

## TRIPLE FOCUSING RECOIL SEPARATOR CARP AT RCNP

S. Morinobu, I. Katayama

Research Center for Nuclear Physics, Osaka University, Suita, Osaka 565 Japan.

H. Nakabushi

Department of Physics, Osaka University, Toyonaka, Osaka 560 Japan.

### Abstract

A reaction product mass separator (CARP) which is now being constructed for use with the AVF cyclotron at RCNP is described. This device is intended to separate unslowed recoiling products in nuclear reactions from the primary beam and to analyze them according to their charge-to-mass ratio. The use as a mass-spectrograph or as a mass-separator is available according to the experimental requirements. The solid angle and the energy range of acceptance will be 10 msr and 20%, respectively.

### 1. Introduction

The heavy-ion induced reactions have offered in the past decade a variety of unique tools in the experimental investigations of nuclear structures and nuclear interactions. The multiplicity of their reaction channels has helped many of the studies to access new phenomena which would not be observed with light ion beams. However, the multiplicity of the reaction channels itself has often made the experiments quite complex and as such has hampered the results therefrom to be fully informative. To identify final channels one has to determine the proton number  $Z$ , the mass number  $A$  and possibly also the kinetic energy  $T$  of the reaction products. The difficulty usually arises in the determination of  $Z$  and  $A$ , which has so far suffered from the rather poor resolution of the identification technique by the particle detectors, especially for medium weight or heavy products. Another important problem in the heavy-ion induced reactions is that the detection of the products has often to be carried out in a shower of undesired background particles. This is particularly so when one observes the fusion products which are emitted preferentially in the forward direction i.e., close to or in the high flux of incident beams and dirty particles.

The last problem has been greatly relaxed in the velocity filter systems at GSI<sup>1)</sup> and BNL<sup>2)</sup> by electromagnetically separating the products from the primary beams and transporting them onto the detectors. Such systems have proved to be quite useful in studying fusion products emitted in the beam direction but the devices themselves do not have any resolving power for  $Z$  and  $A$ .

Since the path of an ion in an electromagnetic field is determined by the charge-to-mass ratio  $q/m$  and the energy  $T$  (or equivalently the momentum  $p$ ), it is indeed possible to have a separation system which possesses resolving power for  $q/m$  as well. The separator of this type

will certainly provide us with a mean to directly determine  $A$  but not  $Z$  of the reaction products. It should be noticed that if a definitive determination of  $A$  is achieved, then it at the same time helps us considerably also to determine  $Z$  by the use of the other existing methods based on the detection of the particles or of the accompanying radiations. The largest merit of this type of separator is that the reaction products are mass-separated and hence will be detected without being masked by the large amount of products of the prevailing channels, if any. This fact will make it feasible to observe such low cross section events as, for example, the production of nuclei beyond the proton drip line.

From these view points, we have chosen to construct at RCNP an electromagnetic device which focuses the reaction products directly from the target onto the detector site with  $q/m$  dispersion. In the following, a brief description will be given of this device which is named CARP (Charge-to-mass Ratio Analyzer for Reaction Products) and now being constructed for use with the heavy-ion beams from our AVF cyclotron. The CARP will have a solid angle of about 10 msr and an energy range of acceptance of 20% (FWHM). We are expecting it to act as a mass analyzer in the reaction mechanism studies and as a mass separator in the decay spectroscopic works especially for the medium weight or heavy nuclei. The separators similar in concept separators are also currently under construction at Daresbury<sup>3)</sup> and MSU<sup>4)</sup>.

### 2. Basic Considerations

Before describing the design of the CARP, we briefly touch on the available reactions at RCNP and the behaviour of the recoiling products to get a practical idea about the separator.

Up to now, the heavy-ion beams of relatively light mass ( $A \leq 22$ ) are available at the energies of  $E/A \sim 10$  MeV from our AVF cyclotron. (The ion source developments for still heavier beams are actively in progress.) At this beam energy, the dominant reactions are fusion and transfer reactions. The latter includes the so-called deep-inelastic collisions also.

