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AN IMPROVED AND MODULAR HELIUM-JET RECOIL-TRANSPORT SYSTEM FOR THE STUDY OF SHORT-LIVED NUCLEI

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An improved, modular helium-jet recoil-transport system for the study of short-lived ($t_{1/2} \lesssim 0.2$ s) is described. Its target irradiation assembly consists of modular pieces, allowing the interchanging of different target holders, different recoil-thermalizing chambers, etc., for economical and convenient setting up of each experiment. A remote-control degrader package allows rapid control of accelerator beam energies. Improved target-preparation techniques are described, including compacting oxides onto foils with a hydraulic press. Auxiliary equipment such as gas supplies, capillaries, pumping equipment, and a stepping tape drive for the counting chamber are described. Different detector arrays and assemblies are used for different kinds of nuclear spectroscopy, and data are presented for some of these, including γ-ray, γ–γ megachannel (multiparameter) coincidence, and β-delayed proton spectroscopy.

1. Perspective

Since the advent of the helium-jet recoil-transport (HeJRT) method in 1962–63 [1,2]), it has undergone a myriad of variations and improvements at many different laboratories. From systems having a simple orifice feeding directly onto an α detector it has developed into complex and sophisticated systems having long capillaries that lead into low-background laboratories far from the target area[3,4]). It has even become possible to perform chemical separations and mass identifications on-line with HeJRT systems[5]). And although the detailed mechanisms of what makes HeJRT systems "work" still remain largely unknown, a fair body of empirical methodology has been developed from which we have gained some insight into the inner workings of these systems[6,7]). Suffice it to say that HeJRT systems have become extremely convenient if not quite essential for the study of nuclei far from stability, and with their recent couplings to on-line isotope separators[8,9]) they have become even more important.

For the past number of years we have been working on innovations and improvements in HeJRT systems in this laboratory, and, partly through systematics and the published results of others, partly by trial and error and serendipity, we have developed a very efficient and easy-to-use modular HeJRT system. In this paper we describe this system. Because much of the empirical systematics of HeJRT have already been published (e.g. ref. 6 and references therein), we limit ourselves to a discussion of the hardware of our particular system and to the salient points that make it work as it does. We then give some examples of its use in studying exotic nuclei far from β stability and its suitability for forming the first stage of an on-line isotope separator.

2. Target irradiation assembly

2.1. Modular target assembly

The target assembly for the HeJRT system is shown in fig. 1. It is of a modular design and is not enclosed in the customary larger container of helium. Each of the components is separate: beam window, collimator, absorbers, target holder, capillary exit flange, etc. All the components are of (local) standard design and are interchangeable. Accordingly, the assembly allows great flexibility in the design of an experiment, and changes are easily made during pauses in an experiment simply by loosening the two wing nuts and sliding in or out new or replacement components. This allows us to make radical changes in the assembly with a minimum of machine-shop time (by not duplicating

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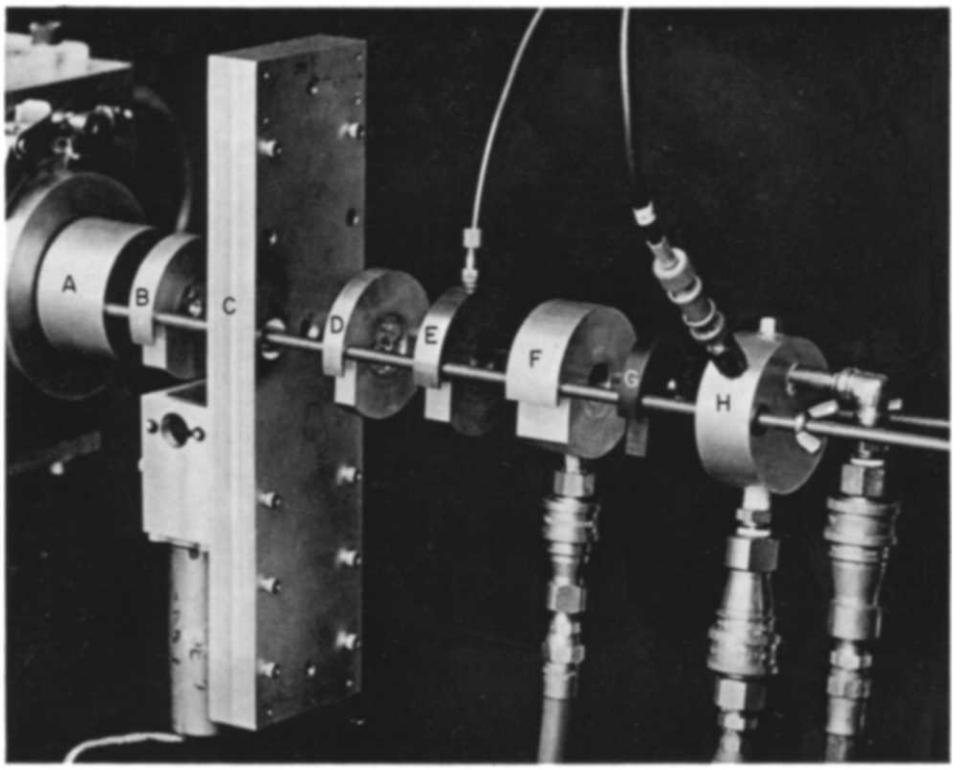

Fig. 1a. Photograph of the modular HeJRT system on the end of a cyclotron beam pipe. The components have been shoved apart for this "exploded" view. For use they are fitted tightly together with "O" rings and the two wing nuts are tightened. The modules are: A, Attachment to end of beam pipe; B, beam collimator, C, absorberdorber; D, target holder; E, capillary exit portion of recoil chamber; F, helium entrance portion of recoil chamber; G, insulator; and H, water-cooled Faraday cup.

the unaltered components) and a minimum of experimental set-up time. It also allows us to minimize trouble-shooting and break-down time – for example, spares are kept for most of the components, especially those such as foils which are easy to burn out or damage. This HeJRT system now is run typically in one of two standard configurations, steady flow[6,7]) and pulsed flow[10]), and work is proceeding on a third "standard" configuration, compound-gas flow, discussed below. Conversion among these can be accomplished by simply interchanging recoil chambers.

