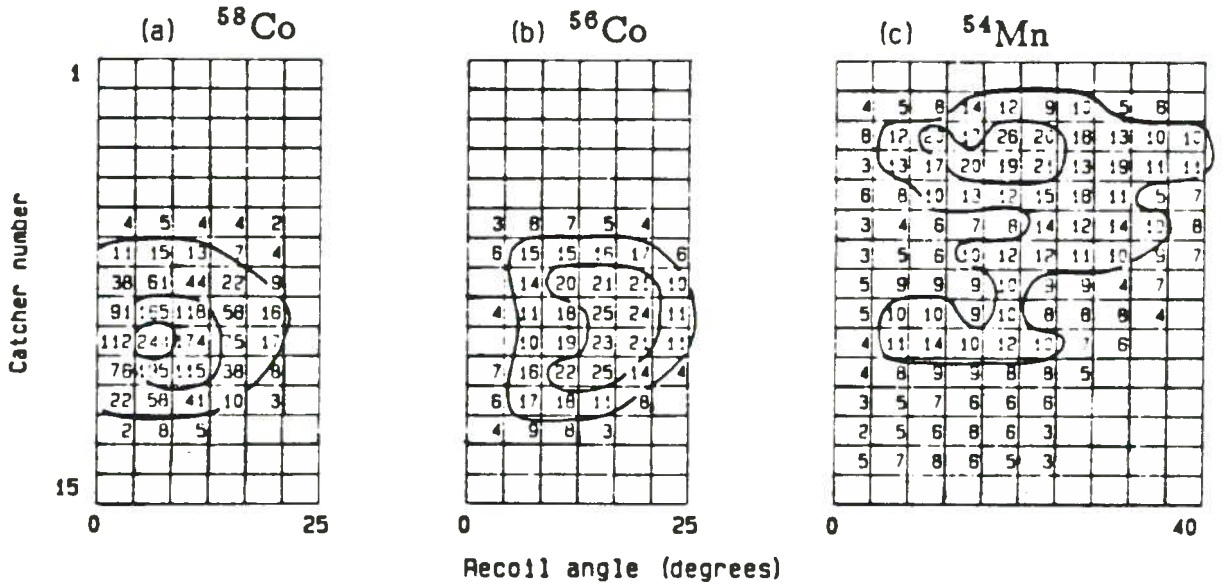

FIGURE 5 - Yields of recoiling ^{54}Mn, ^{56}Co and ^{58}Co ions from the interaction of 72 MeV ^{12}C ions with ^{51}V, plotted as a function of recoil angle and catcher number[19] .

The range distribution is broad and most of the recoils occur at an angle, with respect to beam direction, greater than ≈12°. ^{58}Co, on the other hand, is formed, at this energy, by evaporation of five nucleons from the compound nucleus and, as a consequence, its range distribution displays a rather sharp peak at the expected compound nucleus velocity and a recoil angle smaller than 10°.

Before ending this Section, we wish to discuss some data obtained in the course of last two years, which serve to illustrate how important information may be obtained from recoil range measurements.

(i) The first data refer to the reactions induced by α particles on ^{59}Co[3]. The excitation functions of reactions leading to 14 radioactive residues ranging from Cu to Cr for α energies up to about 170 MeV had previously been measured[6,20,21]. These excitation functions and the spectra of protons and α particles were analysed in the framework of the *Exciton Model*, using the same set of parameters previously used for calculations of spectra and excitation functions of nucleon induced reactions, along with a realistic description of the possible α—nucleus interaction modes[21]. These calculations were quite successful in reproducing the data; however these experimental results *alone* do not provide explicitly the contribution, to a given reaction, of the different *reaction paths*. As a specific example, consider the production of ^{58}Co. The corresponding reaction is usually indicated as $^{59}Co(\alpha,2p3n)^{58}Co$. However physically different reactions may contribute to the process, namely

$$(\alpha,\ \alpha n),\ (\alpha,\ 2p3n),\ (\alpha,\ dp2n\ ),(\alpha,tpn),\ (\alpha,\ ^{3}He2n)$$

and even when the type of emitted particles is specified, the reaction mechanisms leading to their emission may be widely different at different energies. Thus, at low incident α–particle energy, the α particles emitted in the $(\alpha,\ \alpha n)$ reaction are evaporated from the compound nucleus; at higher energy, they may result from an inelastic scattering event which leaves a residue with sufficient energy to evaporate a further neutron. The same observations apply to emission of single nucleons. Near threshold they are evaporated; at higher energy some of them are emitted during the *pre-equilibrium phase* of the de–excitation. The theoretical model one employs, if it is sufficiently sophisticated, obviously includes all these possibilities, however, comparison with measured excitation functions or inclusive spec-

