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論文内容要旨

In this study, two different heavy ion transport Monte Carlo codes, HETC-CYRIC and PHITS were developed by using the intranuclear cascade model and the quantum molecular dynamics model respectively. These two codes are the first multi-purpose heavy ion transport Monte Carlo codes worldwide. Each section is summarized in the following.

In Chapter 2, the heavy ion transport Monte Carlo code HETC-CYRIC is developed, based on the intranuclear cascade and evaporation model HIC. The underlying model of the HIC code is explained and the HIC calculations are evaluated through comparison with experiments. In this comparison, the ISABEL model was also evaluated. Subsequently a heavy ion transport model is developed by using the Shen formula and the SPAR code. Heavy ion attenuation in water is calculated using the developed model and the results show good agreement with data. Finally the heavy ion transport code HETC-CYRIC is built by incorporating the developed heavy ion transport routine HIR into the high energy hadron transport Monte Carlo code HETC-3STEP. This improved HETC-CYRIC code is compared with systematic data on energy spectra of secondary neutrons. The HETC-CYRIC code provided good overall agreement with experimental data. It can be concluded that the HETC-CYRIC code can be applied to the design of heavy ion facilities.

In Chapter 3, the first multi-purpose heavy ion transport Monte Carlo code PHITS is developed, based on the quantum molecular dynamics QMD and on the generalized evaporation model GEM. Firstly the limitation of the output function in the HETC-CYRIC code are pointed out, and the necessity for use of a multi-purpose heavy ion transport code is explained. NMTC/JAM is selected as a base code for developing the heavy ion code, and some of the characteristics of the NMTC/JAM code are introduced. The models of the QMD and the GEM code are described in detail. Secondary, the first multi purpose heavy ion transport code PHITS is developed from the heavy ion transport model HIR, the JQMD model, and the GEM model. The newly developed PHITS code is carefully evaluated through comparison with systematic data on energy spectra of secondary neutrons form thin and thick targets. Not all of the calculated energy spectra agree well with the experimental data, however, possible reasons for these differences between the calculation results and the experimental data are discussed. Generally speaking the PHITS results agree well with the experimental data in a wide energy region and for different types of projectiles and targets of various thickness. It is concluded that the developed PHITS code possesses high accuracy in the neutron emission calculation.

In order to investigate the transport behavior of secondary particles in the target, experiments using large area targets were performed at HIMAC and are discussed in Chapter 4. Neutron energy spectra from four different large targets were obtained. Strong contributions to neutron yields by secondary particles in the large target

bombarded by high energy heavy ions, are notably absent in spectra by the comparison of 400 MeV/nucleon Fe beams on 1.5cm Cu and Pb targets, and 5cm Cu and Pb targets. The yields of secondary neutrons, produced by secondary fragments in very large targets of $20\times20\times11cm^3$ Cu and $20\times20\times20cm^3$ Pb, is also found to be very small. The measured spectra and calculated spectra from large targets are compared. and apart from small discrepancies data generally agree well with calculations. The experimental data are useful for high energy heavy ion shielding designs, and it is concluded that the PHITS code can be applied to evaluate secondary neutron production and attenuation in a large target, bombarded by high energy heavy ions.

In Chapter 5, the behavior of secondary particles is studied and their contribution to secondary neutron yield in the large target is investigated, by PHITS calculations using. Energy spectra of secondary fragments emitted from a very thin target are calculated and the emission process is discussed. The spatial distributions of secondary particles are calculated for the purpose of investigating the effect of different thick targets on secondary particle emission. The spatial distributions are discussed for secondary fragments from neutron to ^{27}Al with targets of different thickness. The obtained yields of heavy ion ejectiles amount to less than 0.1 % compared to neutrons, and the total sum of yields of heavy ions from ^{7}Li to ^{27}Al is about 1% of the neutron yield. The number of ejected particles increases as a function of target thickness up to the range of the projectile. Beyond the range, all secondary particle yields are attenuated in the target. Even though secondary fragments contribute to increase the neutron yield, the neutron yield at twice the depth of range does not exceed the yield at range depth, but rather decreases to 90% of the neutron yield at range position.

