

nearly resonant, σ_{+t} decreases with energy. The total destruction cross section for metastable atoms in the triplet state $\sigma_{t+} + \sigma_{tS}$ is almost independent of the energy.

In conclusion we would like to stress the fact that the large cross sections Σ_{t+} and Σ_{t-} in Cs

vapor make Cs a very useful analyzer of the rate of production and loss of metastable triplet He⁰ atoms in various gas targets. Thus one can measure the cross section σ_{+t} and can obtain $\sigma_{t+} + \sigma_{tS}$ in various gas targets.

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Charge Equilibrium Fractions of a Helium Beam in Hydrogen, Nitrogen, Neon, and Argon from 60 to 850 keV*

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Equilibrium fractions of charge 0, +1, and +2 of helium beams traversing the gas targets H₂, N₂, Ne, and Ar have been measured. Primary beams of (He⁴)⁺ and (He³)⁺⁺ were used. The measurements cover ion velocities corresponding to energies of (He⁴)⁺ between 60 to 850 keV. The charge-equilibrated beam was magnetically separated and charge spectra were recorded by means of a movable detector of equal sensitivity for all three charge components. In the energy interval of overlap, that is between 60 and 200 keV, agreement with Barnett *et al.* is excellent in the fractions $F_{0\infty}$ and $F_{1\infty}$, which make up almost the entire charge-equilibrated beam. The results show a strong dependence of the equilibrium charge distributions on the chemical nature or electronic configuration of the gas target.

I. INTRODUCTION

Charge equilibrium fractions of a He beam in a He gas target were presented in an earlier paper,¹ henceforth referred to as I. The present measurements have been performed with the same basic equipment. Some improvements, to be described below, have been introduced.

The information on charge equilibrium fractions of He beams traversing different gaseous targets, available up to 1962, has been reviewed by Allison and García Muñoz.² From 8 to 200 keV this information is based essentially on measurements

of Stier, Barnett, and Evans,³ and Barnett and Stier.⁴

For the target gases H₂ and He, from 200 to 480 keV the tabulated values are calculated from charge changing cross-section measurements of Allison and others.⁵

For the case of a 200-keV-He beam on a He gas target the discrepancies between the computed charge equilibrium fractions and the corresponding values measured by Barnett *et al.*^{3,4} amount up to 15%, as already mentioned in I. Due to systematic discrepancies the measurements of

Snitzer⁶ which also cover energies up to 480 keV, were not considered by Allison and García Muñoz,² except for the case of the Ar gas target for which no cross-section data were available.

Pivovar *et al.*⁷ measured charge equilibrium fractions of He beams in H₂, He, N₂, Ar, and Kr between 200 and 1500 keV in steps of 100 keV. Agreement with the values tabulated by Allison is generally within 10%. However, there are significant discrepancies. For example in a H₂ target the fraction $F_{0\infty}$ tabulated by Allison and García Muñoz² is 27% lower at 300 keV. At 400 keV the discrepancy in $F_{0\infty}$ amounts up to 45%, and in $F_{2\infty}$ to 11%.

Nicolaev *et al.*⁸ report charge equilibrium fractions of He beams in He, N₂, and Ar gas at four different energies, namely 0.665, 1.30, 2.82, and 5.87 Mev. There is fair agreement with Pivovar's results except for the neutral fraction for which deviations are of the order of 40%.

The results presented in I show reasonable agreement with Pivovar, but the neutral fraction obtained by Pivovar above 300 keV is lower by up to 25%.

Between 60 and 200 keV, where they overlap, there is an almost complete coincidence between the charge equilibrium fractions of He ions in He gas, measured in I, and the results of Stier, Barnett, and Evans³ and Barnett and Stier.⁴ For $F_{0\infty}$ and $F_{1\infty}$ agreement is well within the error limits of $\pm 1\%$ quoted in I. (Only for the doubly charged fraction $F_{2\infty}$, which is smaller than 0.01 below 200 keV, discrepancies are larger, amounting up to 10% at 60 keV.) This striking agreement with Barnett *et al.*^{3,4} makes us confident in the error limits presented in I, which are smaller by about an order of magnitude than the errors which result if one takes into account the above-mentioned discrepancies among different authors.