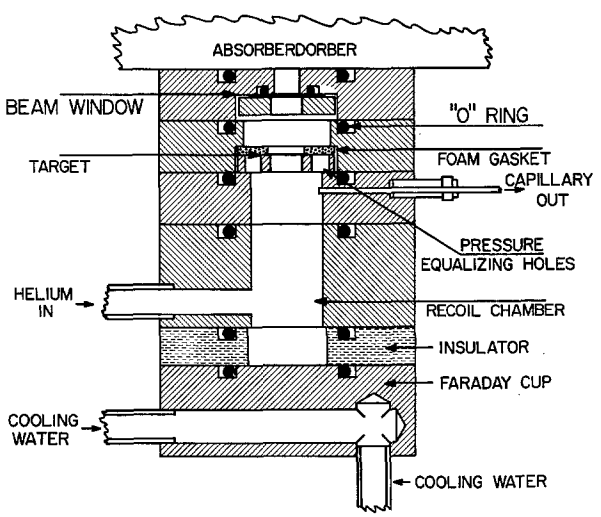

Fig. 1b. Drawing of the modular HeJRT system in an operational configuration.

Only two details about the target assembly components warrant discussion here. First, two holes drilled through the target frame holder connect the recoil chamber with the space between the beam window and the back of the target, as shown in fig. 2. This helps protect the target from large pressure differentials, and a thin foam rubber gasket covering the holes effectively provides a barrier that prevents recoils generated in the beam window from entering the helium flow into the capillary. Second, the target assembly has a "recoil chamber", $\approx$3.8 cm long, added after the target frame holder, when all that is necessary to stop typical recoils from the target is a piece less than $\approx$1-cm long used to

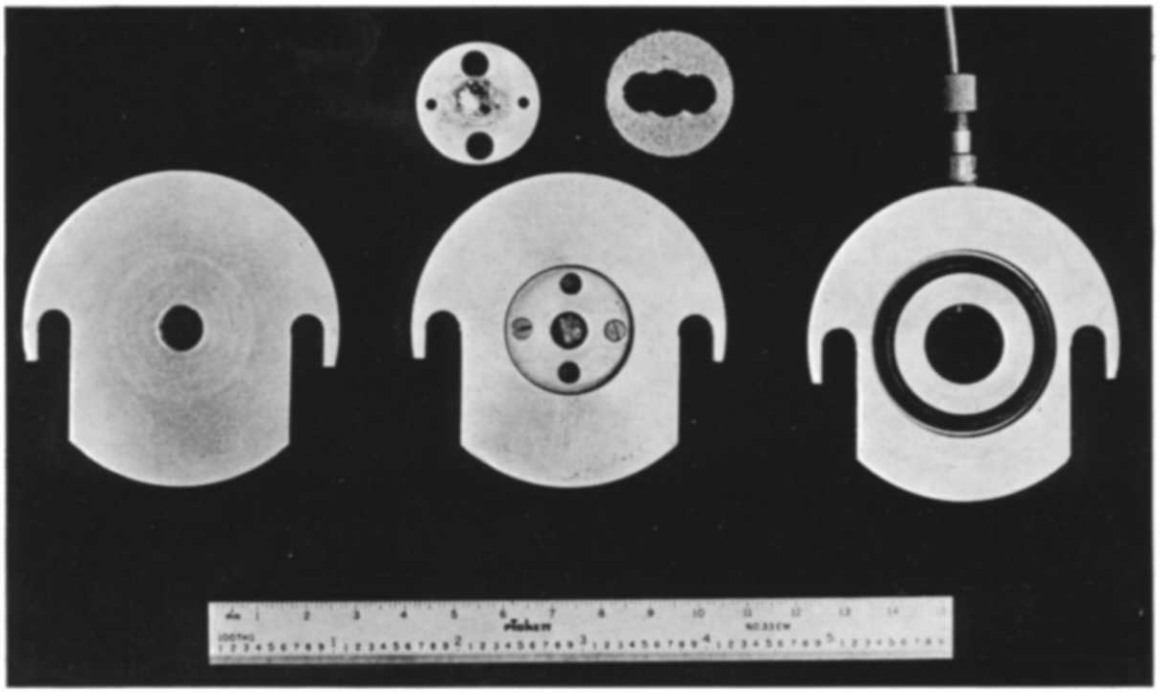

Fig. 2. Photograph of collimator, target holder, and capillary exit modules. The foam rubber gasket and the pressure-equilizing holes are shown separately above the target module.

feed the helium. This added length provides a small increase in transport efficiency when the HeJRT system is run using a very low level of cluster-generating impurities – it provides an added volume (hence, time) for the clusters to develop in the plasma of the beam[11]).