The cross section is the maximum in the fusion reaction and the recoil energies  $T$  imparted to the product nuclei are also the largest. This is the main reason why this reaction has been most successfully used in the experiments with existing separators<sup>2,5)</sup>. In our case, the  $A = 20$  beam ( $E/A = 10$  MeV), for instance,

will produce the  $A = 50 \sim 200$  fusion products of  $T = 80 \sim 20$  MeV with cross sections of several hundred mb or less. They are preferentially emitted in the forward direction. The angular and energy spread of the recoils are expected to be around or less than 100 mr and 10%, respectively, depending on the possible evaporation of light particles.

The transfer reaction may be characterized by the relatively small cross sections and small product energies. The emission angles are usually large typically around  $90^\circ$ . In the  $A = 5$  transfer reaction, for example, on the  $A = 100$  target with the same beam as in the above, a  $30^\circ$  deflection of the projectiles will result in a  $80^\circ$  emission of the products with energies around 10 MeV. In this case, the kinematic energy shifts of the products are so large as  $(1/T)dT/d\theta_{lab} \sim 0.8$ , which brings about an energy spread of 8% within the angular range of 100 mr. The cross section is expected to be less than several tens mb/sr and rapidly decreases as the projectile deflection angle increases i.e., the product emission angle decreases.

The nuclei produced in these reactions progress through and emerge out of the target with various ionic charges, which have close connection to the necessary size of the separator. Fig. 1(a) shows the mean (equilibrium) charge  $\bar{q}$ , which was calculated from the empirical formula by Nikolaev and Dimitriev<sup>6</sup>), as a function of the energy. It may be seen that typically a value of  $\bar{q} = 10 \sim 25$  is expected in our case, depending mainly on

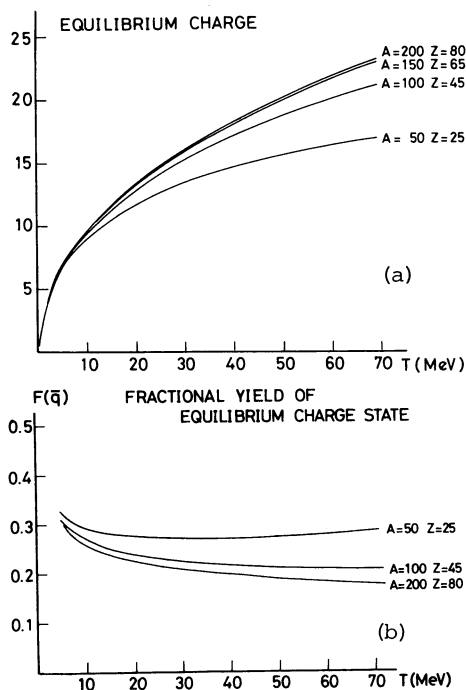


Fig. 1. Equilibrium charge of a particle with the mass number  $A$ , atomic number  $Z$  and kinetic energy  $T$  (a) and fractional yield of the equilibrium charge state (b).

the product energy. The collection efficiency of the separator with  $q/m$  dispersion is partly determined by the fraction of the products at the charge state of  $q = \bar{q}$ . Assuming a gaussian shape for the charge state distribution, the fraction may be estimated from the width formula<sup>7</sup>) as shown in fig. 1(b). The expected yield at the mean charge state is  $20 \sim 30\%$ . In the separator of present concern, the rest of the fraction may be the expense for requiring mass resolving power.

Another factor which may have a large influence on the collection efficiency is the multiple scattering of the products in the target, which causes additional spread in the emission angles. From the estimation<sup>6</sup>) shown in fig. 2, one may conclude that for the fusion products of  $T > 15$  MeV, a target of  $500 \mu\text{g}/\text{cm}^2$  or larger in thickness can be used without the serious loss of intensity, provided the angular acceptance of the separator is set to around 100 mr.