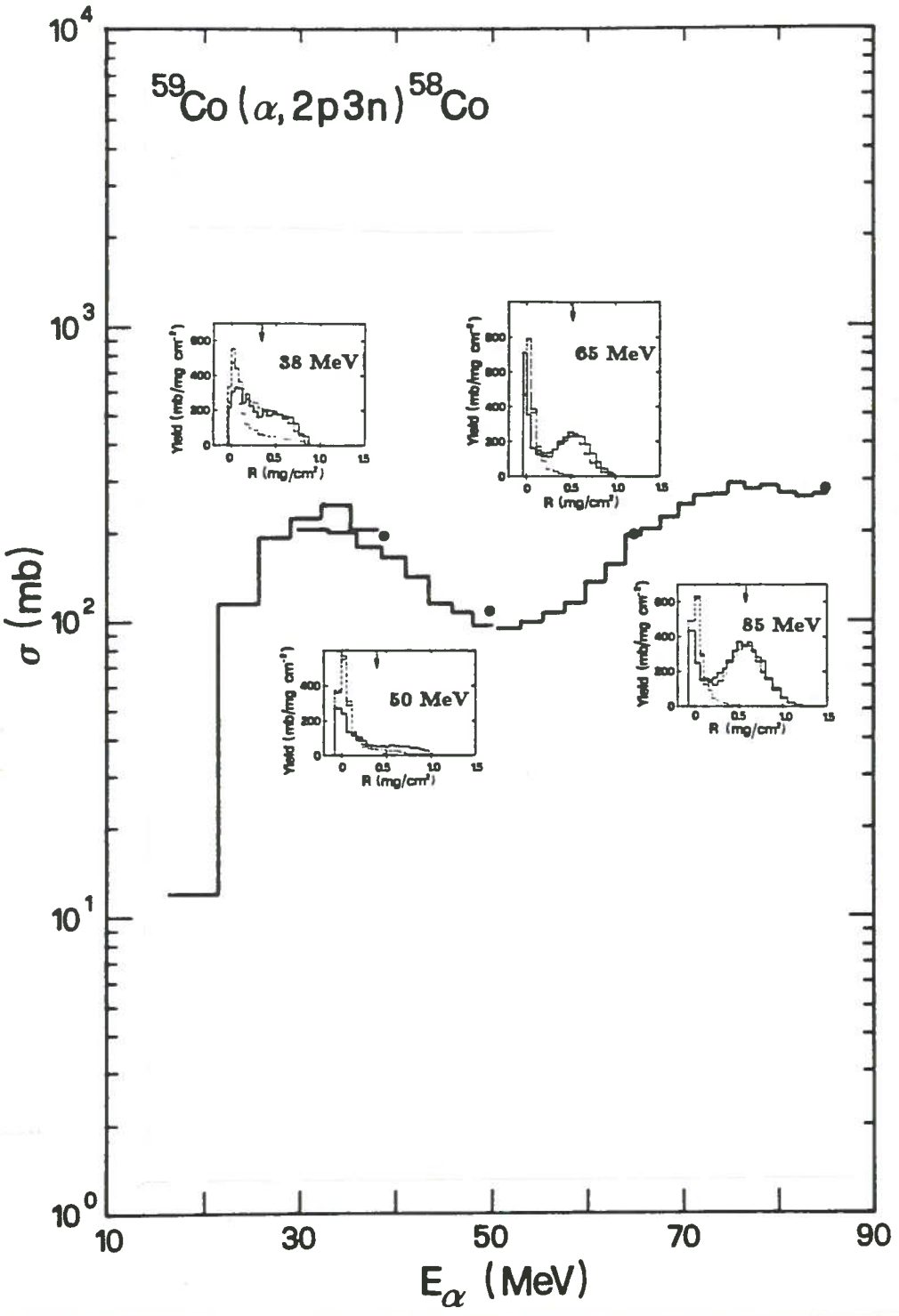

FIGURE 6 - Excitation function for production of ^{58}Co in α-particle bombardment of ^{59}Co (the histograms represent the experimental results, the black points the calculated cross section values at 38, 50, 65, 85 MeV[21] and recoil range distributions of ^{58}Co residues. In recoil distributions, the heavy line and dashed line histograms represent, respectively, the experimental and the calculated distributions, the dotted line histograms the calculated distributions of recoils for processes involving the pre-equilibrium emission of one α-particle[3] . The arrows give the predicted mean recoil ranges in the hypothesis of a compound nucleus process.