The compound-gas flow configuration mentioned above is the combination of a high-purity (i.e., cluster-free) helium-jet system and an ethylene-cluster transport system[12]). (An ethylene-cluster transport system cannot be used directly in the plasma of an accelerator beam because of polymerization and decomposition.) It has a conventional recoil chamber behind the target which is supplied with high-purity helium. The jet of helium leaving this chamber, however, travels only ≈ 1 cm before it enters a second chamber. Thus, the recoil activity supplied to the second chamber is free of the cluster to which it would normally be attached in the standard continuous-flow configuration. A supply of ethylene is fed to the second chamber under conditions (e.g., above its critical point) favoring the presence of ethylene clusters (aerosol droplets). At this point the recoil activity can become bound to the ethylene clusters for transport through a capillary to our counting area. The purpose of attempting to substitute non-irradiated ethylene droplets for the irradiated benzene or water clusters that we normally use lies in the nature of the clusters. We hope the ethylene clusters will be easier to drive off the collecting surface when making "mass-free" sources – this is especially important in coupling the HeJRT system to a time-of-flight on-line isotope separator[9,10]). To date we have had only partial success with this compound-gas flow system, primarily because of residual benzene, pump oil, etc., that is very difficult to eliminate from the system, but further developmental work is in progress.

2.2. Absorberdorber – remote-controlled absorber package

A permanent feature of the target assembly is a remotely controllable beam-energy degrader package – "absorberdorber". This is shown in fig. 3 and consists simply of a pair of motor-driven aluminum slides machined in places to various degrader thicknesses. One ranges from 0.00–0.056 cm (0–22 mil) in approximately 0.0076-cm (3-mil) steps, and the other from 0.00–0.51 cm (0–200 mil) in 0.064-cm (25-mil) steps. It is thus possible to degrade beams of light ions in sub-MeV steps. The slide positions are read out digitally to indicate the degrader thickness, and it has become all but trivial to generate excitation functions to aid in the identification of new nuclides and the optimization of their production.

2.3. Target fabrication

We have made significant progress in the area of target fabrication for the HeJRT system. In the past one had the option of using self-supporting foils, targets evaporated on a backing foil, powdered targets glued to a backing foil, or gaseous target materials added to the helium supply. Self-supporting foils of separated isotopes are very expensive and fragile, require much time to make, and do not stand up well to bombardment. Targets evaporated onto foil backings are still expensive and require a significant time to make, and we have had some problems with the target material evaporating off the backing during bombardments. Our experience with targets made by coating a backing with a film of adhesive and then dusting on a layer of powdered target material has not been particularly rewarding either. Here we had problems with the target material falling off the backing during bombardment, and we had problems with fabrication of uniform targets. The main problem with gaseous targets is of course that of finding volatile materials sufficiently isotopically enriched. Also, in cases where this is possible and economically feasible there is the added requirement that it not interfere with the clustergenerating mechanism.

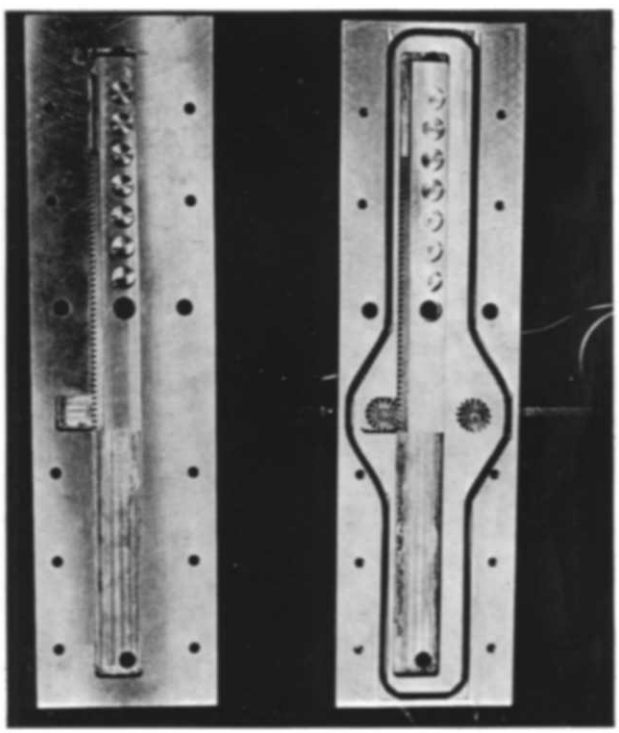

Fig. 3. Photograph of the insides of "absorberdorber", the remotely controllable beam-energy degrader package. The movable Al slides have been machined to varying thicknesses one from 0.00–0.056 cm in 0.0076-cm steps, the other from 0.00–0.51 cm in 0.064-cm steps.

We now use two new techniques for HeJRT target fabrication. The more generally applied one involves pressing powdered target materials onto a foil (usually Al) backing. We use pressures in the range of 28 000 kg/cm^2 (200 ton/in.^{2}) generated with a hydraulic press [a 15 500 kg (17 ton) press purchased from an automotive parts supplier as a wheel puller]. Targets are now fabricated with the die set shown in fig. 4; however, until recently a much less elegant apparatus was used with comparable results. Targets are normally 0.71 cm in diameter on a 0.005-cm (2-mil) Al backing previously affixed to a 2.5-cm circular frame. We typically use between 5 and 10 mg of target material, although targets using less material are possible with this procedure. This represents something of the order of a threefold savings over the amount of target material needed to reduce and evaporate a 1 mg/cm^2 target that might typically be used in a HeJRT system. Targets made with this pressing technique are extremely durable, oxide targets generally having a glassy appearance. An attempt to separate the target from the backing will generally destroy the backing before it can be accomplished. A final attractive feature of these targets is the small amount of time required to make one, normally less than 5 min. Some of the targets made recently with this technique for nuclear spectroscopic studies are oxides of ^{106}Cd, ^{141}Pr, and ^{144}Sm.

