Equilibrium charge states of ^{3}He ions emerging from solid targets at high incident energies

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The yield of ^{3}He^{1+} ions produced by a ^{3}He^{2+} beam in C, Al, Ni, Ag, and Au foils was measured at 68, 99, and 130 MeV in order to determine the electron-capture cross sections σ_c. Measurements were performed using targets thicker than 60 μg/cm^2, where charge equilibrium was found. The results are compared with electron-stripping and -capture theories, which are found to explain fairly well the yield of ^{3}He^{1+}.

The charge distribution of high-energy ions passing through solids is the result of multiple collisions consisting of single electron-capture and single electron-stripping processes.[1] Electron capture at high energies is of current interest in atomic physics. First-order Born-approximation calculations[2] of the electron-capture cross sections σ_c predicting a projectile velocity dependence of V_1^{-12} do not reproduce the measured cross sections in magnitude and velocity dependence. The overestimation of the measured σ_c by the first-order calculation can be improved considerably by second-order calculations.[3] On the other hand, electron-stripping cross sections σ_s are well explained by first-order Born-approximation calculations.[4] Therefore the electron-capture cross section σ_c can be deduced from measurements of the equilibrium charge yield given by $N\sigma_c/\sigma_s$, where N is the beam intensity. The σ_c and σ_s, respectively, correspond to σ_{21} and σ_{12} in Ref. 5, where σ_{if} shows collision cross sections with i and f being the ionic charge state of the projectile before and after the collision. The expression σ_c/σ_s is derived under the assumptions that $\sigma_{12} >> \sigma_{21}$ and $\sigma_{01} >> \sigma_{10}$, which is experimentally justified from the 6–24-MeV data[6] and the neglect of double capture σ_{20} and the double loss σ_{02} contributions. These assumptions are used in the analysis of the 0.2–6.5-MeV data of Ref. 7 and of the 68–130-MeV data of Ref. 8. Direct experimental justification is only known from the investigation of Allison[5] at 150–450 keV.

The target thickness dependence of the ^{3}He^{1+} yield of ^{3}He^{2+} ions passing through carbon foils has been measured recently at 68, 99, and 130 MeV,[8] which allows to extract σ_c and σ_s of ^{3}He in carbon. Electron capture by swift ^{3}He ions becomes an object of current interest as a probe of fusion plasma because of easy identification of ^{3}He from ^{4}He of fusion product.[9] In the present article, we report on equilibrium ^{3}He^{1+} charge fractions for C, Al, Ni, Ag, and Au targets at the same energies. Details of the experimental arrangement of beam line and magnetic spectrometer are described elsewhere.[8] Only the main features are repeated here. The ^{3}He^{2+} beam from the isochronous cyclotron JULIC[10] was focused onto the target in the scattering chamber of the magnetic spectrometer BIG KARL[11] which was set to an angle of $\theta_{\rm lab}=0°$. The ^{3}He^{2+} beam was bent onto the isolated aluminum plate at the inner wall of the first dipole magnet D1 which was used as Faraday cup for beam integration. Independently the beam intensity was monitored by a surface-barrier detector in the scattering chamber. Beam line and spectrometer were carefully adjusted in order to detect the total ^{3}He^{1+} yield from the target. All targets were self-supporting foils of several thicknesses: C (85, 185, 540 μg/cm^2), Al (63, 115, 244, 604 μg/cm^2), Ni (114, 235, 614, 993 μg/cm^2), Ag (68, 137, 272, 586 μg/cm^2), and Au (100, 179, 428, 505, 1037 μg/cm^2). These targets were found to be thick enough to assure charge equilibrium so that the uncertainty of the target thickness of $\pm$10% did not affect the measured charge fractions. The experimental results are summarized in Table I. The overall errors of the measurement mainly due to charge integration uncertainties are estimated to be $\pm$10%.