tra only tests the cumulative effect of all these reaction mechanisms. A much more detailed test of the interpretation adopted may be obtained if one also considers the recoil range distribution of the ^{58}Co nuclei[3]. In Fig. 6 the excitation function for production of ^{58}Co is shown together with the measured recoil range distributions at 38, 50, 65, 85 MeV. The arrow in each inset recoil distribution, shows the range $\overline{R}_{||}$ expected for processes proceeding through formation of a *Compound Nucleus* . At 65 and 85 MeV a broad peak centered about $\overline{R}_{||}$ is present. At 38 and 50 Mev a broad structure is again present around $\overline{R}_{||}$ however its width is substantially larger. This is understandable since at the higher energies the recoiling ^{58}Co associated with compound nuclear processes mainly originate from evaporation of five nucleons from the compound nucleus, while at the lower energies evaporation of one α and a neutron predominates. The perturbation to the motion of the residue due to the evaporation of one α particle with energy *at least* exceeding the Coulomb barrier is much greater than that corresponding to multiple emission of lower energy nucleons. This reflects in the widths of the corresponding recoil distributions. At all the energies the recoil distributions contain a substantial contribution from a second structure centered around an almost vanishing range. This corresponds to processes in which, in the initial α–target nucleus interaction, very little momentum is transferred from the projectile to the ^{59}Co. According to the theoretical model adopted, events of this kind originate from *inelastic scattering* of the alpha particle which transfers a small amount of momentum and energy to the target nucleus, which may further evaporate a single neutron. One clearly sees that the recoil range distributions allow one to identify and *measure* the contribution of this reaction path at the various energies. The theoretical model adopted reproduces quite satisfactorily both the excitation functions and the recoil range distributions so one may conclude that a reasonable interpretation of the reaction mech-

