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論文内容の要旨

Recently, D-T burning plasma experiments have been performed on the Joint European Torus (JET) and the Tokamak Fusion Test Reactor (TFTR). These experiments are expected to bring valuable information for reactor relevant plasmas. In these experiments, the role of fusion products diagnostics, such as neutron diagnostics, becomes more important than ever before. The measurements of neutron flux as well as neutron energy will provide us the information on 1) fusion output, 2) high energy ions produced by the auxiliary heatings and 3) α-heating. These are the major issues not only on those experiments but also on the experiments of the next large tokamak facility such as International Thermonuclear Experimental Reactor (ITER).

During past years, I have developed a new type of neutron spectrometer, named COTETRA (counter telescope with thick radiator), to measure the neutron energy spectra around 14MeV. The COTETRA has a merit of compactness with good energy resolution and high detection efficiency, hence it is suitable for space resolved neutron energy spectrum measurement. It is based on the concept of a proton recoil telescope. In a conventional proton recoil telescope, protons are recoiled by incident neutrons in a thin polyethylene film (radiator). Some of protons enter into a detector (E-detector) placed in a certain geometry, e.g. behind the radiator. The energy of the neutron is evaluated from the recoil proton energy being measured with E-detector, when the energy loss of the proton in the radiator is negligibly small to the proton energy. Therefore, the radiator is preferred to be as thin as possible to measure the neutron energy with good accuracy, although the usage of a thin radiator reduces the detection efficiency of the telescope. In COTETRA, a plastic scintillator (ΔE-detector) is used as a radiator. The energy of newly developed for each set. Two functions are newly applied to the system. One function provides the timing information of neutron events during shots. Another function provides the information of accidental coincidence between ΔE- and E-detector. The accidental coincidence causes serious problem when the neutron flux is extremely high. On the calibration experiment, the effect of accidental coincidence was evaluated by placing a tantalum plate between ΔE- and E-detector. It was not possible to apply this method on TFTR. Therefore, the evaluation was made by the timing-shift technique. Using this technique along with normal coincidence technique, two types of coincidence spectra, called foreground and background spectra, were obtained. The foreground spectrum was obtained by accumulating the coincidence events of the three PMT's (two attached to ΔE-detector and one to E-detector). This spectrum contains events due to accidental coincidences between ΔE- and E-detector as well as those due to true coincidences, in which protons recoiled at ΔE-detector is detected by E-detector. The background spectrum was obtained by coincidence events between the timing signal of ΔE-detector and the 10-nsec shifted timing signal of E-detector. Then, it contains only events due to accidental coincidence. It was verified that these two new functions were working successfully on TFTR.

The Monte Carlo code NESFP was developed to calculate the energy spectra of neutrons emerged from D-T fusion plasmas. With this code, the neutron energy spectrum and the fusion reactivity of a plasma for any velocity distributions of deuterium and tritium ion species can be calculated. The validity of the code was checked by comparing its results with those in other publications in the case where deuterium and tritium ions have Maxwellian velocity distribution.

The D-T fusion plasma experiments have been performed since November 1993 on TFTR. Tritium was introduced to the torus by gas neutron is evaluated by the sum of the energy deposit of recoil proton in ΔE- and that in E-detector. A thicker radiator can be used in COTETRA than a conventional telescope, since the energy deposit of proton in the radiator can be obtained in COTETRA. Therefore, COTETRA has better detection efficiency.

A prototype of COTETRA was constructed to verify its operation principle. The calibration experiments were performed using a D-T neutron generator. The energy resolution of 5.3±0.9% and the detection efficiency of 1.3×10^{-4} counts/(n/cm^2) were achieved.

A Monte Carlo code that simulates its detection process has been developed to evaluate the performance of COTETRA. The calculation agrees with the results of the calibration experiments within its margin of error. The calculation also suggests that the energy resolution up to 3% is achievable with the detection efficiency of $\sim 10^{-5}$ counts/(n/cm^2).

In 1992, two types of COTETRA were developed for the application to TFTR D-T experiments. One uses a Si-diode (set-A) as an E-detector and the other uses NE102A plastic scintillator, instead (set-B). Both of them use NE102A as a ΔE-detector. Set-A was characterized by higher energy resolution, while set-B was by higher counting rate capability and detection efficiency. For the use under high neutron flux rate condition, both sets have smaller detection area and use faster electronics than the prototype. Calibration experiments for these sets were also performed. An energy resolution of 4.0% was obtained for set-A. Set-B is expected to work at a count rate of up to 10^4cps, which corresponds to a neutron flux rate of $\sim 10^9$ (n/cm^2)/s. The detection efficiency of set-B was $\sim 6 \times 10^{-5}$ counts/(n/cm^2).