The second technique is just a modification of the technique where glue bonds a thin layer of target material to a foil backing. We have had surprising success working with a slurry of metal powders as target material and "Zip-Grip 10" (a moisture catalyzed poly-amide adhesive manufactured by Devcon Corp. Danvers, Mass.) as the adhesive for coating foil backings. (We have not investigated many other

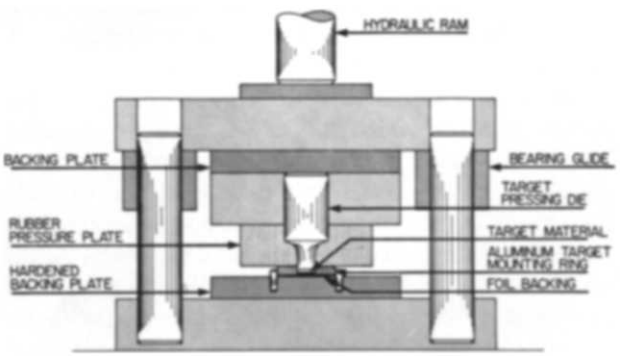

Fig. 4. Drawing of the die set used for pressing oxide targets onto thin foils.

adhesives, but there are undoubtedly others that should work as well.) In our initial attempts we ground off the surface of the metal–Zip-Grip composite in order to expose a surface of metal granules. However, we found this to be unnecessary and found that no additional preparation is necessary. Targets that were untouched after the adhesive had set up gave recoil yields comparable to those that were ground. This was more than a little surprising, but presumably the coating of adhesive over the metal granules is thin enough not to interfere significantly with the recoils leaving the target. Again, as with the previous technique, the targets are durable, relatively inexpensive, and both quick and easy to make; however, this technique will not work with oxides that catalize the setting reaction of the adhesive, and, when attempted with these oxides, produces targets that contain lumpy globs of material. One target made recently with this technique is ^{92}Mo.

2.4. System performance

Deterioration of the performance of the HeJRT system with time as a result of material building up on the target and in the capillary has been largely eliminated by three simple procedures. First, care is taken to evacuate the target assembly repeatedly and to flush it with helium to exclude residual amounts of air (presumably oxygen or water vapor is the culprit) from the assembly. When this is not done, there is often a rapid build-up of dense clusters in the assembly and in the first few cm of the capillary. Second, helium is kept flowing through the target assembly at all times

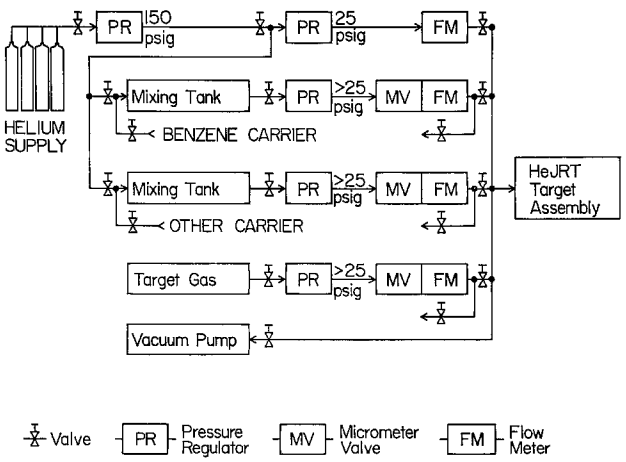

Fig. 5. Diagram of the gas supply system for the HeJRT system. This allows one to mix small, well-regulated amounts of impurity "carriers" into the He supply and also allows one to use gas targets. ("Psig" or pounds per square inch gauge should have 1 atm added for true pressure; thus, 25 psig $\approx$ 2.8 kg/cm^2.)

that the beam is on target in order to help keep the target cool. When the target heats up, the rate of building of a layer of carbon-like substance (presumably from the decomposition of clusters or the cluster-generating impurities) on the target is accelerated. Third, the level of cluster-generating impurities added to the helium flow is kept low ($\leqslant$20 ppm) in an attempt to limit the necessity of the first two precautions. The efficiency for thermalizing recoils and extracting them into the capillary varies with target and with the chemical identity of the element, but when the above precautions are observed it can run well above 50% for many hours.

3. Auxiliary hardware: gas supplies, capillaries, pumping equipment, and tape drive

3.1. Gas supplies

Four separate gas flows can be metered and mixed into the target assembly. A diagram of the plumbing involved is shown in fig. 5. Liquid vapors and atomized liquids can also be introduced into the flow of gas, and this flow can be subjected to an electric discharge or ultraviolet radiation. Thus, it is possible to set up the HeJRT gas supply in a great variety of configurations. However, this collection of equipment is used mainly in experiments intended to develop new techniques [such as chemical separations[5]) and "plasma chemistry" in the target chamber itself[7,13])], and our "standard" gas supply set-up (used in $\geqslant$90% of our experiments) is a simple one. We use a commercial grade of helium (>99.995% purity) fed at a gauge pressure of $\approx$1.7 kg/cm^2 ($\approx$25 psig) to the target assembly. To this we add a second flow typically throttled to $\approx$1% of the primary flow. This second gas is a mixture of helium and benzene vapor made up to a concentration of 1000 ppm, thus yielding a final concentration of $\approx$10 ppm benzene by volume in the helium fed to the target assembly. [Other hydrocarbon impurities also work well, as do water vapor, pump oil, and a wide variety of extraneous impurities[6,7]). In fact, it is possible to perform "plasma chemistry" and achieve reasonable variations in the transport efficiencies of different elements [13]) by varying the types and concentrations of the cluster-forming impurities. A more detailed discussion of this will form the basis for a future publication.]

