

EQUILIBRIUM FRACTION MEASUREMENTS OF HEAVY IONS IN FLUOROCARBON STRIPPERS

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Equilibrium fractions of bromine ions at 12 MeV and iodine ions at 3 and 12 MeV were measured in fluorocarbons. The mean charge was found to be appreciably higher in these vapors than in gases such as oxygen—but not as high as in a carbon foil. The use of fluorocarbons as the terminal stripper material for a large tandem accelerator will allow particles to be accelerated at a higher mean charge thereby increasing the useful energy range of these machines.

The energy of the beams available from a tandem accelerator operating at a voltage V is determined by i , the number of electrons removed from the projectile in the terminal stripper. The beam energy in the terminal is simply eV electron volts and the final beam energy E is given by

$$E = (i + 1)eV \text{ electron volts}$$

The charge of a particular ion traversing the stripper fluctuates as a result of electron loss and capture in collisions with the atoms of the target. After a sufficient number of collisions, an equilibrium distribution of charge states is established which may be described by the fraction of the beam F_i in each charge state i . The values of F_i for a particular projectile and stripper combination, therefore, determine the final energy and intensity of the accelerated beams. These charge state distributions are strongly dependent on the ion being accelerated and on the stripper material used, which may be gas, vapor or thin solid foil. Consequently, in order to obtain the greatest intensity at a particular energy, it is important to be able to select the optimum charge changing material.

The strong dependence on stripper material is clearly illustrated in Fig. 1, which shows charge state distributions for 12 MeV iodine ions traversing a number of gas targets⁽¹⁾ and gold and carbon foils⁽²⁾ of thickness $10 \mu\text{g cm}^{-2}$. It can be seen, for example, that if a carbon foil were used in the terminal of a 12 MV tandem ~ 20 per cent of the beam would emerge with an energy of 144 MeV, whereas for an oxygen stripper, this fraction would be just over 1 per cent and for a hydrogen stripper the amount would be negligibly small.

Unfortunately, the advantages of foil strippers cannot always be exploited when high energy beams are required. Excessive multiple scattering in the

foil results in beam attenuation and for heavy ion beam intensities of $\gtrsim 1 \mu\text{A}$, lifetimes of the foils are often only a few minutes. The precise destruction mechanism is not yet fully understood, and it is possible that improved manufacturing techniques may lead to more rugged foils. Multiple foil-holders may, of course, be employed to increase the effective target lifetime; even so the use of foils is generally limited to the lighter projectiles at low beam currents.

However, the action of foil in producing higher charge states is relatively well understood.⁽³⁾ The difference Δi between the mean charge in a solid compared with a gas stripper was explained by Bohr and Lindhard⁽⁴⁾ in a pioneering paper of 1954, from which we quote below. In this generally accepted model, those collisions of the ions with the target atoms which do not produce ionization result in excitation of the ion's most loosely bound electron. In a dilute gas stripper, de-excitation back to the ion's ground state takes place before the next collision occurs. In a solid, however, the collision rate is too high for such radiative de-excitation to be important. Rather the collisions constantly increase the excitation of the outermost electron until that electron is lost. This reasoning applies consecutively to inner electrons and, consequently, the charge of the ion will steadily increase until the capture cross section becomes large enough to match the probability for loss of the excited electron. A new equilibrium value of the mean ionization is finally maintained by direct competition between capture and loss. Mainly one or, at most, a very few electrons will be in states of fairly high excitation and 'an electron captured into an excited state will be lost from the same state.' Thus, 'suppression of readjustment of ion excitation' is expected to be the principal mechanism for