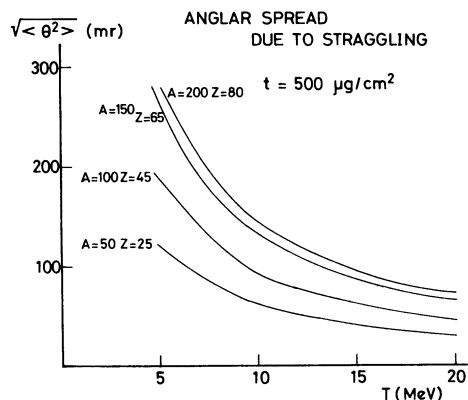


Fig. 2. Mean angular spread due to multiple scattering of a particle with the mass number  $A$ , atomic number  $Z$  and kinetic energy  $T$  in the solid materials of the same constituents.

### 3. Experimental Requirements

There are two different ways of using the separator depending on the types of experiments to be carried out with it. As mentioned before, one is the use in the reaction mechanism study where measurements of both the energy and mass spectra of the products are desired to obtain. The information on the angular distribution is also important there. Another use is in the decay spectroscopic work which requires as many products as possible to be transported irrespective of their energy into a low background area. The measurements are usually performed at a fixed angle of the maximum cross section. In both types of experiments, the collection efficiency should of course be as large as possible.

The CARP has been intended to meet these requirements in a single separator. An important problem arises here from the fact that there is a contradiction among

them in the availability of energy analysis. It is indeed possible to have a system which is dispersive both in energy and mass<sup>9</sup>). However, the energy dispersion would deteriorate the efficiency of the system in collecting the products in a small detection volume. The resulting expense in the product intensity is expected to be serious in the heavy-ion induced reactions where the energy spread due to kinematic effect and/or energy straggling of the products in the target is expected large as was partly discussed in the previous section. Therefore, since energy is the quantity which can most conveniently be measured by conventional detectors, it is the best way to have the separator possess the energy focussing rather than energy dispersive character.

There is also a difference in the use of the detection systems among the above two types of experiments. In the reaction study, one usually uses particle detectors which are less sensitive to the gamma or beta-ray background. Instead, as large a mass range as possible is required for the detectors to cover. In the decay spectroscopic works, on the other hand, the detectors are often for gamma or beta-rays and only one mass line is required to be transmitted. The only way to support these experiments with a separator will be to introduce two focussing positions in it, thereby separating the detector sites according to the experimental purposes. The focussing position for the reaction studies may be at a rather short distance from the last optical device of the separator possibly at the sacrifice of low background level, but a "focal plane" with mass dispersion should exist there. For the decay studies, the focal length should be long enough to allow the detector site to be shielded by appropriate materials. The focal plane may not necessarily be present there but a "focal point" for one mass should be present. The angular distribution measurements in the former will also become available if the vacuum chamber is made separable between these two focussing positions.

#### 4. System Descriptions

Based on the discussions presented in the preceding sections, we adopted the followings for the design guides of the separator:

- (i) The separator should be mass dispersive but not energy-dispersive.
- (ii) The mass resolving power should be  $m/\Delta m \geq 500$  to allow heavy product nuclei to be resolved.
- (iii) The angular range of acceptance be enough wide in both the median and transverse planes to cover emission angles of the fusion products i.e.,  $\Delta\theta$  and  $\Delta\phi \sim 100$  mr.
- (iv) The energy range of acceptance be  $\Delta T/T \sim 20\%$  or larger to prepare for the large kinematic and energy straggling effects.
- (v) The maximum energy accessible be

$T \sim 80$  MeV for the relatively light medium-weight particles at the equilibrium charge states.

- (vi) Two operation modes giving two different focussing positions should be available. They may be called the short arm and long arm modes according to the different focussing lengths. Preferably, a good focal plane be available in the short arm mode.

In order to achieve a mass dispersive device, one usually has to combine two different types of dispersive elements i.e., magnetic dipoles and electric deflectors. The so-called Wien filter<sup>10</sup>) consisting of the crossed electric and magnetic fields also has a dispersive character. However, it is not always possible to produce a magnetic field of a necessary strength in a rather wide pole gap containing electrodes and we have not chosen to use the filter in our separator.

