Z_T Dependence of Matastable Fraction of MeV Neutral Helium Beam Produced by Single Electron-Capture

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Abstract

For a helium neutral beam produced by the electron-capture of He^+ ions in He, Ne, Ar, Kr and Xe at the energies of 0.8, 1.0 and 1.5 MeV, the metastable fraction has been determined by measuring a single electron-loss cross section of the helium atom, and was found to vary with the atomic number Z_T of the neutralizing gas.

1. Introduction

The metastable fractions of helium neutral beams produced by the single electron-capture of He^+ ions have been measured by Miers et al[1,2] in the energy range of 10-30 keV, and by Gilbody et al[3,4] in the energy range of 10-200 keV. It has been found that the metastable fraction varies with the atomic number Z_T of the neutralizing gas. Because the experiments have been performed for only a few kins of neutralizing gases, it has not yet been clarified how the metastable fraction changes with Z_T. At higher energies, the Z_T dependence of the metastable fraction has not been measured.

2. Experimental

In the present experiment, we have measured the metastable fractions of neutral helium beams produced by the single electron-capture of He^+ ions in various neutralizing gases, He, Ne, Ar, Kr and Xe, at the energies of 0.8, 1.0 and 1.5 MeV. The metastable fractions have been measured usually by the attenuation method. In this method, however, the experimental values have large errors due to the temporal fluctuations of the beam intensity and of the attenuation gas pressure. In our experiment, for example, the fluctuations of the beam intensity and of the

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attenuation gas pressure were ~5% and ~3%, respectively, and the metastable fraction measured by the attenuation method may have error larger than 30%. In the present experiment, we have determined the metastable fraction by measuring the single electron-loss cross section of a helium beam in nitrogen gas. By this method, we have been able to determine the metastable fractions precisely because of small experimental errors of the cross sections. The apparent single electron-loss cross section $\sigma^a_{01}(f)$ of the neutral helium beam with the metastable fraction f is represented as follows:

$$\sigma^a_{01}(f) = (1-f)\sigma_{01}+f\sigma^*_{01}, \tag{1}$$

where σ_{01} and σ^*_{01} are the single electron-loss cross sections of the ground-state and of the metastate-state helium atoms, respectively. Therefore, the metastable fraction is written as,

$$f = \frac{\sigma^a_{01}(f)-\sigma_{01}}{\sigma^*_{01}-\sigma_{01}}. \tag{2}$$

A helium beam containing only a ground-state atom can be produced by passing through the attenuation cell with nitrogen gas of which the preesure is sufficiently high. Therefore, we can easily measure the cross section σ_{01}. On the contrary, we can not determine precisely the cross section σ^*_{01} because a helium beam containing only a metastable-state atom is very difficult to be prepared. Since only the quantity $\sigma^a_{01}(f)$ depends on Z_T, the numerator of Equation (2) is enough to represent the Z_T dependence of the metastable fraction. Therefore, we have determined the metastable fraction for gas "X" relative to that for argon gas,

$$\frac{f(\mathrm{X})}{f(\mathrm{Ar})} = \frac{\sigma^a_{01}[f(\mathrm{X})]-\sigma_{01}}{\sigma^a_{01}[f(\mathrm{Ar})]-\sigma_{01}} \tag{3}$$

We used He, Ne, Ar, Kr and Xe as gas "X".

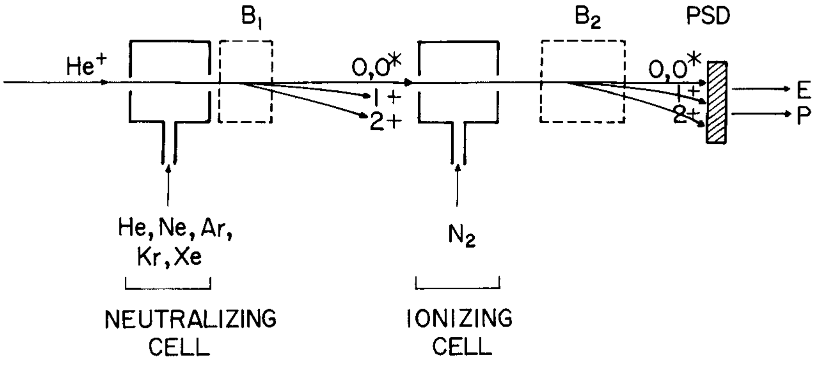

Fig. 1 Schematic diagram of experimental setup.

The experimental setup is schematically shown in Fig. 1. Energetic He$^+$ ions from the van de Graaff accelerator of Kyoto University entered the neutralizing cell (13cm in length). The pressure of the neutralizing gas was kept less than 2×10^{-4} Torr so as to satisfy the single collision condition. The charged components in the helium beam emerging from the neutralizing cell were removed from the beam axis by a magnetic field B_1. The neutral beam was introduced into the ionizing cell. The fraction of the metastable component depends on the kind of neutraling gas. The pressure of nitrogen gas in the ionizing cell was measured by an ionization gauge calibrated by using a baratron. After the charge changing collision with nitrogen gas, each charge state of the helium beam was separated by a magnetic field B_2 and detected with a solid-state position sensitive detector [PSD] . With this method, σ^{a}_{01} (f) was estimated.

For the measurement of σ_{01}, an attenuation cell (82cm in length) was inserted between the neutralizing cell and the ionizing one in order to attenuate the metastable-state component to a sufficiently small fraction. In the case where the pressure of nitrogen gas was larger than 3×10^{-3} Torr in the attenuation cell, the metastable fraction became less than 2×10^{-3} and could be neglected.