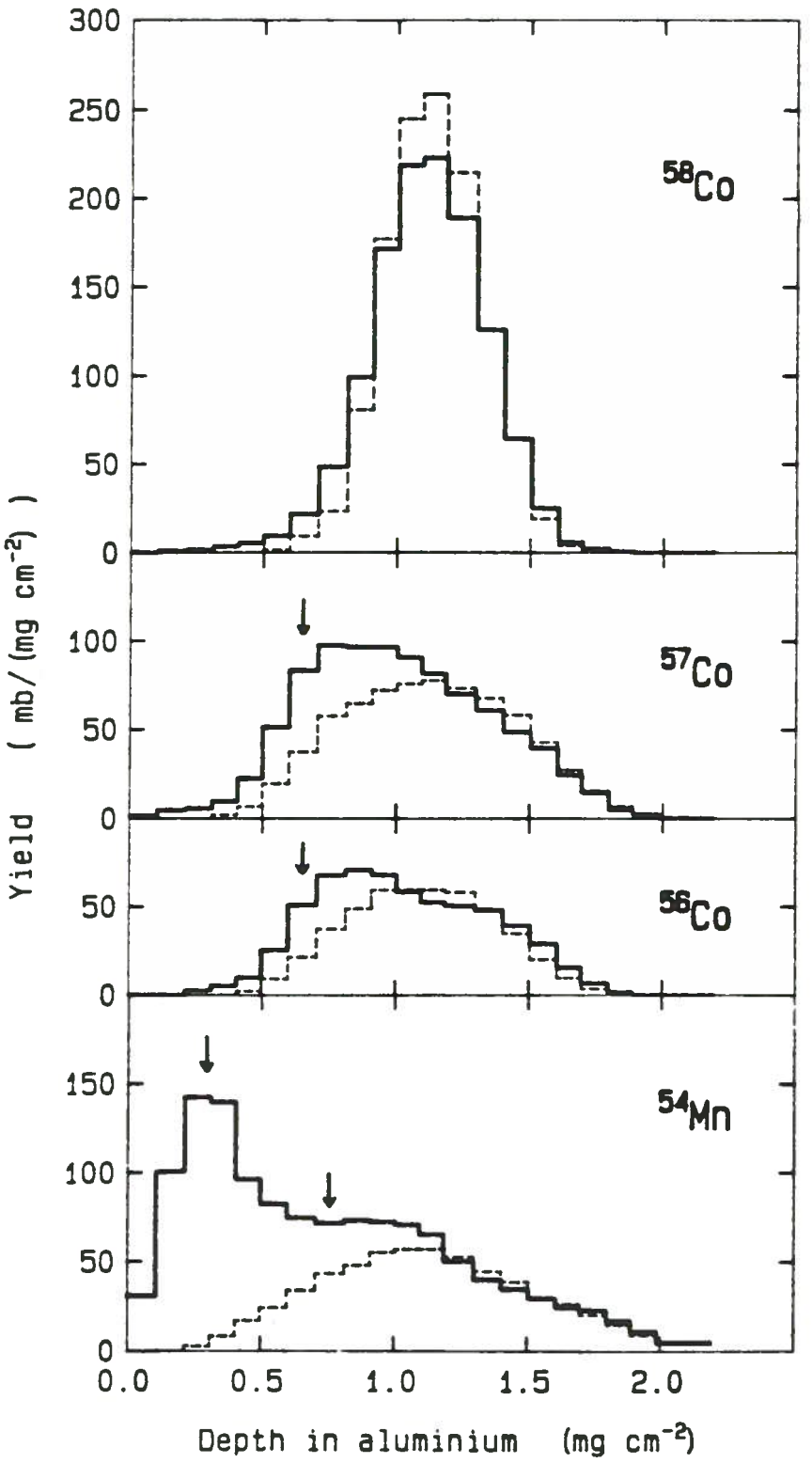

FIGURE 7 - Recoil range distribution of Co isotopes and ^{54}Mn produced in the interaction of 72 MeV ^{12}C ions with ^{51}V. The heavy line and dashed line histograms represent, respectively, the experimental distribution and that calculated assuming complete fusion[11] .

anism has been achieved. The interpretation of the data would be much less conclusive if only the excitation function had been considered.

(ii) Fig. 7 shows the recoil range distribution of four residues from reaction of 72 MeV ^{12}C ions on ^{51}V[11]. Whereas the ^{58}Co distribution consists of a single peak, at the range expected for a residue recoiling with the compound nucleus velocity, the other products show additional components at a lower range. These components correspond to the two incomplete fusion processes $^{51}V(^{12}C,\alpha)^{59}Co^{*}$ and $^{51}V(^{12}C,^{8}Be)^{55}Mn^{*}$, in which respectively an α-particle and a ^{8}Be (or maybe 2 α-particles) act essentially as spectators during the reaction, so that the recoil velocity of the residue is reduced to 2/3 and 1/3 of the compound nucleus value, respectively . These qualitative conclusions have been confirmed by detailed modelling of the effects of the evaporation process on the recoil velocity; excellent reproduction of the data has been achieved, and information on the incomplete fusion cross sections has been deduced[11].

(iii) Another interesting example of recoil results is provided by the recoil distributions of residues produced in the interaction of $\approx$100 MeV ^{20}Ne ions with ^{93}Nb[12]. In Fig. 8 the measured recoil range distributions of residues ranging from ^{109}In to ^{97}Ru are shown. The recoil distributions of the indium isotopes peak around the value of the range expected from complete fusion followed by evaporation. In the case of the silver isotopes complete fusion alone cannot account for the observed distributions; some other reaction mechanism must contribute. Of greatest interest are the results obtained for the rhodium and ruthenium isotopes. Fusion-evaporation may only contribute to production of ^{100}Rh; this reaction path is energetically forbidden in the case of the two other nuclei. Even in the case of ^{100}Rh the main mechanism cannot be fusion-evaporation, as shown by the comparison with the recoil distributions of the indium isotopes. The production of the two Rh isotopes is well reproduced assuming that the