The idea of the dimensions of these devices and the necessary field strengths may be obtained from fig. 3, where the electric and magnetic rigidities of the particles are shown for the equilibrium charge states given in fig. 1. One may note that the magnetic rigidity has a little dependence on the energy and does not exceed 10 kGm for the reaction products of present concern. The value is easily accessible with a rather small magnet having a mean radius of around 1 m or less. By contrast, the electric rigidity increases with energy and the slope becomes larger for the lighter mass particles. If one sets an upper limit of

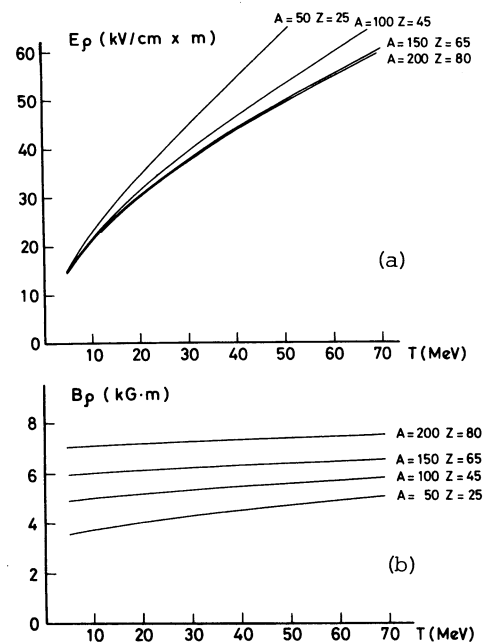


Fig. 3. Electric rigidity (a) and magnetic rigidity (b) of a particle at the equilibrium charge state. The mass number, atomic number and kinetic energy of the particle are denoted by A, Z and T, respectively.

the field strength achievable in vacuum at, say, around 20 kV/cm, it will result in that the electric deflector should have a curvature of a few to several meters to cover a wide enough range of the particle energy. In our case, the length of the system had to be less than 10 m to fit into the available experimental area, which restricted the electrode radius to no longer than 4 m. In practice, taking also the cost into account, the mean radii of the particle orbits in the electric and magnetic devices have been chosen to be 3 and 1 m, respectively.

Aside from the dispersive devices, there is a need for the employment of the separate quadrupole fields, if we require that two focussing positions be available. The use of such fields must follow the consideration to yield triple i.e., energy and doubly directional focus at both of the focal points. The achievement of a "good focal plane" at one focussing position (short arm mode) and a "good focal point" at the other (long arm mode) will further require corrective elements of the sextupoles and possibly also octupoles. They should preferably be devoted to the reduction of chromatic aberrations to obtain a wide range of energy acceptance.

Fig. 4 shows the adopted layout of the separator CARP, which may be abbreviated to a QDEQ system, with Q, D and E being the magnetic quadrupole, magnetic dipole and electric deflector, respectively. For the economy of the system length, no intermediate focus was assumed between the two dispersive fields of D and E. The fields were simply arranged so that the directions of the particle deflections in them be opposite with each other to achieve zero dispersion in energy at the two focussing points F1 (short arm mode) and F2 (long arm mode). The order of the arrangement D and E was determined from the considerations to enable the angular distribution measurements in the largest angular range within the limited

space of the experimental area. The selection of the focal points between F1 and F2 was made possible by switching on and off a weak quadrupole field between the fields D and E (not explicitly shown in fig. 4 but assumed in the element H2).

