THE TANDEM AS A HEAVY ION ACCELERATOR

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Abstract

Tables of the estimated energies obtainable with three types of tandem accelerator are presented and together with a brief discussion of the problems of heavy ion generation and acceleration.

Introduction

Within the last few years the use of heavy ions as nuclear probes has become an important technique in nuclear structure studies. In large measure this popularity of heavy ions is due to the advent of the electrostatic tandem accelerator whose precision, flexibility and absence of phasing and magnetic rigidity limitations make it an excellent user's tool. The present paper discusses the application of several tandem configurations to heavy ion acceleration, considers the ion energies which might be obtained and points out possible techniques for improving beam purity and beam selection.

Single-Stage Tandem

The single-stage tandem, shown in Fig. 1 (a), differs from the conventional two-stage tandem in that the particles are injected as fast neutrals rather than as negative ions. The advantage of this arrangement is that all particles species through the periodic table can be accelerated, using a source external to the pressure vessel, without the intensity limitations that low negative ion yields frequently impose. The injector for such a machine is designed to produce a well-collimated beam of fast neutral particles which travel through the electrostatic fields to the terminal within an insulated vacuum tube. At the terminal the particles are converted into positive ions by a gas or vapor stripper, and injected into the acceleration field.

Depending upon the energy of the neutral particles and the nature of the terminal stripper, one or more electrons will be removed from the incident atoms, allowing the positive ions formed in the terminal to be accelerated to a final energy, E_f, of

$$E_f = (Z^* eV_t + E_i)$$

where
$Z^* e$ = the charge on the ion
V_t = terminal potential
E_i = energy of the injected neutral particles

As the energy of the injected neutral particles is increased more electrons can be stripped from the particles at the terminal producing higher final energies for a given terminal voltage. Although the fraction of the primary positive ion beam which can be made neutral reduces rapidly above $\sim$ 50 keV/amu, there are advantages in neutralizing at as high an energy as possible. Not only is the scattering caused by neutralization reduced but the brightness B of the source of neutral particles increases directly as the energy. i. e.

$$B = \frac{FE}{\epsilon^2} \text{ particles/sec/cm}^2\text{/sterad}$$

where

F = the number of particles generated by the source per second

E = the particle energy (MeV)

ϵ = the source emittance, (radian cm $MeV^{1/2}$)

Table I gives the yields of charge states for the elements up Z = 10 at an energy for which the neutral beam conversion efficiency in the source is 10%. This table shows clearly that, provided the positive ion source emittance (dependent upon the plasma temperature) remains substantially constant, atomic hydrogen beams have the lowest brightness. It can also be seen that the final energy per amu falls rapidly as the particle mass increases; for heavy particles a second stripper part-way down the positive ion acceleration tube is advantageous if higher energies are required.

The Two-Stage Tandem Accelerator

The conventional two-stage tandem accelerator shown in Fig. 1 (b), will accelerate all elements that can form negative ions either as atoms (H^-, O^-) or as compounds (NH^-, UF^-). The elements which have already been accelerated are scattered

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throughout the periodic table; those known to form negative ions are given in Table II. The yield varies with the electron affinity E_b of the element and range from milliamperes for elements such as chlorine ($E_b = 3.82$ eV) to microamperes or less for helium ($E_b = 0.075$ eV) and lithium ($E_b = 0.61$ eV). Negative ions may be formed by a number of processes; those which have proved most useful are, collisional attachment and resonance dissociative capture. While collisional attachment is the process which has hitherto been most commonly employed, processes of the second type appear to offer the promise of higher currents and lower emittances, with less energy spread[5]. Provided that an adequate vacuum is maintained and that a well designed optical system[6] is used the negative ions may be accelerated to the terminal of the accelerator without loss. The loss cross-sections ($\sigma_{-11} + \sigma_{-10}$) shown in Table III are in the order of 10^{-15}cm^2, indicating that pressures of 10^{-6} torr are necessary at the low energy end of the accelerator.