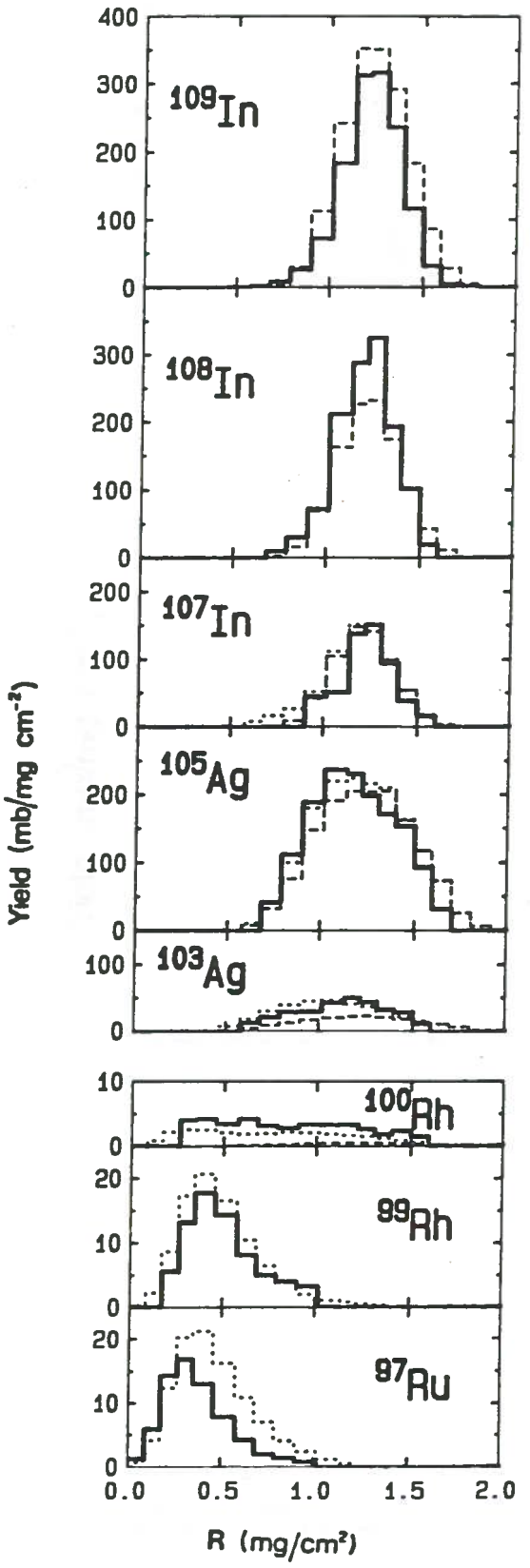

FIGURE 8 - Recoil range distributions of residues from the interaction of ≈100 MeV ^{20}Ne ions with ^{93}Nb. The heavy line and dashed line histograms represent, respectively, the experimental and the theoretical distributions[12] .

main contribution is due to partial fusion of only two α–particles or a ^{8}Be followed by evaporation of, respectively, one and two neutrons from the intermediate ^{101}Rh. Even more interesting is the residue ^{97}Ru which appears to be produced by the partial fusion of a ^{6}Li cluster with ^{93}Nb with subsequent evaporation of 2 neutrons from ^{99}Ru. The narrow recoil distribution provides evidence for a highly selective incomplete fusion process leading to production of ^{97}Ru residues.

The few examples given demonstrate how useful measurements of the recoil ranges of radioactive residues can be in clarifying the reaction mechanisms of reactions induced by both light and heavy ions. As discussed in the next Section, the equivalent experimental information cannot, in most cases, be easily obtained by other experimental methods.

3. OTHER EXPERIMENTAL TECHNIQUES FOR IDENTIFYING HEAVY RESIDUES AND THEIR RANGE (OR ENERGY)

3.1 Bragg curve spectrometers

Considerable efforts have recently been made to develop systems based on measurement of the specific ionization along the track of the residue (the so called Bragg-curve) in a gaseous adsorber. In most cases these systems are Frisch grid ionization chambers with the electric field parallel to the particle track[22]. Ionisation occurs in the gas region between the cathode and the grid and the charge is collected by an anode located at a small distance from the grid. Suitable choices of the cathode-grid and grid-anode distances and for the preamplifier and amplifier time constants are discussed in several papers in the literature[23–26]. It is possible to measure an ionisation current signal with an amplitude time dependence which reproduces, with some unavoidable distortion, the Bragg curve.

The maximum specific ionisation along the track, the so called Bragg

peak, is distinctive of the Z of the residue. Further information is gained through measurement of the specific ionisation at the beginning of the track, which is a measure of ΔE, and of the total ionisation which is a measure of the energy E of the residue. The length of the track gives the range. Attempts have also been made to measure the delay time between the ΔE signal and the signal at the maximum of ionisation (the so called *Bragg peak pulse*) to identify, in addition to the charge, the mass of the residue[25].

Bragg–curve spectroscopy is only applicable for residues whose initial velocity is greater than that corresponding to the maximum stopping power in the Bragg curve and is usually employed for residues with E/A substantially exceeding 1.-1.5 MeV/Amu. This means that these detectors cannot be utilised in energy ranges where the technique of measuring residue recoil distributions by means of the activity induced in thin catchers gives excellent results, as discussed in the previous Section. We may consider for instance the case of reactions induced by energetic light ions. Even in a complete fusion process, a 400 MeV α–particle beam bombarding an A≈100 target nucleus produces heavy residues with E/A of the order of 0.15–0.19 MeV/Amu; in most cases the linear momentum transferred is considerably less than that corresponding to complete fusion. A 1200 MeV C beam bombarding an A≈100 target nucleus will produce target-like residues with E/A at most of the order of 1.3 MeV/Amu and again one must expect that in most cases the residue energy will be much smaller than this. As discussed in the previous Section, in radioactive studies using thin catchers, accurate measurements have been made for residue energies down to (and even less than) 0.005 MeV/Amu.