In Fig. 1 the measured equilibrium charge fractions σ_c/σ_s of the ^{3}He^{1+} at 68 and 130 MeV together with theoretical results are displayed as functions of the atomic number Z_t of the target. The theoretical values for σ_c/σ_s have been obtained in the following way. For the calculation of the capture cross section σ_c we used Nikolaev's model including screening effects.[12] This model achieves agreement between data and calculations by means of a semiempirical normal-

TABLE I. Equilibrium charge fractions σ_c/σ_s of $^3He^{1+}$ in solid targets at 68, 99, and 130 MeV. Errors are ±10%, which are from uncertainties of charge collection. Incident energies are accurate within ±0.35%.

Incident ^{3}He Energy (MeV)	V_1 (a.u.)	$10^7\sigma_c/\sigma_s$ C	Al	Ni	Ag	Au
67.9	29.7	2.28	11.6	22.9	34.2	51.7
99.2	35.7	0.47	3.25	7.31	11.3	17.5
130.2	40.7	0.20	1.44	3.80	6.03	10.3

ization factor (about 0.25 in all our calculations). We used Eqs. (10) and (17) of Ref. 12 to calculate the capture cross section which we call σ_{cn}. The dominant contribution in σ_{cn} comes from the K shell for C and Al, from the $K+L$ shell for Ni, and from the $L+M$ shell for Ag and Au. The arrows in Fig. 1 indicate the positions where the classical-K orbit velocity becomes equal to the projectile velocity V_1. For the calculation of the stripping cross section σ_s we

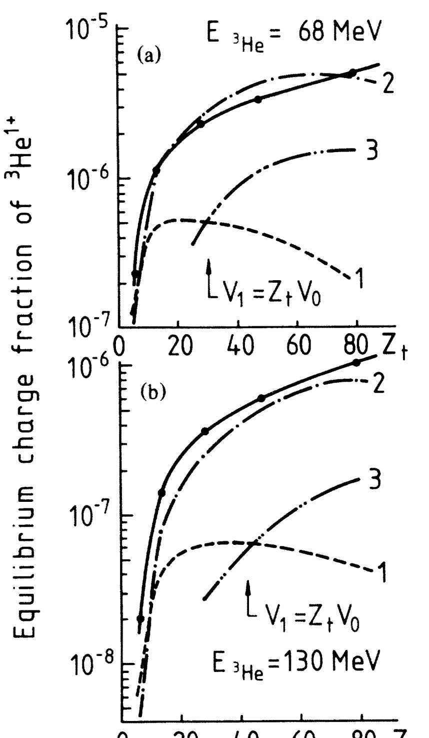

FIG. 1. Fractions σ_c/σ_s of $^3He^{1+}$ ions in thick targets with equilibrium conditions at the lowest and highest measured energies (a) 68 MeV, and (b) 130 MeV, as function of the atomic number Z_t. The data points are connected by solid lines to guide the eye. The curves $i=1,2,3$ represent calculations of σ_{cn}/σ_{si} according to Nilolaev (Ref. 12) and Bohr (Ref. 13). For details, see text.

