Accurate Measurements of the Gas-Solid Difference in Stopping-Powers and Charge-State Distributions of Lead Ions in the Energy Range of (30-300) MeV/u

著者	Ishikawa Shunki
number	95
学位授与機関	Tohoku University
学位授与番号	理博第3378号
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論　文　内　容　要　旨

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氏　　名	石川　竣喜	提出年	令和 3　年
学位論文の 題　　　目	（英語表記） Accurate Measurements of the Gas-Solid Difference in Stopping-Powers and Charge-State Distributions of Lead Ions in the Energy Range of (30-300) MeV/u （日本語表記） 鉛イオンビームを用いた核子あたり 30-300 MeV 領域における阻止能と荷電状態分布に現れる Gas-Solid Difference の精密測定		

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When fast ions penetrate matter, they primarily lose energy due to elastic and inelastic collisions with the atoms of the stopping material. Furthermore, they change their directions and may even vary their ionic charge states depending on their velocities and element numbers. The description of the slowing-down process is characterized by the *stopping power* which is defined by the mean energy-loss value per unit path length of the penetrated matter. Experimental and theoretical studies of the stopping power for both light and heavy ions have been performed in the past since the discovery of radioactivity.

Although the fundamental forces of the ion-atom interaction are well known, the complex many-body collisions are difficult to describe, especially for heavy ions at low to intermediate velocities where charge-changing collisions occur frequently. An example is the longstanding problem of the dependence of the stopping power on the density of the medium: In 1951, Lassen *et al.* experimentally discovered that the mean charge state of fission fragments after penetrating through solid targets became larger compared to gaseous targets. Soon after, Bohr and Lindhard explained this observation by the concept of a higher ionization rate in solids than in gases due to the higher collision frequencies expected in the higher material density. Consequently, they predicted that the stopping powers in solids should become larger than in gases.

Such a gas-solid difference (the Bohr-Lindhard density effect) in slowing-down process is still neglected in most theories, although experimentally the effect has been clearly observed with different experimental methods at low energy. Heavy ions showed near the stopping-power maximum an up to 20% lower stopping power in gases than in solids, which was discovered by the experiment of Geissel *et al.* in 1982. Concerning the effect, an important remaining question is: "How much does the density effect continue and contribute over the velocity range until it vanishes?" Motivated by this question, we performed measurements of stopping powers and charge-state distributions of heavy ions in the velocity range, where the experimental data are scarce.

We performed an experiment with (35, 50, 70, 100, and 280) MeV/u lead (^{208}Pb) ions slowed down in five gaseous (N_2, Ar, Kr, Xe, and C_3H_6) and five solid (C, Ti, Zr, Sn, and $(C_3H_6)_n$) materials, at GSI in Darmstadt, Germany. The partially ionized projectiles were provided by the synchrotron SIS-18 with a moderate intensity of approximately 10^3-10^4 ions per spill. The FRagment Separater (FRS) was used as the high-resolution magnetic spectrometer for the experiment. The primary beams first passed through the stripper targets placed at the F0 area of the FRS, populating the incident charge-state distribution. Only one charge state was selected from the distribution by using the mechanical slits at the first focal plane F1. The selection was carefully performed so that the charge state distribution could reach the equilibrium state immediately in the atomic collision targets, which were installed at the central focal plane F2. From the measurement of the position distribution with the time projection chamber (TPC) inserted at the third focal plane F3, the energy-loss and charge-state distributions of lead ions were measured.

We successfully measured the mean charge states and stopping powers within an accuracy of 1%. The gas-solid differences in mean charge states and stopping powers were clearly observed for all the applied gas-solid target materials. The effect has systematically decreased with higher incident velocities and is vanished at 280 MeV/u. The mean charge states of lead ions emergent from solids were, at the velocity range of (30-100) MeV/u, (3-5)% higher than for the gases with neighboring Z_2 numbers. The corresponding measured stopping powers in solids were (6-8)% higher than in gases at the same velocity.

The comparison of the mean charge state with the theoretical predictions (e.g., the GLOBAL program) showed up to about 5% difference for solid materials at the low velocity range, and for gaseous materials the deviations were found up to about 14%.

The comparison of the stopping powers with the theoretical predictions by the computer programs (e.g., the ATIMA1.4 program) showed up to about 4% difference for solid materials at the low velocity range, and for gaseous materials the deviations were found more than

10%. With the empirical formula fitted to the measured mean charge states, the theoretical prediction by the ATIMA program was significantly improved to reproduce the experimental stopping powers within the accuracy of less than 2% for both solid and gaseous materials.

In summary, from the accurate measurements of the charge-state distributions and stopping powers, the Bohr-Lindhard density effect was clearly observed for all the gas-solid target materials. The effect vanished at 280 MeV/u, and systematically increased as the velocity decreased. We have confirmed that the main factor of the Bohr-Lindhard density effect is due to the difference of the effective charge state of heavy ions inside matter. With our experimental results, an improvement of theoretical descriptions is expected.

別　紙

論文審査の結果の要旨

重荷電粒子線が物質を通過した時のエネルギー損失と荷電状態分布の正確な計算方法の確立は、放射性同位体(RI)ビームを使った実験の計画・最適化、重イオンビームを使った実験結果の解析等において重要な役割を果たす。ドイツの GSI ヘルムホルツ重イオン研究センターでは最も正確な阻止能の計算コード ATIMA が開発され、RI ビーム生成や実験のためのシミュレーションプログラム LISE++, MOCADI, GEANT4 等で使用されている。一方で、気体標的における阻止能は低エネルギー領域で固体標的での阻止能より小さいことが知られている。これは阻止能に物質の密度依存性があることを示しているが、ほとんど研究されておらず、阻止能の計算コードに取り入れられていない。

本論文では、気体－固体における阻止能の相違の原因を解明する目的で、核子あたり 35,50,70,100,280MeV の鉛ビームを原子番号が近い 5 組の気体標的と固体標的に照射し、阻止能と標的通過後の荷電状態分布の精密測定を行い、気体標的と固体標的で比較した結果をまとめた。実験の結果、気体標的と固体標的における阻止能と標的通過後の平均荷電状態の相違は、低エネルギー領域で顕著に現れるが、エネルギーが高くなるに従って減少し、核子あたり 100-200MeV あたりでほぼ消失していることが分かった。気体－固体間の阻止能の相違は、平均荷電状態の相違を考慮するとほぼ説明がつく。気体標的通過後の平均荷電状態を計算する方法が確立できれば、気体標的に対しても阻止能のほぼ正確な計算が可能であることが分かった。本研究は、阻止能と荷電状態分布の密度依存性の理論的研究や正確な計算方法の確立に必要なデータを提供している。

本論文の審査は提出論文の内容、口頭発表、質疑応答に基づき、5 名の審査員(岩佐准教授、田村教授、中村教授、Geissel 教授、Weick 博士)によって行われた。平成 4 年 1 月 11 日に予備審査、1 月 27 日の博士論文発表会を実施した。口頭発表と質疑応答により内容理解を確認した。学位論文執筆、審査は英語で実施したが、議論内容、プレゼンテーションの説得力どれも高いレベルにあり、自立して研究活動を行うに必要な高度の研究能力と学識を有することを示した。したがって石川竣喜提出の博士論文は、博士(理学)の学位論文として合格と認める。