Results obtained so far indicate that Z resolution ($\Delta Z \approx$ 0.5-1.0) may be obtained by means of Bragg curve spectroscopy for residue charges smaller than about 30–40. Mass resolution has up to now been achieved

only for quite light residues (A≤20–26). For heavy residues, as will be discussed in the next paragraph, is doubtful if one can achieve mass resolution by measuring delay times in gaseous systems.

These considerations clearly indicate that Bragg–curve spectroscopy cannot constitute, for a wide range of residue masses and energies, an alternative to measurements based on induced activity in thin catchers.

3.2 Measurements based on the use of ΔE–E telescopes associated with a T O F system

Determination of the charge and mass of a residue together with its energy may be obtained by means of detectors measuring A from the time of flight (T O F) and the energy E and the charge Z from the energy loss ΔE and the energy E.

A great number of devices employing SSD detectors, proportional counters and ionisation chambers, parallel plate avalanche counters (PPAC), microchannel plates (MCP), position sensitive devices in various combinations have been discussed in the literature. We limit ourselves to quoting a few papers which also contain references to previous investigations[27–30]. As representative of the accuracy achievable by these methods, we may refer to the results by Kwiatkowski *et al.*[28]. These authors obtained mass and charge resolutions of ΔA=0.7–0.8 Amu and ΔZ=0.5–0.6 Z units, for Fe–like fragments, at E/A≈7–9 MeV/Amu, using a dual channel plate fast timing system to provide T O F start and stop signals, a two element gas ionisation ΔE_x–ΔE_y position sensitive counter, and a semiconductor E counter.

To our knowledge, up to now, mass resolution (ΔA≈0.5 Amu) has never been obtained for A≥100 nuclides by these methods. In order to investigate further the possibilities offered by devices of this type, we start

from the relation between mass A, energy E, T O F t and flight path l:

$$A = \frac{2Et^2}{l^2} \tag{11}$$

The mass resolution obtainable is related to energy, time and length resolutions by:

$$\frac{\Delta A}{A} = ((\frac{\Delta E}{E})^2 + (\frac{2\Delta t}{t})^2 + (\frac{2\Delta l}{l})^2)^{1/2} \tag{12}$$

We assume that length resolution makes a small contribution to the mass resolution since it is always possible, by accurate positioning, to reduce its contribution to a desired value. In order to investigate the effect of time resolution we shall separately consider its contribution to the mass resolution. Assuming $\Delta E/\mathrm{E}=0$, the following relation holds:

$$E = 0.125\frac{l^2}{A}(\frac{\Delta A}{\Delta t})^2 \tag{13}$$

The minimum path length necessary to achieve a mass resolution ΔA=0.5 Amu, calculated from (13) for a time resolution Δt=100 ps (the present limit to time resolution) is shown in Fig. 9 as a function of the square root of the energy per nucleon, for various residue masses. For a time resolution equal to x100 ps, the minimum length must be multiplied by x. One immediately realizes that the possibilities offered by timing with PPAC are rather limited, expecially for heavier residues at energies exceeding about 1 MeV/Amu. In fact, small area PPAC lead to small solid angles and large area PPAC have a time resolution of some hundred ps. Better results may be obtained by using MCP; however even in this case one needs flight lengths exceeding 1 m for heavy residues with energy exceeding a few MeV/Amu. This again implies quite small solid angles, a fact which may restrict the cross sections which can be measured.

Time resolution limitations are obviously less important for less energetic ions, but in this case energy resolution may become the leading factor in limiting the obtainable mass resolution.