It therefore seemed to be of interest to extend the measurements given in I for the He gas target to other gases, namely, H₂, N₂, Ne, and Ar. Furthermore, there are no data on charge equilibrium fractions of He beams in Ne gas at energies above 200 keV.

The results would also allow a comparison of the charge equilibrium distributions of He beams in gaseous targets of different chemical nature and thus electronic configuration.

II. EXPERIMENTAL APPROACH

The equipment and techniques used in the present measurements are practically the same as those described in I, and only a brief description will be given here.

The beam of the Bariloche Cockcroft Walton accelerator (maximum high voltage 330 kV) is sorted out magnetically and then traverses a differentially pumped interaction cell of 28 cm

length. A needle valve permits adjustment of the gas pressure within the cell which, according to the different beam energies and target gases used, varied between 20 and 320 μ Hg.

The charge-equilibrated beam is then magnetically separated into its components which are measured by one and the same movable detector in such a way, that the corresponding charge spectra are displayed on a XY recorder. When entering the detector each beam component of different charge is newly charge equilibrated after traversing a thin gold foil. As charge equilibria do not depend on the charge configuration of the incoming ions, the detector delivers current signals which are proportional to the number of beam particles in each component, irrespective of their charge. The desired charge fractions are simply given by the corresponding registered peak heights divided by their sum.

Measurements between 50 and 320 keV were performed with an initial (He⁴)⁺ beam. The data at higher energies were obtained by using a doubly charged beam component (He³)⁺⁺ of the isotope He³ put out by the ion source, thus avoiding the presence of a component of molecular ions of hydrogen (H₂)⁺ not magnetically separable from (He⁴)⁺⁺. As cross sections for charge change and consequently charge equilibrium fractions for ions of isotopes of the same element are to be compared at equal ion velocities, the data obtained with (He³)⁺⁺ are displayed at equivalent energies of (He⁴)⁺ given by $\frac{4}{3}$ the true energy of the (He³)⁺⁺ ions.

Regarding the precision of the present measurements the same general considerations as in I apply here. However, an improved beam stability of the accelerator resulted in a reduction of the statistical error limits, especially concerning the high-energy measurements performed with the (He³)⁺⁺ beams.

The beam energies were determined with a precision better than 0.3% by using a cylindrical electrostatic analyzer calibrated with electrons accelerated through voltages from a John Fluke Model 410 B source and also with protons of 163.1 keV whose energy was known from the resonance reaction $B^{11}(p, \gamma)C^{12}$. This improved beam energy calibration gave coincidence with the calibration by magnetic deflection described in I.

Typical statistical errors of the present measurements are given in Table I for the case of the Ne gas target and different ion energies.

III. RESULTS AND DISCUSSION

Figures 1 through 4 show the charge equilibrium fractions $F_{0\infty}$, $F_{1\infty}$, and $F_{2\infty}$ of the beams in the gases H₂, N₂, Ne, and Ar, as resulting from the present measurements. We include the results

TABLE I. Percentage errors in $F_{0\infty}$, $F_{1\infty}$, and $F_{2\infty}$ for the Ne gas target.

E (keV)	$F_{0\infty}$ $\pm \%$	$F_{1\infty}$ $\pm \%$	$F_{2\infty}$ $\pm \%$
50	0.5	1	2
200	1	0.5	1
400	1	0.5	1
600	1.5	0.5	0.5
800	2	0.5	0.5

of Stier, Barnett, and Evans² and Barnett and Stier³ (up to 200 keV), and of Pivovar *et al.*⁷ (from 200 keV up).

Charge equilibrium fractions as resulting from graphical interpolation in Figs. 1-4 are given in Table II.