3.2. Capillaries

While we have used glass, stainless steel, teflon, and polyethylene capillary tubing to transport activities to the counting area, we prefer polyethylene (with teflon

a close second) because of its ruggedness, low cost, and flexibility. One does not have to worry much about keeping it from crimping, and it can even be tied in (gentle) knots without severely affecting its performance. The present capillary is a single piece 15 m in length with an inside diameter of 1.4 mm. Normally, many are strung at once, so if the efficiency of a particular capillary decreases because of the buildup of deposits on its inside walls (usually after a few months), we can switch to another one. One can rejuvinate a dirty capillary by flushing it out with acetone or a similar solvent; however, because of the low cost of polyethylene we have found it easier just to switch capillaries. Using one of these capillaries with a target assembly pressure of 1.7 kg/cm^2 (25 psig) and running into a vacuum of $\approx$10 torr at the counting end, we experience a helium flow rate of $\approx$110 cm^3/s STP. The time required to transport activities to the counting area varies with the target assembly; indeed, the thermalizing chamber behind the target contributes a large amount of delay, but we have experienced transit times of $\approx$0.2 s for a 15-m length with typical set-ups. For a further discussion of capillaries and the flow characteristics, see refs. 6 and 7.

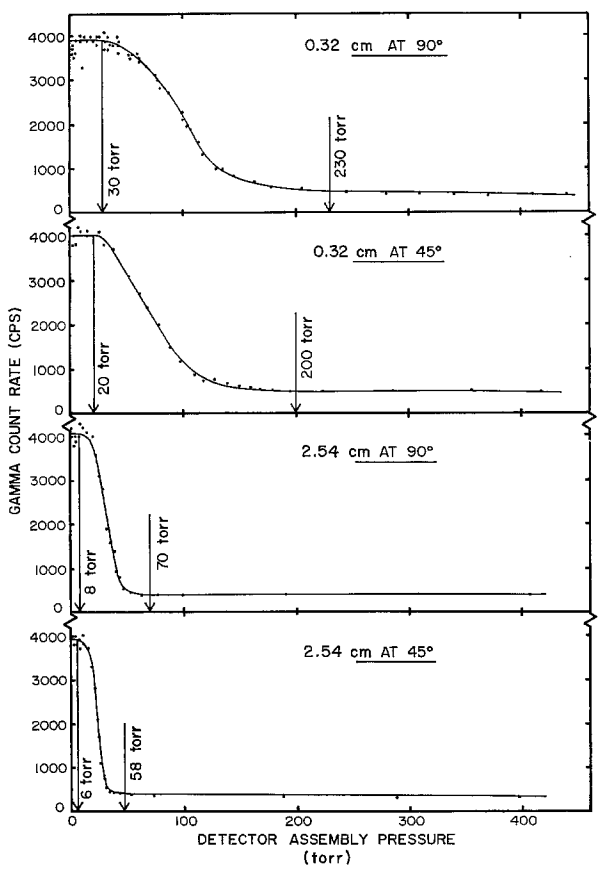

Fig. 6. Curves expressing the relationship between detector-assembly pressure and total system efficiency for various capillary-to-tape angles and distances.

3.3. Pumping system

Although our initial pumping system had a capacity of 8.5×10^3 l/min (300 ft^3/min), our present system works well using only a 4.2×10^2 l/min (15 ft^3/min) mechanical vacuum pump. And when we are performing external chemistry (cf. section 4.4), we use no vacuum pump at all. Thus, the pumping requirements for the system are minimal. We have found no loss in the total system efficiency when running into a vacuum until the pressure rises to $\approx$20 torr [7]). At this point the efficiency for collecting recoil activity leaving the capillary starts to fall off rather gently, as shown in fig. 6. The smaller (4.2×10^5 cm^3/min) pump is able to draw our detector system assembly down to $\approx$8 torr, which is adequate for charged-particle detection. However, the gas load on the pump is such that it tends to run hot and thus requires more maintenance than normal. Again, for a more detailed discussion of pumping requirements, see refs. 6 and 7.

3.4. Tape drive

Activities transported through the capillary are sprayed onto a collecting surface in the detector assembly. This collecting surface is usually a moving tape which can be advanced in either direction at speeds up to 25 cm/s by a tape drive external to the detector assembly. The most frequently used tape is 2.54-cm paper tape (computer perforation tape – Singer P/n 1218 tape); however 2.54-cm aluminized Mylar and 1.27- or 1.91-cm magnetic computer tape can also be

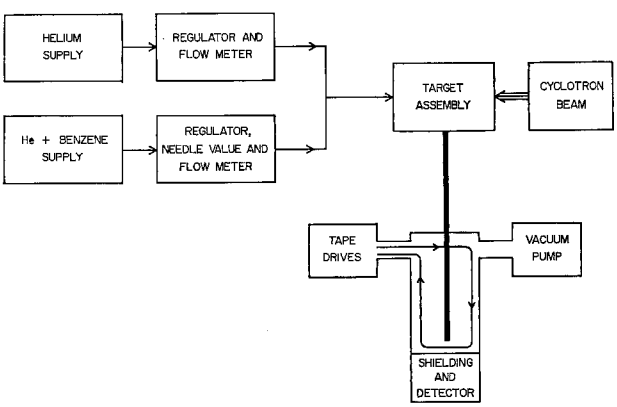

Fig. 7. Block diagram of HeJRT system set up for a straightforward γ-ray singles experiment.