The charge states formed in the stripping process depend not only on the velocity but also on the nature of the stripping material. In the energy region of interest to tandem accelerators ~ 1 MeV/amu foils have the marked advantage of producing a higher mean charge and hence higher energy particles. There is the additional advantage that no gas need be added to the vacuum system. The target thickness required to establish the equilibrium charge distribution is reached provided

$$(\sigma_{i,j})_{max} t \geq 3$$

$(\sigma_{i,j})_{max}$ being the largest cross-section and therefore the principle factor in determining the rate equilibrium is approached, and t is the target thickness. Typically $(\sigma_{i,j})$ is of the order 10^{-16} cm^2 indicating that a target thickness of 3×10^{16} atoms/cm^2 or a 0.6 μg/cm^2 carbon foil would be adequate. However, foils thinner than 4 μg/cm^2 are difficult to make, of variable thickness, and are fragile under heavy ion bombardment.

An alternative suggestion to foils has been described by Roos et al[7], and is a water vapor stripper. While not providing as high an average charge state as the foil, it shares the advantages of large aperture and zero gas flow and also has the stability of a gas stripper. The practical importance of these factors makes the vapor target an attractive alternative to the foil or gas target.

The particle energies which can be reached using a single stripper in the terminal have been estimated from the available data and are shown in Table IV. It is worth noting that the current drain on the accelerator is increased by the large average charge of the stripped beam, and this rather than the source is likely to limit the intensity of the output beam.

Multiple Stripping

In the absence of charge changing beyond the stripper, the analyzed beam from the accelerator would appear as a series of clearly separated peaks, see Fig. 2 (a). The distribution shown is Gaussian, typical of a stripped beam, when the mean charge Z^* is well removed from the extremes $Z^* = 0$ and Z. Because the analyzing system normally employed with a tandem accelerator has a high resolving power > 1000 and the beam from the machine is homogeneous to this order or better, any isotopes of the element which are injected as negative ions are clearly resolved; see Fig. 2 (b). If it is desired to work with an isotope present in small amounts, the problems of stabilization and identification of the component becomes difficult. The usual method of slit controlled corona stabilization may in fact become inadequate and alternative methods have to be used. The problem may be avoided by employing separated isotopes in the source, or by using an injection system with sufficient resolving power to act as an isotope separator.

In practice it is usually impossible to avoid some charge changing in the positive acceleration tube and drift regions and a continuum of particles of different charge and energy is formed, see Fig. 2 (c). The distances involved between the stripper and the analyzing magnet are large ~ 15 m and therefore at a mean pressure of 5×10^{-6} torr, the probability of a collision occuring is ~ 0.05; this is quite enough to cause a large background and usually with a gas stripper the mean pressure is considerably higher. In part this unwanted charge changing can be minimized by good vacuum engineering and by the use of solid or vapor strippers in the terminal. The difficulties can also be reduced by careful injection techniques which rejects the bulk of unwanted isotopes before tandem acceleration.

If in the future these approaches are inadequate to provide the purity of beams needed for sophisticated heavy ion experiments further analysis can be achieved by including a velocity or energy sensitive component in the beam transport system. A simple electrostatic analyzer provides $\frac{E}{Ze}$ resolution but has the disadvantage of deflecting the beams; the sue of such a device has been allowed for, however, in the design of the 10 MV HVEC accelerator analyzing system where a beam can be extracted at 70° to the tandem axis (rather than 90°) to permit a further 20° or 25° of electrostatic deflection into the target area.

An alternate solution is a Wien velocity filter of crossed electric and magnetic fields. This solution is attractive as no deflection of the wanted paraxial particles takes place and the optical effects of the Wien filter are small. The introduction of such a filter was considered for the MP where it is planned between the quadrupole doublet and the object slits of the analysis magnet.

Moak et al[8] have shown how to take advantage of the high ambient pressures within the accelerator to produce a small intensity of ions of very high energy. They found on examining a narrow slice of the background with a solid state detector that, because a magnetic analyzer at fixed field passes all momentum ions with a particular value of $\frac{ME}{(Z^{*} e)^2}$, many narrow slices of the continuous momentum distribution can be transmitted simultaneously producing an energy spectrum similar to that shown in Fig. 3. With a terminal potential of 7 MV iodine ions with an energy exceeding 120 MeV was obtained.