Both of them were installed at the multichannel neutron collimator of TFTR in 1993. At this location, COTETRA's are viewing plasmas perpendicularly to the magnetic field. A data acquisition system was puffing and/or by neutral beam injection (NBI). As auxiliary heatings, the NBI heating and ion cyclotron range of frequency (ICRF) heating were provided.

The D-T neutron energy spectra were obtained for 'NBI and ICRF' heated plasmas and for NBI heated plasmas. These were the first D-T neutron spectra obtained from D-T plasmas in the world. The full width at half maximum (FWHM) of the peak for the ICRF heated plasma is wider than that for NBI heated plasma. The calculated energy spectra suggested this broadening was due to the existence of the high energy tritium ion tail of 100~400keV. The calculation also suggested that, for D-T plasmas, it is necessary to measure the energy spectrum in evaluating the existence of high energy ions besides the total neutron yield, which might decrease at higher ion temperature.

Space resolved measurements of D-T neutron energy spectra will be necessary for ICRF heated D-T plasma experiments on the next large tokamak, such as ITER, to evaluate the mechanism of ICRF heating in the plasma. The COTETRA will be a suitable diagnostic for this purpose because of its good energy resolution and compactness.

論文の審査結果の要旨

長壁正樹氏は、薄いポリエチレンフィルムによりプロトンを発生させるプロトンリコイル法を用いた従来の中性子検出器を改良し、高性能の中性子エネルギー分析器を完成した。その努力は国際的に認められ、長壁氏はプリンストン大学TFTR装置で行われたはじめての本格的なDT核融合実験 に開発した測定器を適用する機会に恵まれた。そしてDT核融合プラズマから発生する14 MeV中性子のエネルギー分布を測定し、プラズマ中のイオンの速度分布関数等を推定する等、他の計測器では得ることの出来ないデータを取得し、非常に意義のある仕事を行った。これらの仕事をまとめて博士論文としている。

長壁氏の考案した中性子検出器は、検出効率をあげるため、初段の薄膜フィルムをプラスチックシンチレーターに替え、そこでのエネルギー損失と後段の検出器でのエネルギー損失を測定し、その和をもって中性子エネルギーとする方法であり、まだ原子核実験等で使用されたことのない新しい方法である。彼はこの考案した検出器の較正実験を大阪大学14 MeV中性粒子発生装置を利用して行ない、エネルギー分解能5.3 %　検出効率1.3×10^{-4}counts/neutron/cm^{2}を得ている。その後も中性子検出器を改良し、TFTRのDT実験に適用した。TFTRのDT実験には多くの中性子検出器が設置されているが、中性子のエネルギー分析が可能で、イオンの温度分布関数の情報を得ることが出来るのは、長壁氏の中性子検出器のみであることからも、同氏の研究が高度なものであり、核融合DT実験への貢献も高いと推定することが出来る。

TFTRのDT核融合実験の厳しい安全性の規制と強いDT 中性子フラックスのなかで、彼は着実にデータのS/N比を改良した。そしてNBIとICRFを併用したDT実験においては、トリチウムのイオン温度分布が300 keV程度まで広がっていることをはじめて実験的に確認した。検出器に関する研究は既に２つの論文としてReview of Scientific Instrumentsに発表され、あるいは印刷中であり、DT核融合実験での計測データは、プリンストン大学でも非常に貴重なデータとして他の論文にも要旨は発表され始めている。これらのことから、本論文は学位授与の対象として十分な内容を持っていると判断した。

試験は審査委員全員の出席を得て実施した。まず、審査委員で論文内容に関し討論を行ない、問題点の整理を行った。その後、出願者に出席を求め質疑応答を行った。出願者は、用意された厳しい質問にもほぼ完璧に答え、研究分野の新しい点や研究内容の重要性についても良く理解していることは確認できた。博士論文は、２報の学術論文を基礎としたものであり十分な学問的内容を持ったものである。

本人の外国語に関する能力は、提出論文が英語で書かれており、十分であるものと判断した。公開発表会における発表はよく整理され、かつ、高度な内容を持つものであった。質問に対する回答も適切であった。論文内容、口述試験、公開発表いずれも十分に準備され、総合的にも高い評価を与えることができるものであり、合格と認定される。