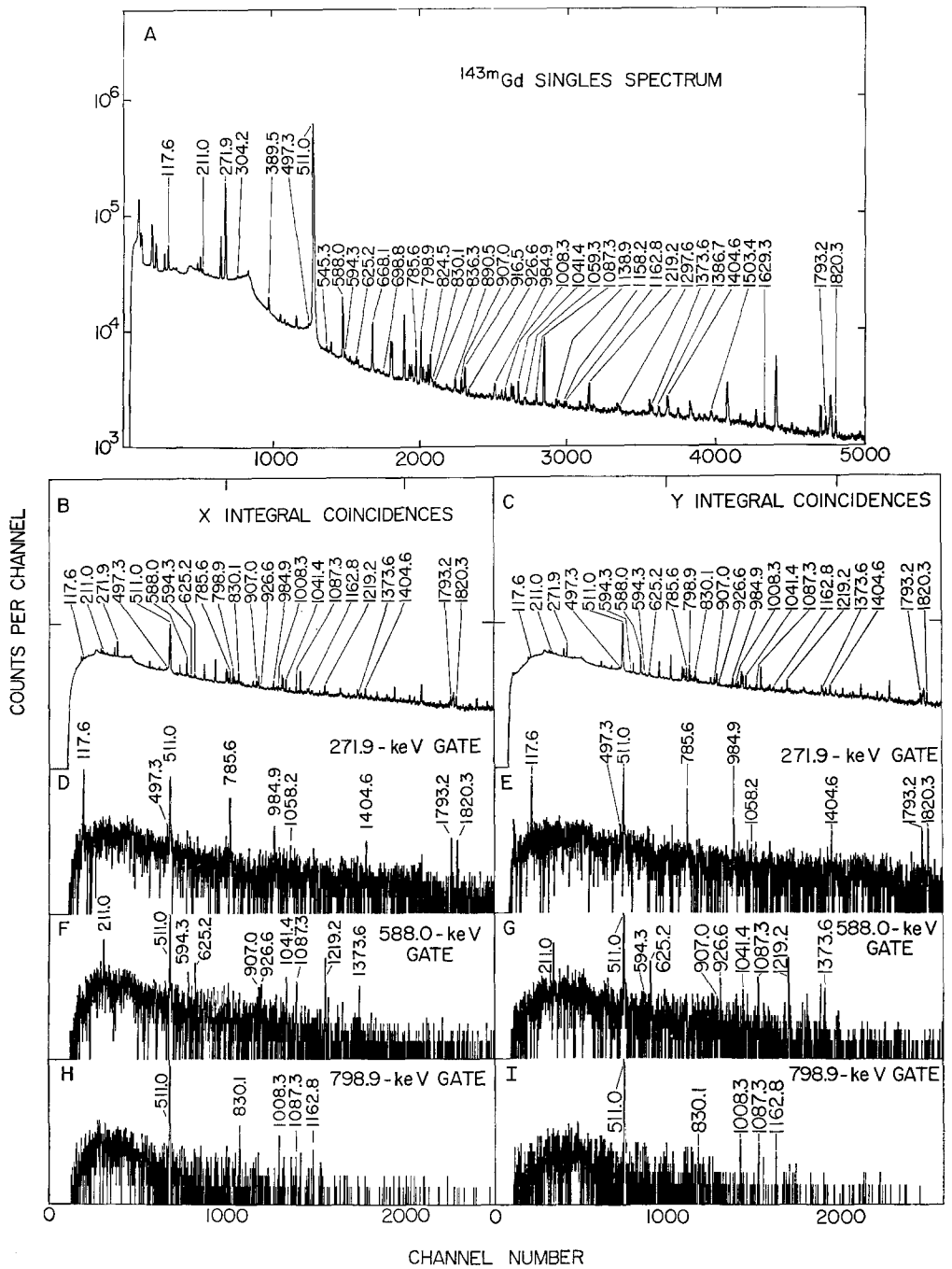

Fig. 8. Sample γ-ray spectra obtained using the configuration described in sect. 4.2. These spectra were obtained from 39-s ^{143g}Gd and 112-s ^{143m}Gd, produced by the ^{144}Sm$(\tau, 4n)$ reaction. A, Singles spectrum taken with an 18% efficient Ge(Li) detector; B, integral coincidence spectrum taken with a 10% efficient detector, using the 18% detector as the gating detector; C, integral coincidence spectrum with the detectors reversed; D and E, respective gated spectra in coincidence with the 271.9-keV γ, which deexcites the $7/2^+$ first-excited state in ^{143}Eu and consequently other relatively low-spin states from above; F and G, also H and I, gates on γ rays that deexcite 977.5- and 1188.4-keV states which are states in a multiplet of (three-quasiparticle) high-spin ($9/2^-$, $11/2^-$, $13/2^-$) states in ^{143}Eu.

used. Fig. 7 shows a block diagram of the HeJRT system set up for a simple γ-ray singles experiment. The tape is advanced using a capstan-pinch roller assembly driven by a stepping motor. The speed of the tape is set to a precision of $\pm 1\%$ using a pulse generator and can be monitored to a precision of $\pm 0.1\%$ using a frequency counter when running at average tape speeds, assuming no slippage of the tape on the capstan. Hooked in with the pulse generator is a sixteen-channel preset sequencer (Electronic Counters and Controls, Inc. Lake Bluffs, Ill.), which can have the intervals set independently of one another. In addition to controlling the motions of the tape, this sequencer furnishes logic pulses that are used for routing spectra, turning the cyclotron on and off, and other useful tasks for performing complex spectroscopy.

