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ABSTRACT

The cross sections σ_{21} and σ_{20} for single and double electron capture of $^3He^{++}$ ions with energies between 7.2 and 181 keV have been measured in thin targets of He. Our results join quite smoothly to other measurements at higher and lower energies. There is good agreement with the calculations of Ferguson and Moiseiwitsch and those of Fulton and Mittleman for double electron capture.

INTRODUCTION

The total cross section for double electron capture by He^{++} in He has been investigated in several theoretical papers.[1-6] Measurements to test these calculations have been available only for energies greater than 38 keV/nucleon.[7-9]

Single electron total capture probabilities in He have received less theoretical attention.[6,10] However, the experimental coverage is a little broader: measurements have been reported for energies from 0.25 to 2 keV/nucleon[11] and for energies above 38 keV/nucleon.[7,8,12] Some of these results do not agree within their experimental uncertainties.

We have measured the cross sections σ_{21} and σ_{20} for the capture of one and two electrons respectively by $^3He^{++}$ passing through He in the energy range 2.4 to 60 keV/nucleon, and compare our results with published measurements and calculations.

In addition to the total-cross-section measurements summarized in this paper, differential cross sections for large angle deflections[13] and equilibrium fractions[14] have been reported for the energy range considered here. However, it is not possible to deduce total capture cross sections from them.

APPARATUS AND PROCEDURE

The apparatus and method of measurement were idential to those described in the preceding paper.[15] A momentum-analyzed beam of $^3He^{++}$ ions passed through a 9.5-cm-long gas cell, and the increase in population of the He^+ and He^0 components was measured as a function of the pressure in the target. At each energy, approximately ten different measurements were made at various pressures, from background ($< 10^{-5}$ torr) to about 3×10^{-3} torr.

DATA REDUCTION

The method of data reduction was similar to that described in the preceding paper (Ref. 15). At our lowest energy the cross section σ_{10} for the capture of one electron by He^+ is five times σ_{20} and ten times σ_{21}.[16] Because this cross section is so large the σ_{10} corrections at the low energies were somewhat larger than those of the nitrogen target. The σ_{10} correction amounted to 45% in F_1 and 15% in F_0 for the highest pressure in the worst case (7.2-keV $^3He^{++}$). The effect on the uncertainty in the cross sections we report here is not very large, however. A 10% uncertainty in σ_{10}[16] propagated through our analysis turns out to give a 4% uncertainty in σ_{21} and a 1.5% uncertainty in σ_{20} for this case.

At high energies, the σ_{01} corrections are largest; however, they never exceeded 0.5% in F_1 and 2% in F_0 at the highest pressure for the worst case (181-keV $^3He^{++}$). The ambiguity in the cross section σ_{01} for electron loss by helium atoms which arises because of metastable atoms (see comments in Ref. 15) seems to be less for a He target than for a N_2 target.[17] Our results are very insensitive to this cross section, for we find that an uncertainty of 100% in σ_{01} would, at worst, change our value of σ_{21} by 1% and σ_{20} by 1.5%.

For the helium target at low energies, there was a relatively high He^+ background which, for the thickest target used, sometimes was as large as 20% of our He^+ yield. This background, which is attributed to the relatively large σ_{21} in the residual air in the drift sections, increases the uncertainty of our low-energy measurements.

RESULTS AND DISCUSSION

The results for σ_{21} and σ_{20} in He are listed in Table I. To facilitate comparison with other measurements our results are also shown in Fig. 1, where we have chosen the abscissa to be the energy of ^4He ions of the same velocity as the ^3He ions used in our experiment. Our cross sections connect smoothly with the high-energy results of Pivovar et al.[8] and Nikolaev et al.[9,12] and, within the experimental uncertainties, with the low-energy σ_{21} measurements of Hertel and Koski.[11] The measurements of Allison,[7] on the other hand, are approximately one-half ours.[18] The cross section for two-electron capture decreases monotonically with increasing energy, whereas that for one-electron capture has a maximum at a $^4He^{++}$ energy of about 150 keV. These general characteristics are as expected for resonant and nonresonant charge transfer.

In Figs. 2 and 3 we represent experimental results by a dashed line and compare these with available theoretical calculations. All theoretical results shown are for capture into the ground state, whereas the measurements include capture into all states. This implies that the experimental results should lie somewhat above theory.