In Chapter 6, the PHITS code is evaluated concerning its usefulness to other applications, by comparing calculations with three different types of experimental data on heavy ion studies. Spatial distributions of residual nuclei production induced by high energy heavy ions are calculated using the PHITS code, compared to data and discussed carefully from the perspective of the heavy ion transport and the creation of secondary particles. The spatial distributions of experimental data are well explained by the calculations. Next neutron emission spectra created by high energy heavy ion reactions attenuated in thick shielding are calculated and compared to experimental data. The results show good accuracy for up to 200 cm concrete shielding. In addition, a calculation for tissue equivalent material is compared with experimental data with the aim to explore the possible use of PHITS in medical applications. The calculated spectra agree rather well with the spectra.

In summary, the PHITS code performs well in particular when compared with other high energy transport Monte Carlo codes. It is concluded that the PHITS code can be applied to various fields of heavy ion studies.

The developed codes, HETC-CYRIC and PHITS are useful to various studies in the field of heavy ion reactions. In particular, the new PHITS code offers highly accurate results for multi purpose use. It is hoped that the HETC-CYRIC and the PHITS code will contribute to the progress in various heavy ion studies in science and engineering.

Further studies have begun to develop a new heavy ion transport model by using the ATIMA code and by including the equations of the nucleus-nucleus total reaction cross section of Tripathi et al., in order to obtain a highly accurate heavy ion transport calculation down to the low energy region.

論文審査結果の要旨

現在様々な目的のために稼動・建設されている高エネルギー重イオン加速器施設においては、発生する二次粒子とそれによる二次反応の影響を評価することが重要である。また高エネルギー重イオンを含む厳しい放射線環境である宇宙においては、乗組員の被曝評価と宇宙船の遮蔽設計が今後の人類の宇宙進出において不可欠である。しかし、高エネルギー重イオンによる二次粒子生成に関する測定データはまだ十分ではなく計算コードに至っては一次元の輸送コードが存在するのみであった。本論文は高エネルギー重イオン輸送を行える三次元モンテカルロ計算コード HETC-CYRIC と PHITS を二つの異なる核モデルに基づいて開発するとともに、実験と比較してこれらコードの精度評価を行ったものであり、全編６章よりなる。

第１章は序論である。

第２章では、世界に先駆けて、フェルミ自由ガスモデルに基づくカスケード・蒸発コード HIC とハドロンカスケードコード HETC を結合して、重イオン輸送モンテカルロコード HETC-CYRIC を新しく開発している。HETC-CYRIC は高エネルギー重イオンによる二次生成中性子に関して実験値をよく再現し、計算時間も早い優れた利点があるが、出力が限定され、利用可能範囲が限られている。

第３章では、この欠点を改良し、さらに高精度の量子分子動力学モデルに基づくコード QMD とハドロンカスケードコード NMTC/JAM を結合して、より汎用の高い重イオン輸送モンテカルロコード PHITS を開発している。

第４章では、輸送現象をより明らかにするために、大きなターゲットを用いた重イオンによる二次中性子生成データを、放射線医学総合研究所の重イオン加速器を用いて測定している。異なる厚さの結果から標的内二次粒子の中性子生成の寄与について検討するとともに PHITS コードが実験値をよく再現することを示している。

第 5 章では、PHITS コードを用いて、いろいろな二次粒子の標的内生成分布と生成した二次粒子や二次重イオンの生成割合について議論している。

第 6 章では、PHITS コードの様々な分野への応用のための実験的評価を行っている。いずれの計算においても PHITS コードは実験値を良く再現し、重イオン加速器施設の遮蔽設計のみならずより広い重イオン研究分野への応用が期待できることを示している。

第５章は総括である。

以上要するに、本論文は世界に先駆けて高エネルギー重イオン輸送コードを開発するとともにその精度を幅広く実験的に評価したものであり、放射線工学、加速器工学、宇宙工学の発展に寄与するところが大きい。

よって、本論文は博士（工学）の学位論文として合格と認める。