4. Detector assemblies and arrays for spectroscopy

4.1. Singles experiments

The capillary feeds into an evacuated box approximately 22 cm × 26 cm by 18 cm deep. This box has a removable plexiglass top through which one can view the detectors, the capillary, and the moving tape onto which the activity is sprayed. The detector assembly was designed to allow considerable flexibility in the selection of experimental arrangements. There are three ports for external detectors such as Ge(Li) γ-ray detectors that require cryostats. Smaller detectors such as surface-barrier Si detectors for charged particles can be mounted inside the evacuated box. One arrangement is a detector telescope used to detect β-delayed protons. Provision has been made to enhance selectively activities having particular half-lives by allowing arbitrary positioning of the nozzle spraying activity onto the tape and by arbitrary choice for the speed of the tape carrying the activity to and past each of the detectors. During an accumulation, say, of γ-ray spectra for energy determinations, a collection of standard sources can be mounted within the box and counted simultaneously with the activities deposited on the tape.

4.2. Coincidence experiments

Although the design of the detector chamber is flexible enough to allow a wide variety of coincidence experiments, to date we have used it only for Ge(Li)–Ge(Li) γ–γ multiparameter coincidence experiments. The detectors are slid into "top-hats" from opposite sides of the chamber for end-to-end geometry. (One detector can be slid in from an end of the chamber if 90° geometry is preferred.) There is a tapered, graded (Pb–Cd–Cu–Al) absorber between the detectors. The tape for these experiments is 1.27-cm magnetic computer tape and is run around the edge of the absorber. This geometry is very effective both in terms of detector solid angle and for eliminating Compton scattering between the detectors[14]). (The geometry is not quite 180° because the activity on the moving tap is offset from the center line of the detectors.)

An example of the use of this coincidence arrangement is given in fig. 8, which shows some γ-ray spectra from the decays of 39-s ^{143g}Gd and 112-s ^{143m}Gd. Singles and sample coincidence spectra from a 4096 × ×4096 megachannel coincidence experiment[14]) are shown. These nuclides were produced by the ^{144}Sm(τ4n)^{143}Gd reaction, using a 70-MeV τ beam from the MSU sector-focused cyclotron and degrading it with absorberdorber. Excitation functions obtained in this manner are shown in fig. 9.

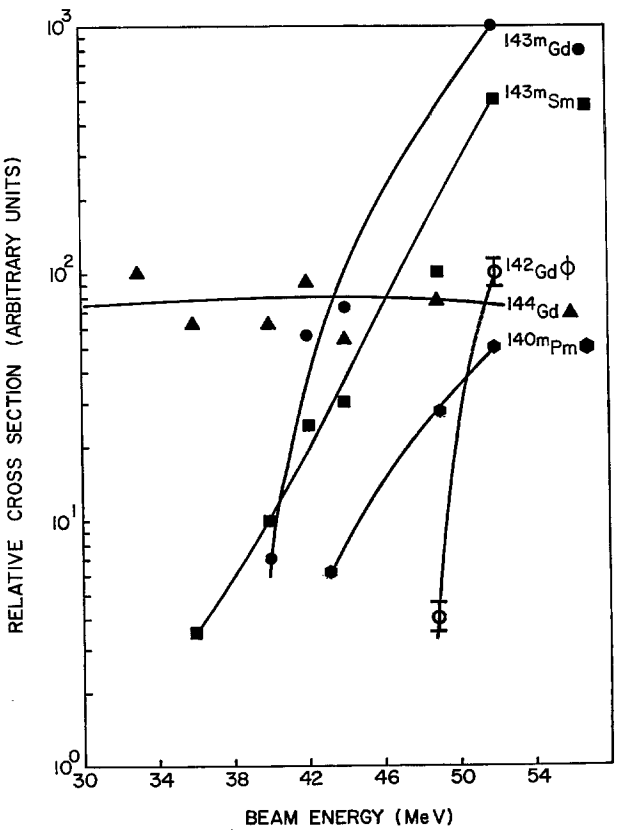

Fig. 9. Excitation functions obtained for various ^{144}Sm(τ, ?) reactions using the HeJRT system with "absorberdorber". One important point that should be noted is that "charged-particle out" (mostly p and α) reactions compete quite favorably with (τ,x n) reactions in this region relatively far from β stability. Thus, the excitation functions are not expected to and indeed do not follow simple bell-shaped curves.

4.3. Half-life determinations

After a half-life has been estimated from spectra collected at various tape speeds an accurate determination can be made. A source is made by collecting on the tape while it is stationary. This source is then advanced to a detector where it is counted for timed intervals and stored as separate spectra. The source that was collected while counting was taking place is disposed of by advancing the tape past the detector. The procedure is then repeated. The 16-channel preset sequencer is programmed to control all tape movements and to route spectra within the computer. (In cases when the tape speed might be too slow, we anticipate using a shutter assembly to interrupt the flow of activity in the detector assembly.) Fig. 10 shows some half-life curves obtained for $^{143m+g}$Gd by these procedures.

4.4. Fast on-line chemistry with the HeJRT system

Some time ago we found it was readily possible to couple the HeJRT system to an on-line system for performing fast aqueous chemistry[5,15,16]). This is accomplished simply by combining the flow of activity carrying helium and the aqueous solution used in the chemistry. The vacuum pump is eliminated and the performance of chemistry is simplified by running at atmospheric pressure. A recent on-line set-up is shown in fig. 11. The flow of helium carrying recoils attached to clusters is brought together with a flow of an aqueous solution in a small mixing chamber. Because of the high flow rate of helium, the mixing is quite turbulent and the transport of activities to and through the ion-exchange column is quite rapid. After the ion-exchange column the eluant passes to a waste container where helium escapes and is swept away. A γ-ray detector can be set up to look at activities on the column, and, by using a longer length of tubing leaving the column and looping it about a second detector, activities passing through the column can be looked at. With this set up we have been able to achieve quite clear separations in total transport plus chemistry times of $\lesssim$1 s. Although we have not made a careful study, we have not found any relation between the pH of the