One-electron capture is shown in Fig. 2. The Brinkman-Kramers calculation (B-K) is a first Born approximation considering only the interaction of the incoming nucleus and the electrons of the target.[10] It is a high-energy theory, and one does not expect good agrement with experiment at low energies. The curve labeled F-Mi is the result of a three-atomic-state approximation by Fulton and Mittleman[6] and is applicable in this energy range. This theory yields a maximum in the cross section near the energy of the experimentally observed maximum, but the magnitude of the cross section is only one-fourth the measured value.

The results of theoretical calculations for double electron capture are shown in Fig. 3. The methods used for these calculations may be divided into three categories: (1) Calculations that use the Born approximation (but are philosophically different) by Gerasimenko and Rosentsveig[1] (G-R) and by Fulton and Mittleman[5] (F-Mi III, F-Mi IV); (2) the impact parameter method, with an approximate solution by Betts and Jackson[2] (B-J) and a more complete calculation by Ferguson and Moiseiwitsch[3] (F-M); and (3) the method of perturbed stationary states by Basu, Mukherjee, and Sil[4] (BMS), who neglected the translational motion that the electrons have because they are attached to a moving nucleus, and by Fulton and Mittleman[6] (F-Mi I, F-Mi II) who included this motion. The two results F-Mi I and F-Mi II arise from different approximations that have been made because the exact wave functions for the helium atom are not known. Each curve is drawn over an energy range that the respective authors have suggested as the region of vailidty for their calculations.

Our results are in good agreement with the calculations of Ferguson and Moiseiwitsch (F-M) and those of Fulton and Mittleman (F-Mi II).

It is interesting to note that the curves F-Mi of Fig. 2 and F-Mi III of Fig. 3 result from the same type of calculation, yet the σ_{21} measurements do not agree as well with this theory as the σ_{20} measurements.

ACKNOWLEDGMENTS

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Table I. Measured cross sections for one-electron (σ_{21}) and two-electron (σ_{20}) capture by $^3He^{++}$ in He (in units of 10^{-16} cm^2/atoms).

$^3He^{++}$ Energy (keV)	σ_{21}	σ_{20}
7.2	0.49 ±0.10	1.7 ±0.25
12	0.59 ±0.10	1.8 ±0.25
16	0.69 ±0.12	1.8 ±0.25
30	1.4 ±0.2	1.7 ±0.25
38	1.7 ±0.2	1.4 ± 0.2
66	2.8 ±0.3	1.3 ±0.2
94	3.2 ±0.4	1.2 ±0.2
116	3.2 ±0.3	1.0 ±0.15
154	3.2 ±0.3	0.77 ±0.12
181	3.0 ±0.3	0.65 ±0.10

FOOTNOTES AND REFERENCES

*This work was done under the auspices of the U. S. Atomic Energy Commission.

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18. It is interesting to note that Allison's cross sections were deduced from equilibrium fractions (i.e., thick targets), whereas all the other measurements were for thin targets. Pivovar et al. in an earlier paper[19] also deduced σ_{21} from equilibrium fractions and obtained values that were lower than their thin-target measurements. In fact, these earlier results were only 20% larger than Allison's, a discrepancy covered by the experimental uncertainties. This discrepancy between thin- and thick-target measurements seems to be peculiar to helium; for a N_2 target no difference is noticeable between thin- and thick-target measurements.