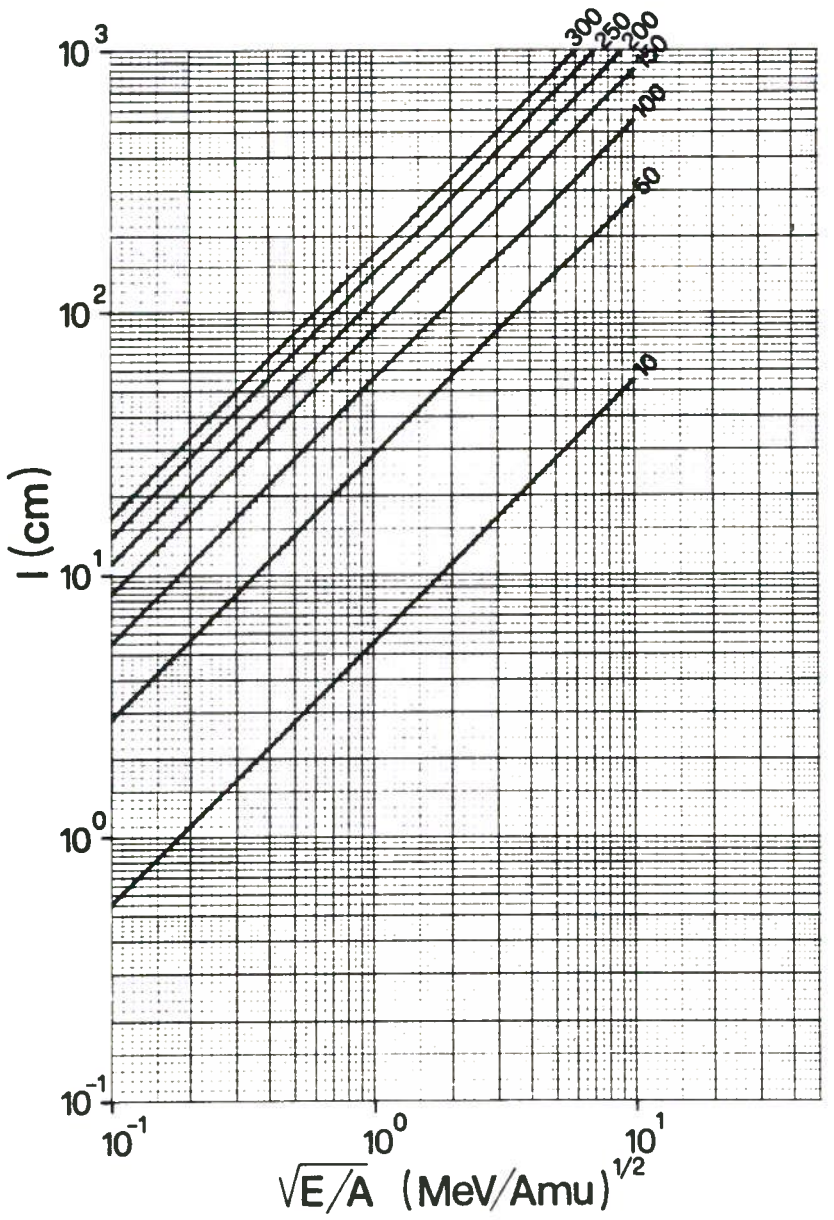

FIGURE 9 - Minimum path length for achieving a mass resolution ΔA = 0.5 Amu from T O F measurements, for a time resolution of 100 ps, assuming a negligible uncertainty in energy determination.

Most papers report that with gaseous counters an energy resolution of about 1% may be achieved. This obviously limits mass resolution to masses substantially lower than 100 even in the absence of any contribution from time resolution.

From a study by Bass *et al.*[31], one may relate the energy resolution, obtainable with SSD, to the residue mass through the following expression:

$$\frac{\Delta E}{E} \approx 5 \quad 10^{-3}(\frac{A}{E})^{1/2}(1. + 0.01A) \tag{14}$$

In Fig. 10, $\Delta E/E$ is shown as a function of the square root of energy per nucleon for various residue masses. The intercept of the lines labelled ΔA=0.5 and 1 with the straight lines gives the energy resolution necessary to achieve the indicated mass resolution, assuming zero contribution from time resolution. It may be seen that SSD detectors cannot allow mass separation for A$\geq$100 residues at energies below 1 MeV/Amu.

These considerations indicate that the possibilities offered by conventional ΔE–E–T O F detector systems are quite limited, expecially in the case of low energy heavy residues as produced in fusion and partial fusion processes. Further difficulties, both in the case of Bragg spectrometers and Counter Telescope–T O F systems arise from measurements at very forward angles where one must usually try to reduce detector damage and counting dead time by suitable means such as a beam stop and rejection of undesidered events by coincidence-anticoincidence methods.

3.3 Mass spectrometers

Mass resolution may be also obtained by use of spectrometers utilising electric and/or magnetic dipole fields and auxiliary detectors measuring the position of residues in the focal plane, their energy and energy loss, the T O F over the spectrometer flight length and possibly prompt and/or delayed γ-rays[32].