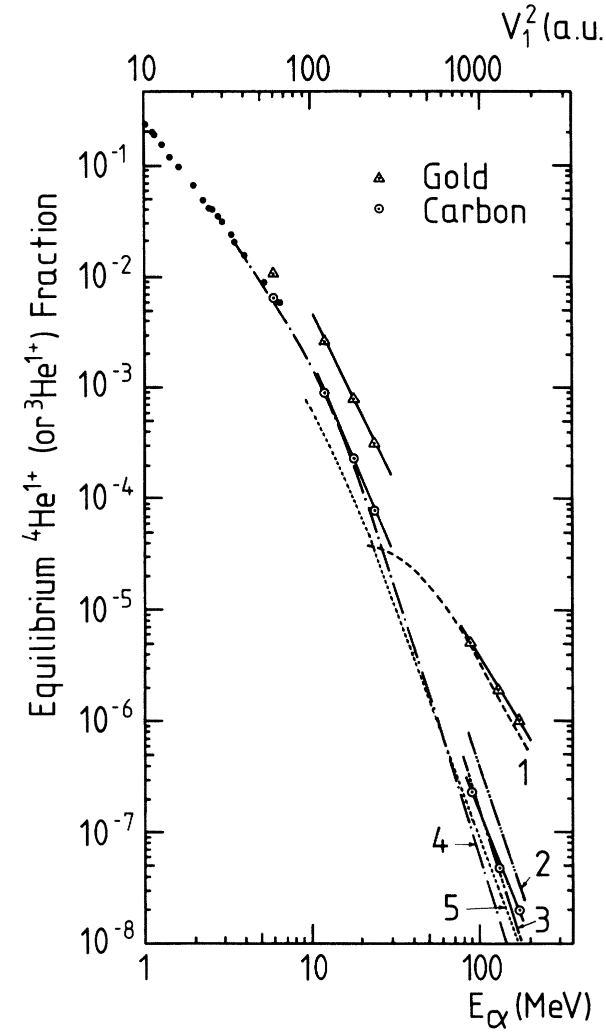

FIG. 2. Energy dependence of the equilibrium He^{1+} fractions of C and Au (results for Al, Ni, and Ag, see Table I). The data for 1–10, 6–24, and 90–180 MeV (^{3}He: 68–130 MeV) are from Ref. 7, Ref. 6, and the present study, respectively. Solid lines are to guide the eye. For theoretical curves 1, 2, 3, 4, and 5, see text.

used Bohr's expressions[13] which are valid for different regions of atomic numbers Z_t: (1) $\sigma_{s1}=4\pi Z_p^{-2}(Z_t^2+Z_t)V_1^{-2}a_0^2$ for small Z_t, (2) $\sigma_{s2}=\pi Z_t^{2/3}Z_p V_1^{-1}a_0^2$ for intermediate Z_t, and (3) $\sigma_{s3}=\pi a_0^2$ for large Z_t. Here, Z_p is the atomic number of the projectile, V_1 the projectile velocity in units of $V_0=2.18\times10^8$ cm/sec, and a_0 the Bohr radius. The curves marked $i=1,2,3$ represent the calculated yields σ_{cn}/σ_{si}. The general shape of our data curve is in agreement with curve 2 representing σ_{cn}/σ_{s2}. There are, however, two discrepancies to be noticed: (1) The calculated value for carbon is too small, and (2) the measured Z_t dependence is almost linear (in contrast to the Z_t dependence at 12-MeV α energies[6]), while the calculations show a maximum at around $Z_t=60$ for 68 MeV and around $Z_t=70$ for 130 MeV. It should be mentioned that, by use of a different empirical normalization factor, good agreement of curve 3 and the data can be achieved for large Z_t. A constant value of σ_c/σ_s for different Z_t was observed for the 6-MeV data which, according to the authors,[7] is due to the surface contaminations of the target.

In Fig. 2 the energy dependence of the measured equilibrium charge fractions for $^3He^{1+}$ in C and Au is shown together with results from previous $^4He^{1+}$ measurements[6,7] at lower energies. For a better comparison of the present data with the previous results, the energy is given in corresponding α energies. These are the energies $E_\alpha=E_{^3He}m_\alpha/m_{^3He}$ of α particles having the same velocity as ^3He particles of 68, 99, and 130 MeV. The curves 1, 4, and 5 show the calculations of σ_{cn}/σ_{s2} for Au and C and σ_{cn}/σ_{s1} for C, respectively. The empirical normalization factor of about 0.25 for σ_{cn} is adequate to explain low-energy C data and the present Au data, but the present C data are not reproduced by either σ_{cn}/σ_{s1} or σ_{cn}/σ_{s2}. Gillespie has performed Born-approximation calculations of σ_s for projectiles with a single electron in He, N_2, and Ar targets.[14] From the interpolation of his result, we obtained $\sigma_s=2.15\times10^{-18}$ and 1.15×10^{-18} cm^2/atom for $^3He^{1+}$ in C at 68 and 130 MeV, respectively, which agree well with our experimental results[8] of $(2.7\pm0.2)\times10^{-18}$ and $(1.5\pm0.3)\times10^{-18}$ cm^2/atom correspondingly. The comparison of the theories and measurements of σ_c of ^3He in carbon has been discussed elsewhere.[8] Curve number 2 in Fig. 2 shows σ_c/σ_s for ^3He in carbon, where σ_c is calculated within the second-order Born theory[3] and σ_s is the interpolated Gillespie's calculation. The difference between the theory and the present experimental data is significantly reduced in curve 3, where the σ_c is calculated with the strong potential method by McGuire.[15]