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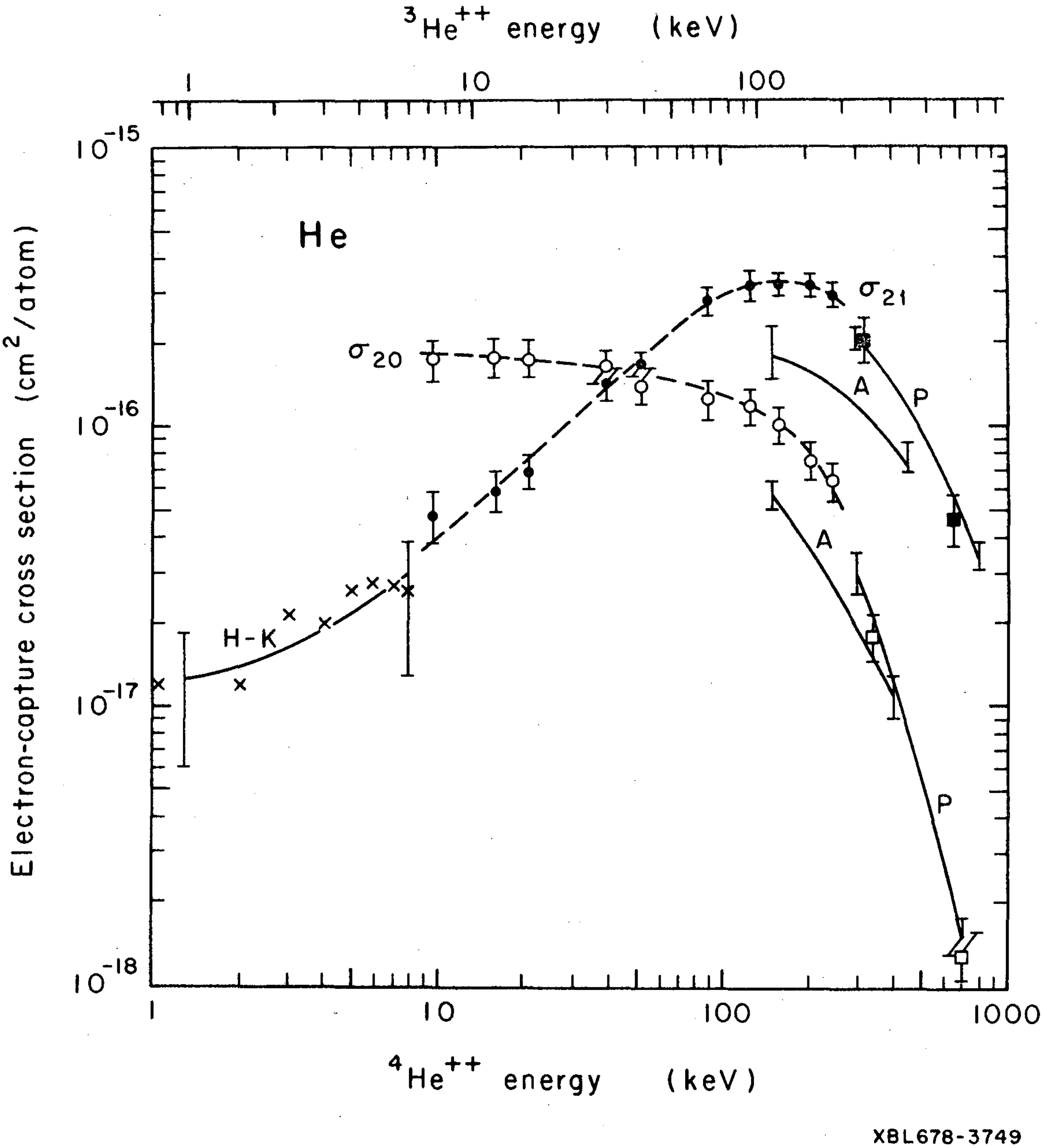
FIGURE LEGENDS

Fig. 1. Results of cross-section measurements for the capture of one (σ_{21}) and two (σ_{20}) electrons by helium nuclei in He: ●, o this paper; x and line marked H-K, Hertel and Koski (Ref. 11); ■ Nikolaev et al. (Ref. 12); □ Nikolaev et al. (Ref. 9); the line marked A represents the results of Allison (Ref. 7); the line marked P, Pivovar et al. (Ref. 8).

Fig. 2. Comparison of theory and experiment for σ_{21} in He. The dashed line summarizes the experimental results of Refs. 8, 11, 12, and (●) this paper. The theoretical predictions are: B-K, Brinkman and Kramers (Ref. 10), and F-Mi, Fulton and Mittleman (Ref. 6).

Fig. 3. Comparison of theory and experiment for σ_{20} in He. The dashed line summarizes the experimental results of Refs. 8, 9, and (o) this paper. The theoretical predictions are: B-J, Betts and Jackson (Ref. 2); BMS, Basu, Mukherjee, and Sil (Ref. 4); F-M, Ferguson and Moiseiwitsch (Ref. 3); F-Mi I and F-Mi II, Fulton and Mittleman (Ref. 6); F-Mi III and F-Mi IV, Fulton and Mittleman (Ref. 5); and G-R, Gerasimenko and Rosentsveig (Ref. 1).