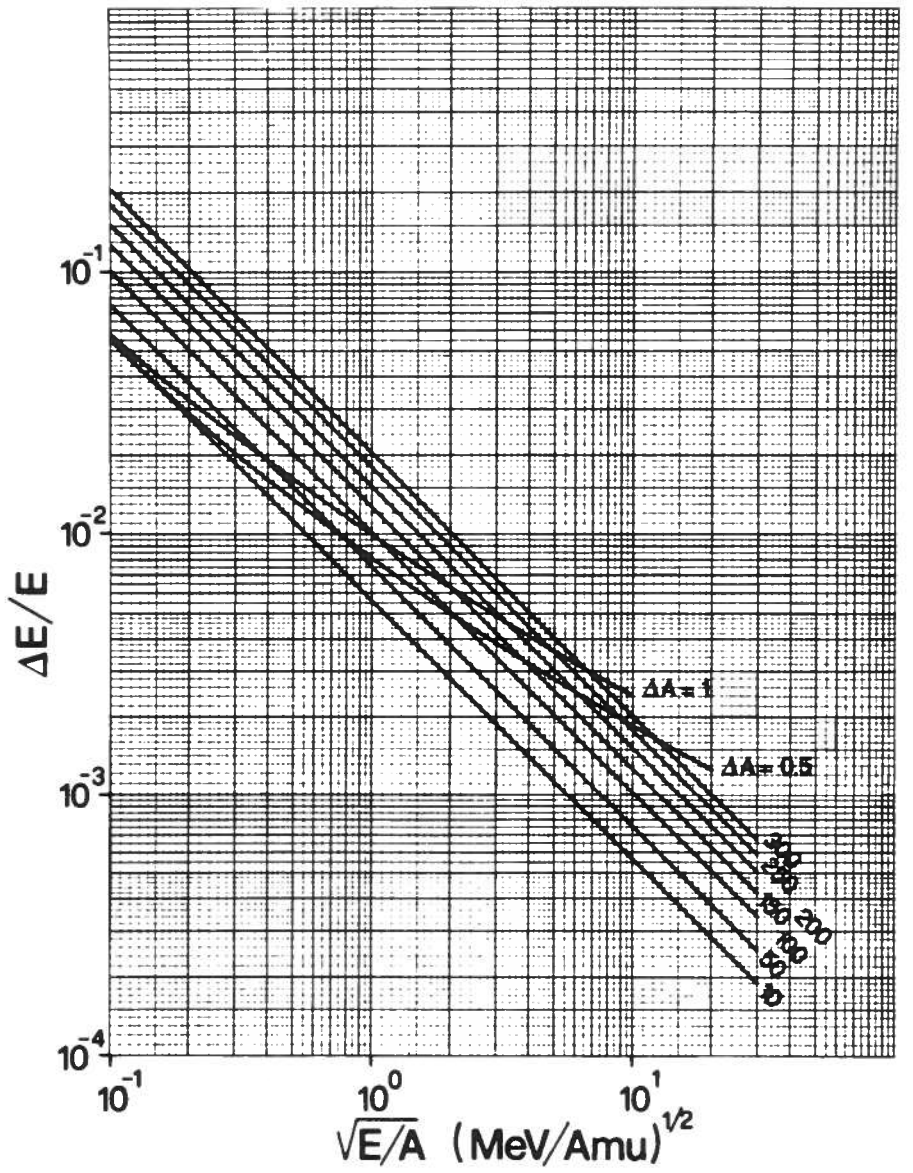

FIGURE 10 - Percentage error in energy determination with solid state detectors. The intercept of the lines labelled $\Delta A=0.5$ and 1 with the straight lines gives the energy resolution necessary to achieve the indicated mass resolution, assuming a negligible contribution from time resolution.

When comparing such devices with the possibilities offered by measurement of induced activity in catcher stacks, one has to consider the enormously different cost of such devices in terms of money for their construction, their housing, their use and maintenance. Other elements of comparison relate to the solid angle acceptance, the A/Z and energy ranges of the residues one may investigate in a single run. While the use of such devices seems to be unavoidable in particular experiments (for instance if one wishes to measure decay properties of new isotopes or to measure very small cross sections for production of stable isotopes) in many other instances the gain in their use may not be great when compared to the possibilities offered by activation technique methods.

3.4 Detectors measuring the energy of residues identified by means of their γ decay

As previously discussed, mass and charge identification of residues through measurement of their energy, energy loss and T O F may be impossible to achieve in several cases. One could try to *identify* the residues by in-beam γ–ray spectroscopy methods and their energy either directly or through T O F measurements. The energy resolution obtainable by either method (while insufficient to enable mass identification) is perfectly adequate for studies of reaction mechanisms.

In the case of measurements, at forward angles, of evaporation residues from fusion or partial fusion reactions, serious problems may arise connected with radiation damage, counting dead time, measurement of small cross sections in the presence of intense background and so on. However a few recent works, in which detectors are described which are able to reveal the weak production, at forward laboratory angles, of evaporative residues in the presence of strong fission competition, indicate that cross sections as small as a few mb may be measured[33,34]. Detectors made for the simultaneous measurement of the residue energy, at very forward angles, and of

the cross section for their production have not yet been described in literature, to our knowledge. Careful study for their planning and construction is, in our opinion, strongly advisable.

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