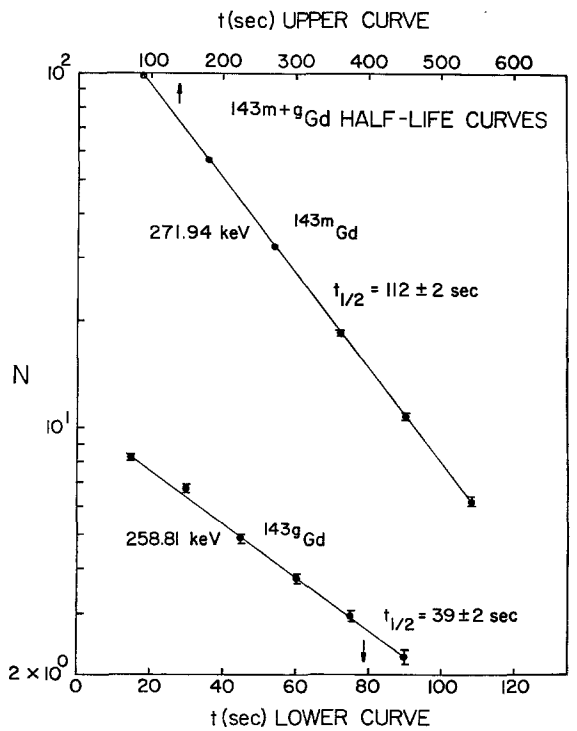

Fig. 10. Half-life curves for ^{143m}Gd and ^{143g}Gd obtained with the HeJRT system.

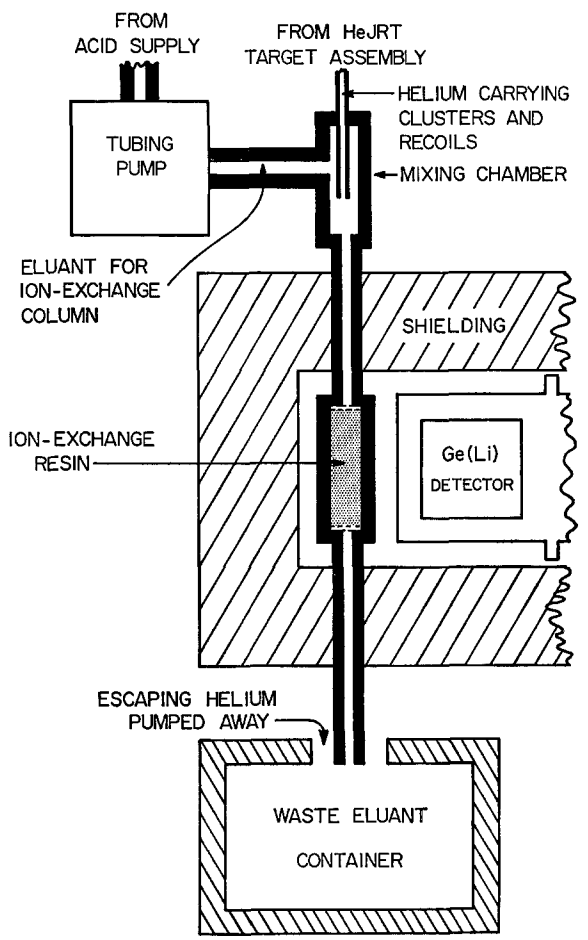

Fig. 11. Diagram of the experimental set-up for performing fast ion-exchange aqueous chemistry with the HeJRT system.

aqueous solution and its ability to free the activities carried on the cluster from the cluster upon mixing with the solution. (This separation is necessary if chemistry characteristic of the recoil is to be observed.) One of the reasons for obtaining the 16-channel sequence programmer, mentioned above, was to use it to control and automate more complex chemistry in conjunction with the HeJRT system. For a more complete discussion, see refs. 5 and 7.

5. Conclusion

The HeJRT system described in this paper is now routinely used to derive decay schemes for nuclei more remote from β stability than can be studied with conventional techniques. Interestingly enough, the HeJRT efficiency is great enough, and it is so convenient to maintain just the desired activity in front of the detector, that we now use it for many experiments involving nuclides with longer half-lives as well. With the new target-making techniques it is now possible to make, simply and economically, almost any desired target. An especial advantage is that a few mg of target material will suffice for a prolonged experiment, whereas conventional techniques often require activation of a fresh sample for every counting period. The versatile modular target assembly makes it an easy matter to run in any of several modes and to switch conveniently among different modes and configurations. The remote-controlled absorber package (absorber-dorber) simplifies and saves time doing excitation functions. The 16-channel sequencer, by controlling the tape drive, operating other equipment such as the cyclotron itself, and routing signals for the computer, makes precision half-life determinations routine. Provision is made for equipment and detectors to collect singles or multi-parameter coincidence spectra of γ-rays, electrons, protons, and α particles. In many instances it has been possible to remove ambiguities and to simplify spectra by coupling the HeJRT system with fast on-line chemistry, which can also be automated. Further, each of the above techniques is applicable to nuclides with half-lives less than 1 s and in many cases with half-lives of ≈ 0.1 s.

The decay of $^{143m+g}$Gd, which furnished some of the illustrations, was recently completed[17]) using the system as described in this paper. Other current projects using this system are studies of 182-ms ^{40}Sc, 45-s ^{141}Eu, 10.5-s ^{144}Eu, and new transuranium isotopes, searches for ^{39}Sc, ^{141}Gd, and ^{142}Gd, and the finding of β-delayed protons from ^{143}Gd. With the coupling of the HeJRT system to the time-of-flight "on-line" isotope identifier, it should prove possible to study even more complex reactions and mixtures of nuclei quite far from β stability.

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