$^3He^{++}$ energy (keV)
1
10
100
10^{-15}
10^{-16}
10^{-17}
10^{-18}
He
σ_{21}
σ_{20}
A
P
A
P
H-K
Electron-capture cross section (cm^2/atom)
1
10
100
1000
$^4He^{++}$ energy (keV)
XBL678-3749

Fig. 1

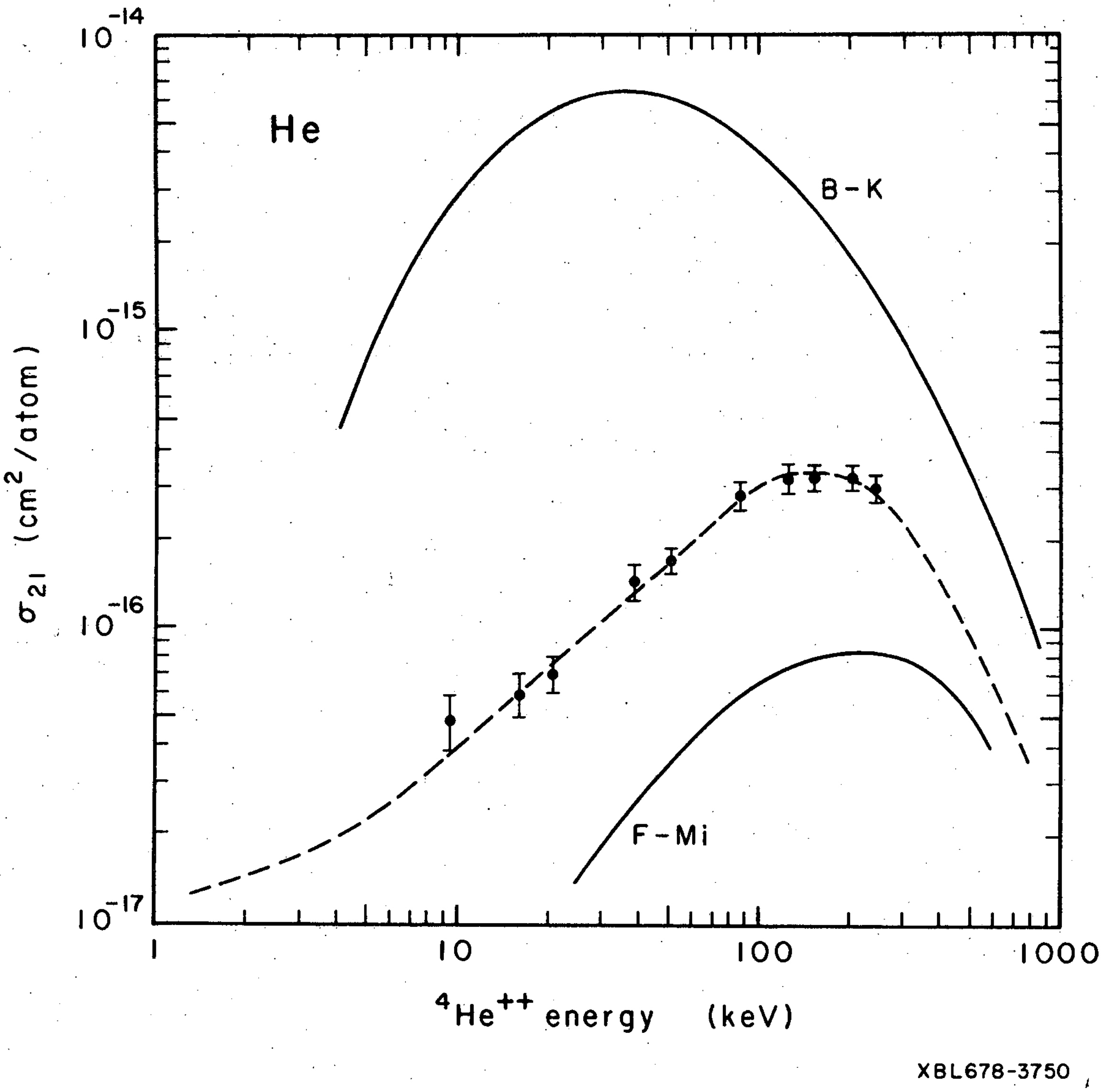

He
B-K
F-Mi
10^{-14}
10^{-15}
10^{-16}
10^{-17}
σ_{21} (cm^2/atom)
1
10
100
1000
^{4}He^{++} energy (keV)
XBL678-3750