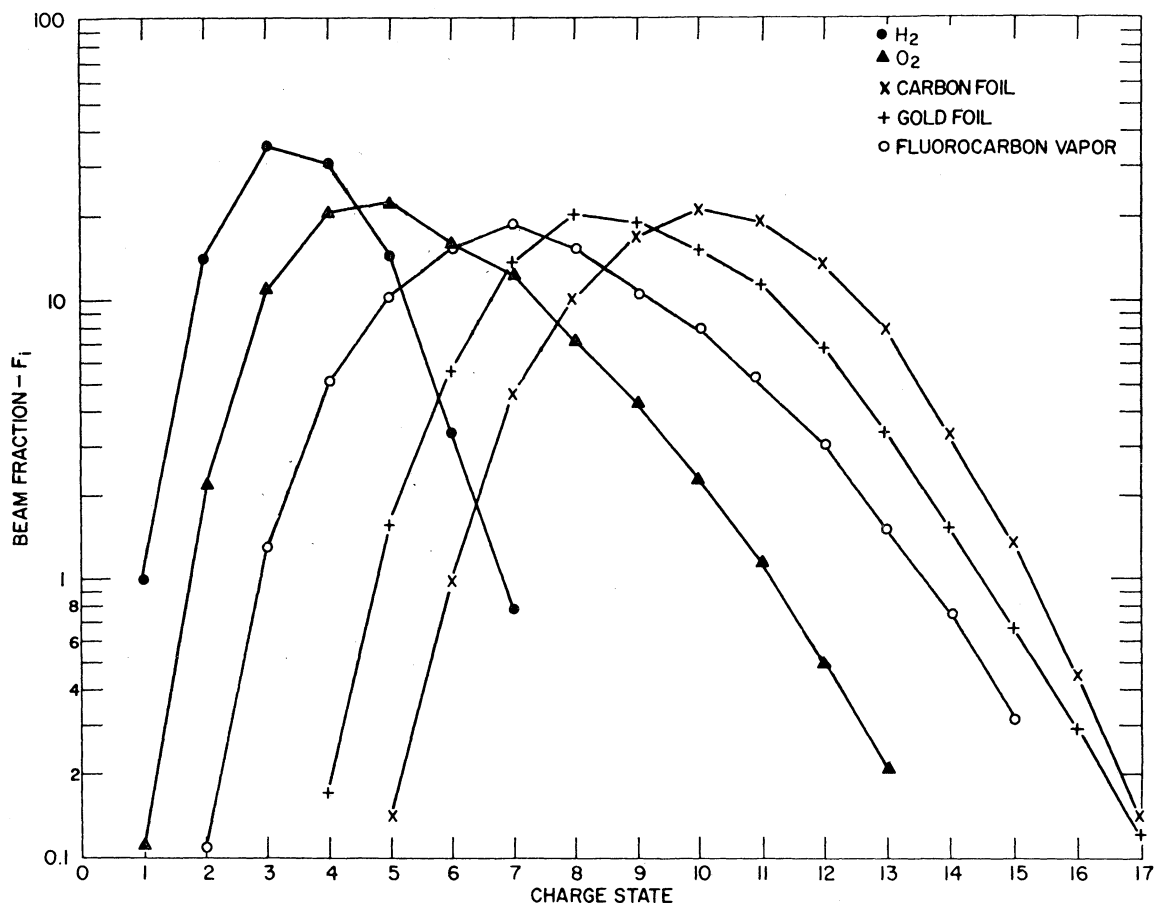


FIG. 1. Equilibrium fractions of 12 MeV iodine ions in H₂ and O₂ gases, fluorocarbon vapor and gold and carbon foils.

increasing the charge inside solids to the values observed after the ions passed through the target, though Bohr and Lindhard also state that 'the high excitation of the ions in solids may result in a subsequent emission of electrons from the ions immediately after their escape into vacuum, which increases the mean charge to a certain extent.' This latter view is now thought to be the correct explanation.⁽³⁾

For a number of years efforts have been directed towards finding a replacement for foils, one which would produce higher mean charge than the gases, yet have a longer lifetime than a foil. Perhaps the earliest of several schemes was suggested to the authors and tried by us in 1963. Diffusion pump oil, composed of large hydrocarbon molecules, was proposed as a possible material. In order to test its properties, the beam was passed through the center of an operating diffusion pump. However

before tests with this elementary target could be started the diffusion pump oil had transferred itself from the pump, through the beam ports and into the vacuum system. Van de Graaff,⁽⁵⁾ in 1965, suggested another route—one which was equally unsuccessful in practice, although several versions were tried out. Here carbon dust, each particle only 100 Å diameter, was used as the stripping medium. It was found, however, that the dust clustered into large blobs of 200–300 particles, held together by electrostatic forces. These clusters were large enough that most 10 MeV ions were either scattered at large angles or stopped within the cluster.