The optics calculations were performed with a computer code ORBIT<sup>11</sup>) which was especially developed in our group to enable the optimization of the optical parameters. The deflection angles of  $\phi_m = 55^\circ$  and  $\phi_e = 32^\circ$  in the elements D and E (see fig. 4) are the results of the detailed mapping of the phase space volume, which is a product of the solid angle and energy width of acceptance, in the  $\phi_m - \phi_e$  plane. In this mapping, the strengths of the quadrupole fields and exit angle of the dipole were calculated for every combination of  $\phi_m$  and  $\phi_e$  under the constraint of yielding triple focus at the focal points. The general tendency was that the smaller  $\phi_m$  is and the larger  $\phi_e$  is, the larger the phase space volume becomes. However, the practical considerations on the system magnifications, resolutions, field strengths and space limitations forced us to make a compromise. The coordinates of the particle orbits obtained for the present system are shown in fig. 5. It may be seen that the quadrupole Q1 acts to taper the particle envelope in the transverse plane to fit through the gap (9 cm) of the magnet D, and Q2 to adjust the slopes of the particle orbits to meet at the focal points.

The second order calculations were mostly concentrated in making the focal line at the short arm mode focal point F1 perpendicular to the beam axis and furthermore in achieving triple focus over the practically whole length of it. In general the directional and energy focal lines (denoted as  $\delta$  and  $\alpha$  focal line in fig. 4) deviate from each other and only intersect on the central trajectory. For this reason, the chromatic and geometric

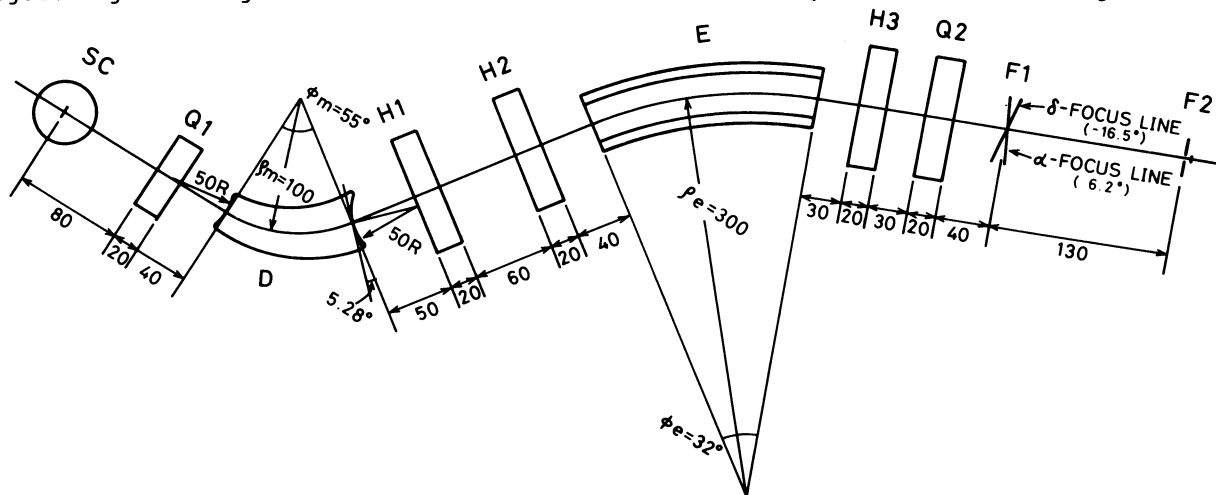


Fig. 4. Layout of the recoil separator CARP at RCNP. The lengths are given in cm. SC; Scattering chamber, Q1; First quadrupole magnet, D; Dipole magnet, H1; First sextupole magnet, H2; Second sextupole magnet, E; Electric deflector, H3; Third sextupole magnet, Q2; Second quadrupole magnet, F1; Focal point in the short arm mode, F2; Focal point in the long arm mode.

aberrations in the median plane had to be dealt with separately. This apparently is an impossible work to do with only the curving parameters at the dipole field boundaries. We could approximately attain our aim by introducing three sextupole magnets (H1, H2 and H3 in fig. 4) together with the aid of the re-adjustment of the focussing length in the short arm mode. In the present design, the relative angle of the two focal lines is made as small as  $23^\circ$  and there practically is "a triple focal line" inbetween. The introduction of the sextupoles was also quite effective in the long arm mode in reducing the chromatic aberrations in the median plane. Those in the transverse plane were again minimized by re-adjusting the focal length but the relative angle of the two focal line remained at about  $110^\circ$  in this case. The third order chromatic aberrations were finally treated for both the modes by admixing octupole components in these corrective sextupole and the first quadrupole (Q1) fields. The obtained specifications of the separator CARP are summarized in Table 1. The expected spectrum calculated by simulating the particle rays which are uniformly distributed both in emission angles and in energy are shown in fig. 6 for the two focussing modes of the short arm and long arm ones. The transmission in the short arm mode was found to vary by about 20% in the present simulation as one goes from the center to the edge of the focal line.