As in the case of the He target (see Fig. 4 in I), in the four gas targets measured we obtain practically complete agreement with the results of Barnett *et al.*^{3,4} for the fractions $F_{0\infty}$ and $F_{1\infty}$. Throughout the region of overlap, between 50 and 200 keV, discrepancies are smaller than 0.5% for the H_2 target and vary between 1 and 2% for the targets N_2 , Ne, and Ar. Only near 200 keV a slight systematic difference appears in Ne and Ar, the neutral fraction being up to 3% larger in the results of Barnett. Again, as in I, discrepancies are significant only for the doubly charged fraction $F_{2\infty}$, which is small below 200 keV. Our values result larger for all target gases, differ-

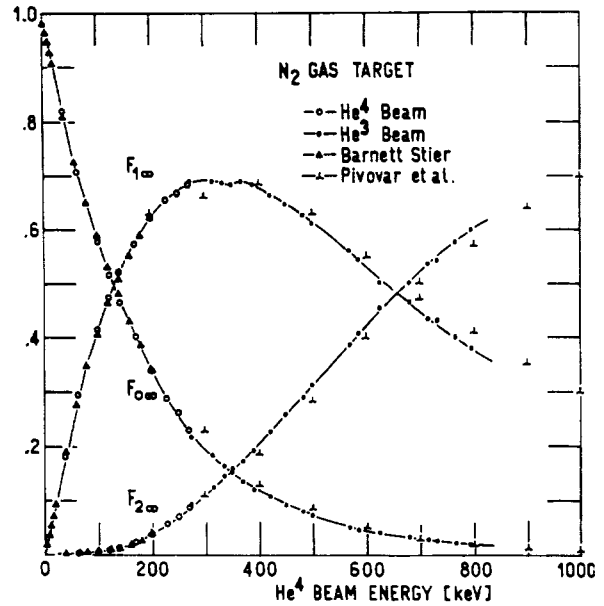


FIG. 2. Charge equilibrium fractions $F_{0\infty}$, $F_{1\infty}$, and $F_{2\infty}$ of He ions in N_2 gas between 60 and 800 keV.

ences amounting up to 40% at the lowest energies. However these large relative differences in the small fraction $F_{2\infty}$ have negligible effect upon $F_{0\infty}$ and $F_{1\infty}$ which practically make up the entire charge-equilibrated beam at these low energies. We note that Barnett *et al.*^{3,4} measure the fraction $F_{2\infty}$ only where it is larger than 0.001; for

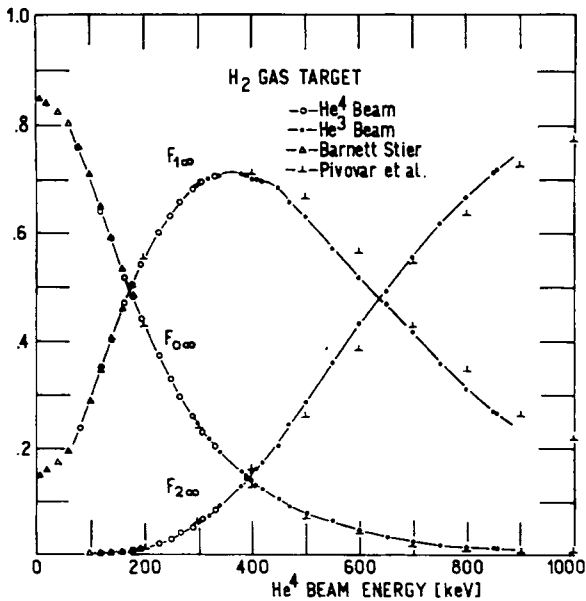


FIG. 1. Charge equilibrium fractions $F_{0\infty}$, $F_{1\infty}$, and $F_{2\infty}$ of He ions in H_2 gas between 60 and 850 keV.