Another attempt was made by one of the present authors (A.W.) in 1965, when two relatively heavy hydrocarbons, butane (C₄H₁₀) and 2,2-dimethylpropane (C₅H₁₂) were used as the charge-changing medium.⁽⁶⁾ The results of these experiments were

TABLE I
Some chemical and physical properties of Fluorocarbons⁷

Name	Chemical Description	Molecular Weight	Boiling Point
Perfluoromethylcyclohexane [Flutec 2]	C ₇ F ₁₄	350	76 °C
Perfluorodimethylcyclohexane [Flutec 3]	C ₈ F ₁₆	400	—
Perfluorodecalin [Flutec 5]	C ₁₀ F ₁₈	462	142 °C

TABLE II
Charge state fractions of Iodine and Bromine beams in Fluorocarbons

Ion Beam	I	I	I	I	Br	
Energy (MeV)	3	12	12	12	12	
Target	F ₃ (C ₈ F ₁₆)	F ₃ (C ₈ F ₁₆)	F ₅ (C ₁₀ F ₁₈)	F ₂ (C ₇ F ₁₄)	F ₃ (C ₈ F ₁₆)	
Mean Charge \bar{i}	3.79	7.59	7.62	7.47	6.81	
Distribution Width σ	1.81	2.28	2.29	2.29	1.81	
Distribution Skewness γ	0.61	0.46	0.44	0.47	0.40	
Charge State Fractions— F_i per cent	0	0.41				
	1	6.18				
	2	20.4	0.12	0.13	0.14	0.12
	3	23.2	1.35	1.37	1.68	1.58
	4	17.7	5.36	5.39	6.18	7.16
	5	14.3	11.7	11.4	12.6	15.6
	6	8.90	15.8	15.0	15.8	20.4
	7	5.63	18.7	18.6	18.2	23.0
	8	2.23	15.2	15.7	15.2	15.4
	9	0.81	12.2	12.2	11.5	8.88
	10	0.24	8.38	8.57	8.0	4.76
	11		5.48	5.51	5.13	2.09
	12		3.0	3.30	2.98	7.7 10 ⁻¹
	13		1.5	1.61	1.48	3.1 10 ⁻¹
	14		7.5 10 ⁻¹	0.80	0.70	5.3 10 ⁻²
	15		3.3 10 ⁻¹	0.33	0.30	6.0 10 ⁻³
	16		1.4 10 ⁻¹			6.0 10 ⁻⁴
	17		5.0 10 ⁻²			3.6 10 ⁻⁵
	18		1.3 10 ⁻²			
	19		3.1 10 ⁻³			
	20		6.7 10 ⁻⁴			
	21		1.1 10 ⁻⁴			
	22		1.2 10 ⁻⁵			

disappointing but the reason for the lack of success was not appreciated until the recent data presented in Figure 1 were obtained. It was then apparent that the hydrogen in the hydrocarbons, a producer of low charge states, negated any benefit which might have accrued from the use of a large molecule. This paper presents measurements of equilibrium fractions obtained using a number of fluorocarbon compounds, containing no hydrogen atoms, as the charge-changing medium.

EXPERIMENTAL DETAILS

The experimental method has been described in detail in an earlier publication.⁽¹⁾ For equilibrium fractions F_i greater than ~ 1 per cent the total estimated probable error is less than ± 5 per cent whereas, for fractions less than ~ 1 per cent the probable error may be as large as ± 10 per cent.

Fluorocarbons used as target materials are listed in Table I. Although fluorocarbons are available with higher molecular weights, it has not yet been possible to find one with suitable vapor pressure characteristics.

RESULTS AND DISCUSSION

The results are shown in Table I and in Fig. 1. Although the fluorocarbons are not as effective as a carbon foil for producing highly stripped ions, they are appreciably more so than the best of the 'standard' gases, which in this case was oxygen and almost as effective as a gold foil. It is also worth noting that due to the large size of each fluorocarbon molecule, very little vapor was

required to produce charge state equilibrium; because of this losses due to scattering are no worse than with the more standard stripping gases and appreciably better than in foils.

Fluorocarbon vapors have not yet been used in a tandem terminal, and neither the short nor long term effects on the voltage holding ability or lifetime of accelerator tubes are known. However, the number of fluorocarbon atoms entering the acceleration tubes can be kept to a minimum by the addition of cooled vapor-condensing baffles at either end of the terminal stripper assembly. If these baffles are installed, it is felt that the influence of these heavy molecules on acceleration tube performance will be slight. The use of fluorocarbons as the terminal stripper material for a large tandem will then allow particles to be accelerated at a higher mean charge thereby increasing the useful energy range of these machines.

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