In this paper we have presented measurements of equilibrium charge state fractions for atomic numbers from $Z_t=6$ to 79. From these measurements electron-capture cross sections σ_c can be determined by using stripping cross sections which are well reproduced by first-order Born-approximation calculations. It has been shown that σ_c/σ_s calculated from Nilolaev's and Bohr's theory including screening effects reproduce fairly well the measured Z_t dependence for all Z_t, which allows us to use the theory to estimate the charge equilibrium fraction in practical use. The energy dependence of σ_c for C is also fairly well reproduced by the calculations of the recent electron-capture theory.

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[1]M. C. Cross, Phys. Rev. B 15, 602 (1977).
[2]J. R. Oppenheimer, Phys. Rev. 31, 349 (1928); H. C. Brinkmann and H. A. Kramers, Proc. K. Ned. Akad. Wet. 33, 97 (1930).
[3]R. M. Drisko, dissertation (Carnegie Institute of Technology, 1955) (unpublished); M. R. C. McDowell and J. P. Coleman, *Introduction to the Theory of Ion-Atom Collisions* (North-Holland, Amsterdam, 1970).
[4]K. L. Bell and A. E. Kinston, *Atomic Process and Applications,* edited by P. G. Burke and B. L. Moisewitsch (North-Holland, Amsterdam, 1976), p. 493.
[5]S. K. Allison, Rev. Mod. Phys. 30, 1137 (1958).
[6]A. Gladieux, A. Chateau-Thierry, and B. Delaunay, J. Phys. B 12, 3591 (1979).
[7]J. C. Armstrong, J. V. Mullendore, W. R. Harris, and J. B. Marion, Proc. Phys. Soc. London 86, 1283 (1965).
[8]I. Katayama, G. P. A. Berg, W. Hürlimann, S. A. Martin, J. Meissburger, W. Oelert, M. Rogge, J. G. M. Römer, J. Tain, B. Styczen, and G. Gaul, Phys. Lett. 92A, 385 (1982).
[9]M. Sasao (private communication).
[10]J. Reich, S. A. Martin, D. Protic, and G. Riepe, *Seventh International Conference on Cyclotrons and Their Applications, Zürich, Switzerland, 1975,* edited by W. Joho (Birkhaüser, Basel, 1975), p. 235.
[11]S. A. Martin, G. P. A. Berg, A. Hardt, W. Hürlimann, M. Köhler, J. Meissburger, T. Sagefka, and O. W. B. Schult, in *Proceedings on Magnetic Spectrometers in Nuclear Physics,* edited by N. E. Sanderson (Daresbury Laboratory, Daresbury, England, 1979), p. 847.
[12]V. S. Nikolaev, Zh. Eksp. Teor. Fiz. 51, 1263 (1966) [Sov. Phys. JETP 24, 847 (1967).
[13]N. Bohr, K. Dan. Vidensk. Selsk. Mat. Fys. Medd. 18, No. 8, 1 (1948).
[14]G. H. Gillespie, Phys. Rev. A 18, 1967 (1978).
[15]J. McGuire (private communication).