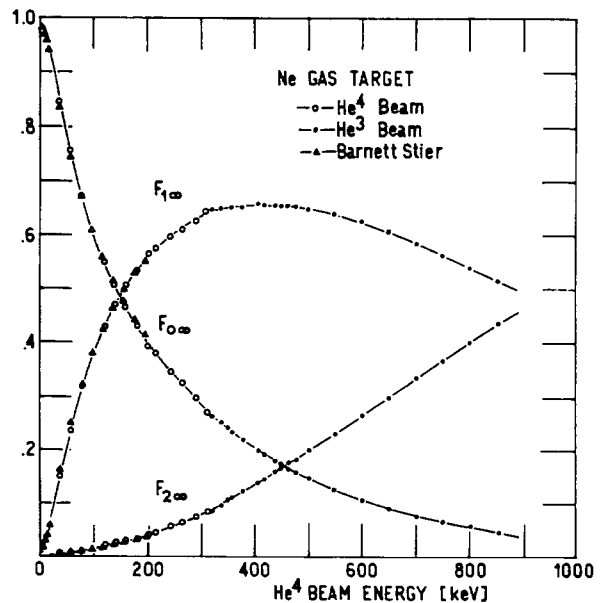


FIG. 3. Charge equilibrium fractions $F_{0\infty}$, $F_{1\infty}$, and $F_{2\infty}$ of He ions in Ne gas between 40 and 860 keV.

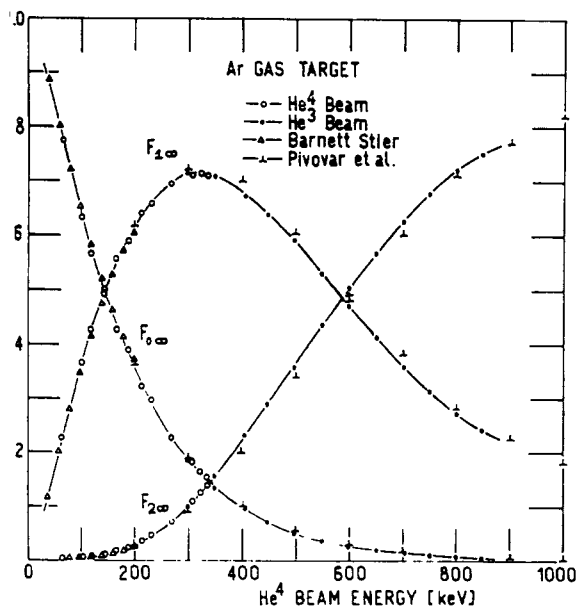


FIG. 4. Charge equilibrium fractions $F_{0\infty}$, $F_{1\infty}$, and $F_{2\infty}$ of He ions in Ar gas between 60 and 850 keV.

example, at energies above 100 keV in the case of the H_2 target.

The simple method of beam detection employed in this work gives results of an internal consistency within 2% even for the small fraction $F_{2\infty}$ at

low energies.

Our measurements show, in general, larger discrepancies when compared to the results of Pivovar *et al.*⁷ In H_2 gas there is an excellent agreement up to 400 keV. At higher energies the agreement is best for the Ar gas target. In all cases it is observed that the results of Pivovar are larger in $F_{1\infty}$ and smaller in $F_{2\infty}$ at energies above 400 keV. These discrepancies amount up to 10% in the case of the H_2 target.

The results presented in Figs. 1 through 4 - including Fig. 4 in I - show a remarkable dependence of the charge equilibrium distributions on the chemical nature of the gas traversed by the He beam.

For example at 300 keV, where differences are largest between the charge equilibrium fractions measured in He and Ar, $F_{0\infty}$ is 0.385 in He, but 0.188 in Ar, i.e., smaller by 90%. Comparing Ne and Ar targets at 800 keV we find that $F_{1\infty}$ is 100% greater in Ne and $F_{2\infty}$ 80% greater in Ar. These two fractions make up more than 95% of the total charge-equilibrated beam. The small fraction $F_{0\infty}$ is as much as 900% greater in Ne than in Ar at this energy.

It might be worth noting that for energies above 300 keV the gas targets investigated can be arranged in two groups, namely, H_2 , N_2 , Ar and He, Ne. In the first group we observe a relatively fast decrease of $F_{0\infty}$ and $F_{1\infty}$ and correspondingly a fast increase in $F_{2\infty}$ as a function of energy,

TABLE II. Charge equilibrium fractions as resulting from graphical interpolation of the present measurements.