Fig. 2

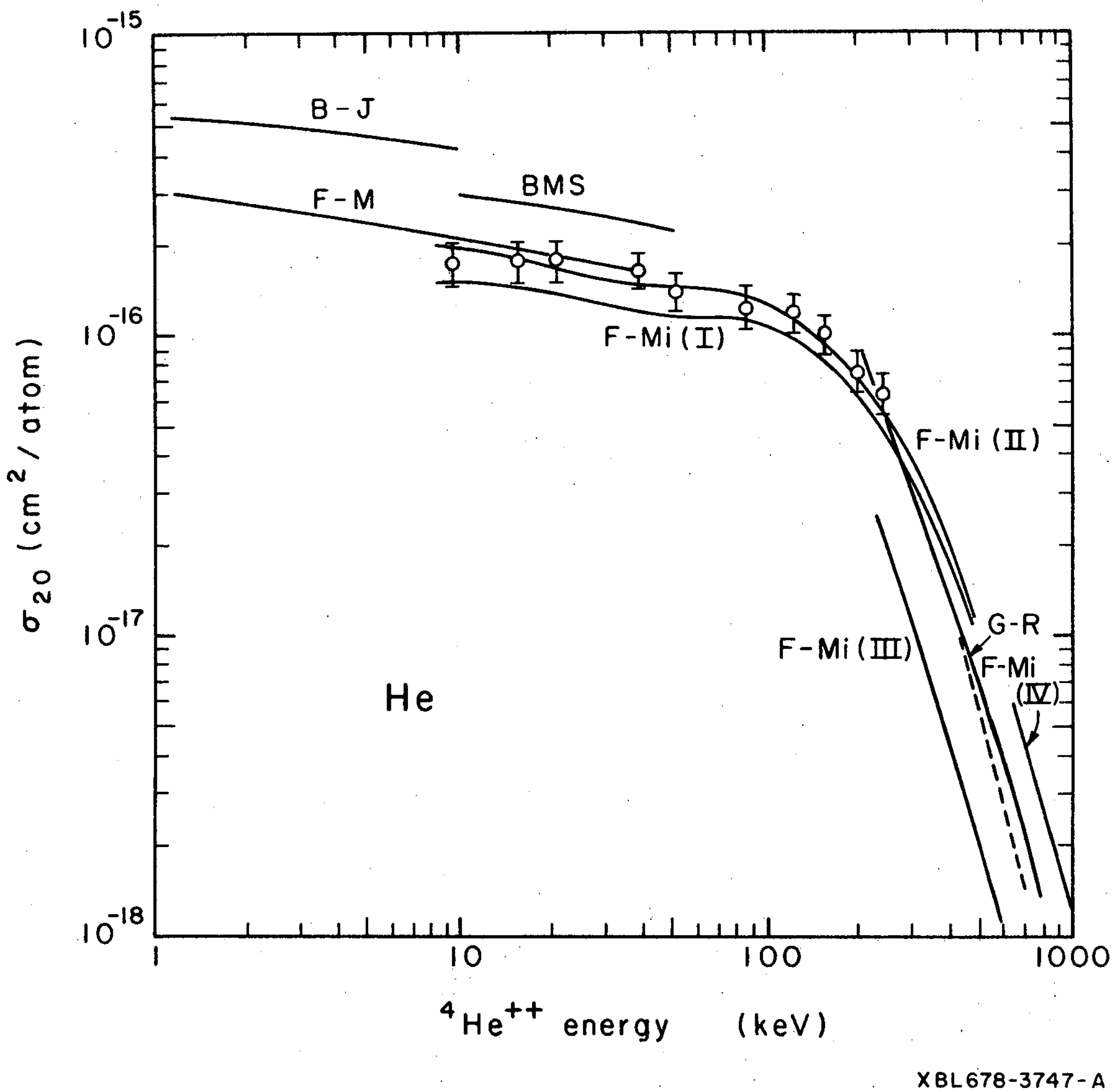

B - J
F - M
BMS
F-Mi (I)
F-Mi (II)
F-Mi (III)
G-R
F-Mi
(IV)
He
10^{-15}
10^{-16}
10^{-17}
10^{-18}
σ_{20} (cm^2/ atom)
1
10
100
1000
^{4}He^{++} energy (keV)
XBL678-3747-A

Fig. 3