## 5. Summary and Application

The mass separator for reaction products CARP has been designed for use with the cyclotron at RCNP and is now under construction. This device has a structure which may be abbreviated to a QDEQ system and achieves triple i.e., energy and doubly-directional focus for two modes of operation. In one mode of operation, there is a good focal line of 20% mass width and in the other a focal point for one mass line at a reasonably long distance from the last optical device of the system. These facts together with the large solid angle of 10 msr will allow the use of the CARP both as a mass spectrograph in the reaction mechanism studies and as a mass separator in the decay spectroscopic works. The application to the in-beam spectroscopic study will also be feasible in both types of usages. Requiring also coincidences between the products on the focal plane and the radiations detected by other detectors will lead to the detailed understanding of the nuclear phenomenon under investigation. Fig. 7 illustrates the possible arrangements of the detectors currently being considered to cover these experimental purposes. To take the full advantage of the CARP, its support should be pivoted at the target center in as large an angular range as possible. In the present design, however, the range available is only  $-10^\circ \sim 30^\circ$  to the beam, which has resulted from the space limitations of the experimental area. We are expecting in the future that we will be able to transport the beam onto the target also from another direction, which allows the CARP to effectively reach

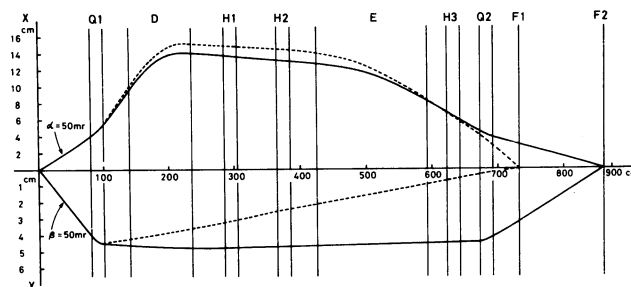


Fig. 5. Calculated trajectories of a particle with the central mass. The trajectories in the short arm mode are shown by dotted lines and those in the long arm mode by the solid lines.

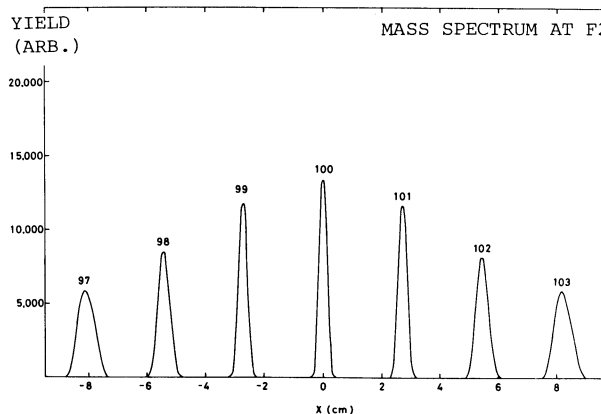
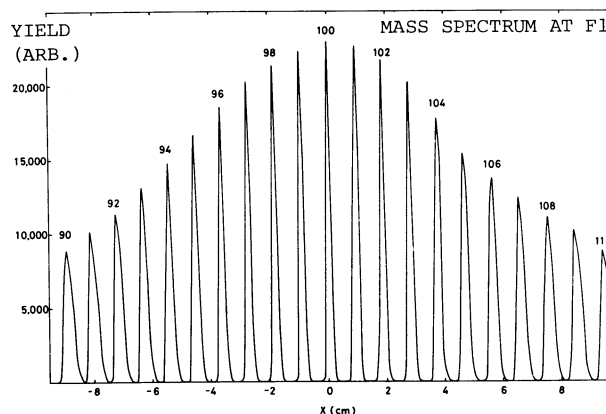