The Three-Stage Tandem Accelerator

The development of a new design d. c. accelerator with higher terminal potential occurs infrequently. It is therefore useful to consider what increases in beam energies can be obtained by employing an extra stage of acceleration. This may be achieved in two ways as shown in Fig. 1 (c) the ion source being either at ground potential, if neutral beam injection is employed, or in the terminal. The energies which may be expected are shown in Table V. It can be seen that the additional stage is particularly important for the lighter elements.

Table I. The charge composition of beams of ions Z = 1-10 passed through foils at an energy for which $F_{0\infty}$ = 0.10. The table was estimated by extrapolation of the published data[2,3,4].

Element	Neutral Beam Energy keV	Energy keV/amu	I_o^* mA	I^+ μA	I^{2+} μA	I^{3+} μA	I^{4+} μA	I^{5+} μA	I^{6+} μA
H^1	134	134	1.0	900					
He^4	448	112	1.0	610	290				
Li^7	350	50	1.0	720	140				
Be^8	360	45	1.0	560	290	60			
B^{10}	500	50	1.0	440	380	100			
C^{12}	600	50	1.0	500	340	50	10		
N^{14}	630	45	1.0	230	400	240	70		
O^{16}	800	50	1.0	200	390	190	100	10	
F^{17}	629	37	1.0	450	270	50			
Ne^{20}	800	40	1.0	210	250	400	40		

I_o^* is the equivalent current of the beam of neutral atoms.

Table II. Observed atomic negative ions. The value of $F_{-1\infty}$ (maximum) in hydrogen is given where this fraction is known.

	I	II	III	IV	V	VI	VII	VIII
1	H^- (.02)							He^- (0.00023)
2	Li^- (0.00035)	Be^-	B^-	C^- (0.034)	N^-	O^- (0.11)	F^- (0.09)	
3	Na^-	Mg^-	Al^-	Si^-	P^-	S^-	Cl^-	
4	K^-					Cr^-		Fe^-, Co^-, Ni^-

Table II. (continued)

	I	II	III	IV	V	VI	VII	VIII
5	Rb^-							
	Ag^-		Sn^-	Sb^-	Te^-	I^-		
6	Cs^-							
	Au^-		Tl^-	Pb^-	Bi^-			
7			U^-					

Table III. Loss cross-sections for some negative ions. The fraction of negative ions lost traversing 1 meter of a diatomic gas at a pressure of 10^{-6} torr is given by $f = 7.08\ (\sigma_{-11} + \sigma_{-10}) \times 10^{12}$. The cross-sections are given in units of 10^{-16} cm^2. 9, 10

Ion	H^-		He^-	O^-		I^-	
Stripper gas	H_2		H_2	N_2	O_2	N_2	
Energy (keV)	σ_{-11}	σ_{-10}	$(\sigma_{-11} + \sigma_{-10})$	σ_{-10}		σ_{-10}	σ_{-11}
3.6		5.1		7	22		
10	.44	5.1					0.6
15	.43	4.6				10*	1.0
40	.43	3.5					
50	.43	3.0					
150		1.5	13.5*				

*$(\sigma_{-11} + \sigma_{-10})$ is likely to lie between 20-30 x 10^{-16} cm^2 at 40 keV

Table IV. Energies which can be reached using a two stage tandem for heavy ion acceleration. The estimates were made using published data and for different stripping energies.

Element	Terminal Potential (MV)											
	5				10				15			
	MeV	Yield	MeV	Yield	MeV	Yield	MeV	Yield	MeV	Yield	MeV	Yield
Li_3^7	---	----	20	1.0	40	1.0	---	-----	60	1.0	---	----
F_9^{19}	40	.06	45	.004	90	.16	100	.008	135	.13	150	.025
Cl_{17}^{35}	50	.05	55	.01	110	.09	120	.02	165	.09	175	.015
Br_{35}^{79}	---	----	---	----	130	.14	150	.02	225	.08	255	.006

Table V Energies obtainable using the three-stage tandem. Both accelerators are assumed to have the same terminal potential.