Energy (keV)	v (10^8 cm sec $^{-1}$)	H_2			N_2			Ne			Ar		
		$F_{0\infty}$	$F_{1\infty}$	$F_{2\infty}$	$F_{0\infty}$	$F_{1\infty}$	$F_{2\infty}$	$F_{0\infty}$	$F_{1\infty}$	$F_{2\infty}$	$F_{0\infty}$	$F_{1\infty}$	$F_{2\infty}$
60	1.70	0.806	0.194	0.0004	0.720	0.279	0.0012	0.752	0.242	0.0055	0.795	0.204	0.0008
100	2.20	0.710	0.289	0.0014	0.578	0.416	0.0055	0.607	0.379	0.0144	0.638	0.359	0.0036
140	2.60	0.591	0.406	0.0039	0.467	0.519	0.0145	0.511	0.465	0.0239	0.505	0.485	0.0104
180	2.95	0.481	0.509	0.0102	0.377	0.595	0.0285	0.438	0.530	0.032	0.402	0.578	0.0205
220	3.26	0.390	0.590	0.020	0.304	0.647	0.049	0.376	0.579	0.045	0.316	0.645	0.039
260	3.54	0.308	0.652	0.038	0.240	0.681	0.079	0.329	0.611	0.060	0.242	0.691	0.067
300	3.81	0.245	0.693	0.062	0.195	0.692	0.113	0.286	0.636	0.078	0.188	0.712	0.100
340	4.05	0.194	0.710	0.094	0.162	0.688	0.150	0.250	0.651	0.099	0.144	0.712	0.144
380	4.29	0.158	0.712	0.130	0.130	0.686	0.184	0.220	0.657	0.123	0.112	0.694	0.194
420	4.51	0.125	0.700	0.175	0.108	0.668	0.224	0.193	0.659	0.148	0.086	0.663	0.251
460	4.72	0.100	0.674	0.226	0.090	0.642	0.268	0.169	0.658	0.173	0.064	0.628	0.308
500	4.92	0.082	0.633	0.284	0.076	0.614	0.310	0.149	0.652	0.199	0.049	0.587	0.364
540	5.11	0.066	0.588	0.346	0.060	0.584	0.356	0.131	0.645	0.224	0.039	0.540	0.421
580	5.30	0.054	0.542	0.404	0.049	0.551	0.400	0.115	0.634	0.251	0.030	0.494	0.427
620	5.48	0.043	0.500	0.457	0.040	0.518	0.442	0.101	0.621	0.278	0.023	0.449	0.528
660	5.65	0.033	0.458	0.509	0.034	0.480	0.486	0.089	0.605	0.306	0.018	0.402	0.580
700	5.82	0.026	0.415	0.559	0.030	0.446	0.524	0.079	0.588	0.333	0.014	0.361	0.625
740	5.98	0.022	0.372	0.606	0.026	0.417	0.557	0.069	0.571	0.360	0.011	0.321	0.668
780	6.14	0.019	0.331	0.650	0.022	0.390	0.588	0.060	0.552	0.388	0.009	0.287	0.704
820	6.30	0.016	0.295	0.689	0.019	0.364	0.617	0.052	0.532	0.416	0.007	0.258	0.735
860	6.43	0.014	0.263	0.723	0.044	0.515	0.441	0.006	0.232	0.762

whereas for He and Ne transitions are appreciably slower. Thus the crossing of $F_{1\infty}$ and $F_{2\infty}$ occurs at 590 keV in Ar, but, according to the curves measured up to 860 keV, in the case of Ne, this crossing would be reached at the considerably higher energy of about 930 keV. The trend of the experimental curves shows that the transition to the situation at which the total of the beam is doubly charged in He, and more so in Ne, would be attained at considerably higher energies than in the other gases measured, specially in Ar for which $F_{2\infty}$ is equal to 0.75 already at 850 keV.

We conclude that the equilibrium charge distribution of He beams measured in five (including I) different gaseous targets show very significant differences which, however, are not simply related to their electronic configurations or chemical nature.

It is, for example, surprising that for the noble

gas Ar we find a behavior more similar to H₂ and N₂ than to the noble gases He and Ne.

Due to this strong dependence of equilibrium charge distributions on the target gas, it does not appear to be feasible to compute charge equilibrium fractions by semiempirical methods as that proposed by Dmitriev⁹ and based on the charge distribution of hydrogen beams in a given target.

It is finally observed that the curves of $F_{1\infty}$ in H₂ and N₂ show a small dip near their maximum. The corresponding points have been measured with special care and better statistics than the rest of the data. We have no explanation for this effect.

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