Fig. 6. Calculated line profiles on the plane perpendicular to the central ray for the short arm mode (upper) and the long arm mode (lower). The mission angles and energies of the particles are assumed to be uniformly distributed within  $\Delta\theta$ ,  $\Delta\phi < 100$  mrad and  $\Delta T/T \leq 20\%$ . The source width and height are 1.5 and 3 mm, respectively. The optical transfer matrix elements in the second order approximation have been used. The numbers placed at the top of the peaks denote the relative values (%) of  $m/q$  ratio.

Table 1. Specifications of the CARP

	short arm mode (F1)	long arm mode (F2)
mean orbit radius in D	100 cm	
maximum magnetic field in D	10 kG	
maximum magnetic rigidity	1000 kGcm	
mean orbit radius in E	300 cm	
maximum electric field in E	25 kV/cm	
maximum electric rigidity	7.5 MV	
maximum energy	3.8 MeV/charge	
solid angle of acceptance	10 msr	
mass range	10 %	—
energy range	20 %	20 %
mass dispersion	92.2 cm	271.6 cm
magnification in median plane	-0.71	-2.2
magnification in transverse plane	-9.0	-2.1
mass resolution (1 mm wide beam spot)	1310	1230
directional focal line angle	-16.5°	-55°
energy focal line angle	6.2°	5.3°
total path length	730 cm	860 cm
second order aberrations	0.2 cm	0.1 cm

the angles of up to 90° or larger.

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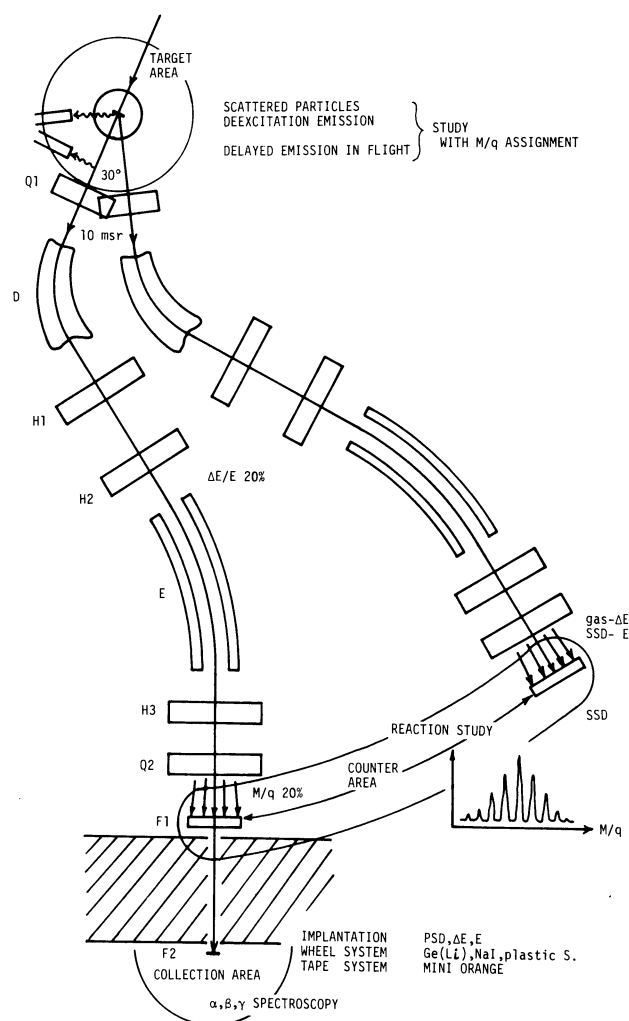


Fig. 7. Possible arrangements of the detection systems for the reaction products and other radiations, as expected in the practical experiments of various types.