Element	Terminal Potential (MV)							
	10				15			
	MeV	Yield	MeV	Yield	MeV	Yield	MeV	Yield
H_1^1	30	1.0	---	----	45	1.0	---	----
He_2^4	40	1.0	---	----	60	1.0	---	----
Li_3^7	50	1.0	---	----	75	1.0	---	----

Table V (continued)

Element	Terminal Potential (MV)							
	10				15			
	MeV	Yield	MeV	Yield	MeV	Yield	MeV	Yield
F_9^{19}	100	.23	110	.01	165	.10	---	----
Cl_{17}^{35}	140	.07	150	.007	225	.06	240	.008
Br_{35}^{79}	170	.09	180	.02	285	.07	300	.02

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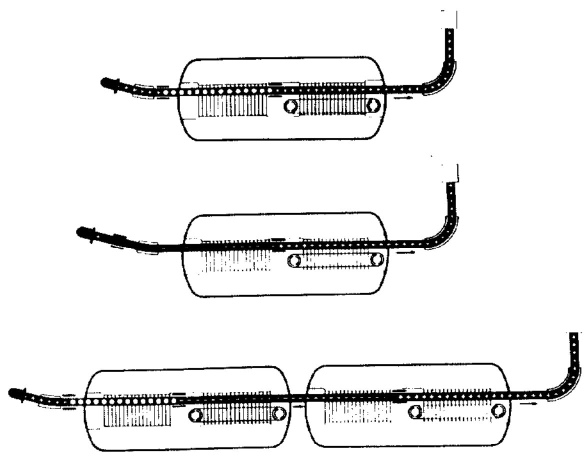

Fig. 1. (a) The One-Stage Tandem Accelerator. (b) The Two-Stage Tandem Accelerator. (c) The Three-Stage Tandom Accelerator which may employ either a neutral beam injector to form negative ions or a terminal ion source.

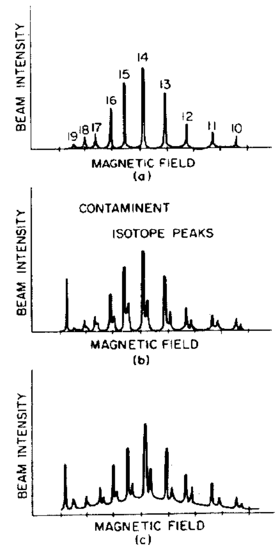

Fig. 2. (a) The magnetically analyzed beam from a tandem accelerator illustrated an idealized situation with no charge changing after stripping. (b) The addition of isotopes and contaminents. (c) The addition of the background due to charge changing collisions with the residual gas in the accelerator.

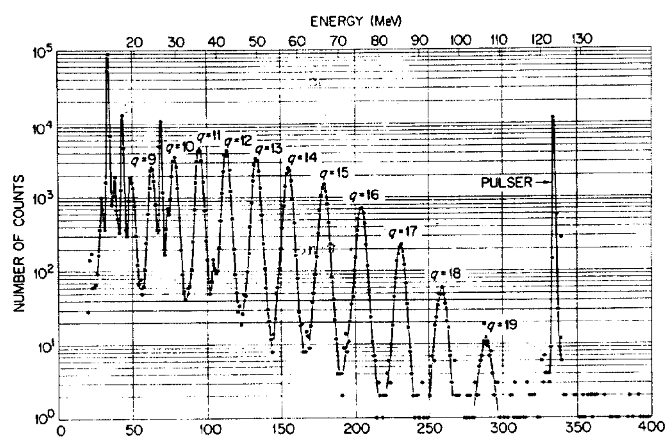

Fig. 3. The pulse height spectrum of iodine ions from the Oak Ridge Tandem Accelerator. The ions are deflected through a 90° analyzing magnet onto a silicon surface barrier detector. Moak et al.