3. Results and Discussion

The experimental values of relative metastable fractions defined by Equation (3) are plotted in Fig. 2 as a function of Z_T at the energies of 0.8, 1.0 and 1.5 MeV. It is clearly seen that the metastabe fraction changes significantly with the atomic number Z_T of the neutralizing gas, and that the features of the Z_T dependence at different energies are very similar; f (He) and f (Ne) are smaller than f (Ar) , while f (Kr) is larger than f (Ar) , and f (Xe) is smaller then f (Kr) . It should be noted that, at lower projectile energies[1-4], the feature of the Z_T dependence resembles the present ones. It is also seen that the amplitude of variations of experimental values at 0.8 and 1.0 MeV is about the same, while it becomes somewhat larger at 1.5 MeV.

If the neutral beam is produced by the two step process, that is, the electron-capture into a highly excited state followed by the decay to the ground and metastable-states, it is expected that the metastable fraction does not depend on the target. The existance of the Z_T-dependence of the metastable fraction, therefore, means that the direct electron-capture to the final state of the projectile atom contributes significantly to the formation of a neutral helium beam.

We have compared the present data with the simple theoretical calulation. Under the single collision condition in the neutralizing cell, the metastable fraction of the produced neutral helium beam is expressed as follows,

$$f=\frac{\sigma^{*}_{10}}{\sigma_{10}+\sigma^{*}_{10}} \tag{4}$$

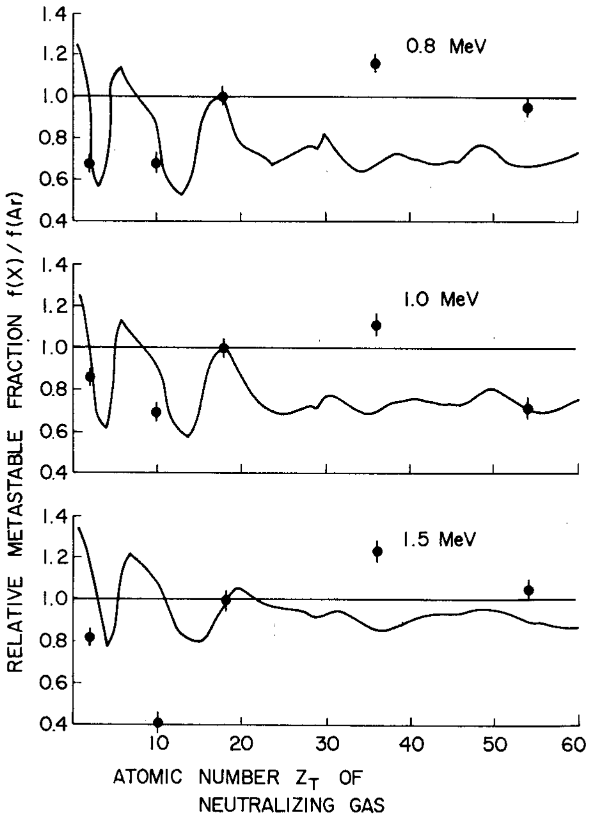

Fig. 2 Experimental relative metastable fraction as a function of atomic number Z_T of neutralizing gas at the energies of 0.8, 1.0 and 1.5 MeV. Error is mainly due to the uncertainty of the ionizing gas pressure. Theoretical results are also shown with solid curves.

where σ_{10} and σ_{10}^* are the cross sections of the single electron-capture to the ground-state and to the metastable-state of projectiles, respectively. The cross section of a single electron-transfer from a definite state in the neutralizing gas atom to a definite state in the projectile atom is calculated with the O. B. K. approximation[5], and is given by

$$\sigma_{\mathrm{OBK}} = \frac{8.53\times10^{-10}E_f^{3/2}(E_i^m)^{5/2}E_K^4}{[E_k^2+2E_k(E_f+E_i^m)+(E_f-E_i^m)^2]} \tag{5}$$

where E_i^m and E_f are the binding energies of the initial state (m-th shell) in the neutralizing gas atom and of the final state in the projectile atom, respectively, and E_k denotes the kinetic energy of an electron which has equal velocity to that of the projectile atom, and all energies are in the unit of eV. When the initial state is not selected, the single electron-capture cross section σ_t is easily calculated if there is no correlation between electrons in the neutralizing gas atom. By summing up all possible initial states, the cross section is written as,

$$\sigma_t(E_f,E_k) = \sum_m n_m \sigma_{\mathrm{OBK}}(E_i^m, E_f, E_k), \qquad (6)$$

where n_m is the number of electrons in the m-th shell of the neutralizing gas atom. For the initial binding energies E_i^m, we used the theoretical values calulated by J. P. Desclaux$^{6)}$, and for the final binding energies E_f, we used 24.6 eV for the ground-state and 4.8 eV for the metastable-state helium atom. The single electron-capture cross sections σ_{10}^* and σ_{10} are given by

$$\sigma_{10}^*\ (E_k) = \sigma_t(E_f = 4.8\ \mathrm{eV},\ E_k), \qquad (7a)$$

$$\sigma_{10}(E_k) = \sigma_t(E_f = 24.6\ \mathrm{eV},\ E_k). \qquad (7b)$$

The relative metable fractions calculated with Eqations (4), (7a) and (7b) show clearly the oscillatory dependence on the atomic number Z_T (solid curves in Fig. 2). The experimental amplitude of variation is the same order as the magnitude to the theoretical amplitude of oscillation. With increasing projectile energy, however, the theoretical amplitude decreases. This tendency is opposed to the experimental finding mentioned above. Further, it should be noted that the krypton data deviates remarkably from the theoretical value. In order to make clear the Z_T dependence of a metastable fraction, more experimental data is necessary.

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