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# 核データ研究の 40 年

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## 1. はじめに

2023 年 3 月末日をもって東京工業大学での退職を迎えたが、日本原子力研究所・日本原子力研究開発機構での 28 年間、東工大での 11 年間に加え、東北大学での学生時代を含めると約 40 年に亘って核データ研究に従事した。原子力機構時代の前半は中性子核物理の研究、核データ評価研究を行い、後半は先端基礎研究センターに所属したが、研究テーマとしては核データを中心テーマとして原子核理工学の広い分野に亘り原子核反応の理工学的側面を『課題解決型基礎研究』、あるいは『パスツール型基礎研究』として広く研究した。退職講義の報告という本稿の性質上、多少の自己賛美を含む内容となっているがご容赦いただければ幸いである。

初期には中性子核データの測定に従事し、原子炉及び核融合炉開発に必要な核種の中性子散乱断面積の測定を行うとともに、その理論解析評価手法の開発及び検証を行った。開発した軟回転体模型に基づく原子核の集団準位構造解析とその情報を取り込んだチャンネル結合法による散乱断面積の解析手法は、その後多くの核種に適用され、中性子断面積解析手法の標準的手法の一つとして現在でも世界で広く用いられている。

続いて原子炉及び核融合炉開発用の核データの整備を実施した。整備のために必要な計算手法としては上記で開発した手法と統計模型を組み合わせ、国内の JENDL(Japanese Evaluated Nuclear Data Library-3.3,4,5, JENDL-Fusion File)、米国の LA150 核データライブラリーの評価に中心的に参加した。また、その成果が IAEA が ITER 開発用に整備する世界共通核データライブラリーである FENDL(Fusion Evaluated Nuclear Data Library)に多数採用された。

原子力発電所の使用済み燃料の核変換処理として、1.5GeV の陽子加速器を用いる ADS

(Accelerator-Driven System)の検討が本格的となり、従来の 20MeV を超える中間エネルギー核反応データを整備することが必要になり、3GeV 程度までのエネルギー領域で適用できる QMD(Quantum Molecular Dynamics、量子分子動力学)理論の開発を実施した。さらに J-PARC 建設における遮蔽設計が必要となり、3TeV 程度までの核反応を記述できるカスケード模型 JAM を共同で開発した。QMD 及び JAM は、上記 JENDL と共に、国産の標準的な放射線輸送計算システム PHITS に採用され国内外で広く利用されている。

中性子断面積の計算で用いる統計模型を高度化しアイソスピンの自由度を取り入れ、さらに殻模型で計算された原子核構造の情報を使用してニュートリノ及び反ニュートリノ反応断面積の計算を実施する手法を開発し、ビッグバン及び超新星爆発時に発生するニュートリノによる元素合成計算のグループに提供し共同研究を実施した。また QMD の手法を発展させ、中性子星の表面構造の研究に適用した。さらには相対論的平均場模型を適用して高密度核及びハドロン物質の状態方程式や中性子星の内部構造の研究を実施した。

原子力機構時代の最後の数年間では重イオンを用いる代理反応手法を提案し、文部科学省(MEXT)原子力研究開発事業のプロジェクトリーダーとして予算獲得、プロジェクト管理を行い、また手法の妥当性を検証する理論計算を実施した。その間、東日本大震災を経験しプロジェクト進行に支障をきたしたが、東海研のタンデム加速器の免震構造が機能し比較的早期に実験を再開できたことは不幸中の幸いであった。

東工大に移動後は約 10 年間に亘って核分裂に関する系統的な研究を実施した。新たに開発した 4 次元ランジュバン模型を用いて、アクチノイド領域の核分裂に関して知られていた核分裂片の質量数分布と全運動エネルギーの系統的な性質と特異的な現象を統一的に理解できることを示した。特にランジュバン計算を 4 次元化することで可能となった、断裂時における軽いフラグメントと重いフラグメントの形状の相違やそのエネルギー変化を適切に理解できたことがそのキーとなった。また、超重原子核の核分裂では、これまで知られていなかった殻効果が重要な役割を果たすこと等を見出した。加えて反対称化分子動力学、密度汎関数法、相対論的平均場理論、β 崩壊の大局的理論、統計崩壊模型など多くの理論を用いて異なる側面からの研究を遂行することで核分裂に対する理解を深めることができた。さらに、これらの知見を駆使して、国内では初となる核分裂収率データの整備を行った。

## 2. 具体的研究内容の紹介

中性子断面積の測定と解析、核データ整備、中間エネルギー核子入射核反応機構、核分裂機構の解明等、軽イオン入射核反応データの整備に関連する実験および理論的な研究を行って来た。また核データのさらなる高度化を目指し核子多体系として関連する高密度核物質や天体における元素合成に必要なデータの研究に従事した。その内容は以下

のように分類できる。
(1) 軽イオン入射核反応断面積の測定と理論解析
(2) 核データの評価
(3) 中間エネルギー核子入射核反応機構の研究
(4) 天体核物理の理論研究
(5) 重イオン代理反応の研究
(6) 核分裂の理論研究

**2.1　軽イオン入射核反応断面積の測定と理論解析**

JAEA 東海研のタンデム加速器を用いて中性子及び陽子入射核反応断面積の測定を行い、主として核融合炉開発で必要とされるエネルギー領域の核データ測定と、結果の理論解析により理論模型パラメータの決定と反応機構の精密化による予測精度の向上を遂行した。核融合炉用核データで必要なエネルギーでありながら中性子源の制約により測定が極端に困難であった 7～13MeV 領域での準単色中性子を発生するために様々な反応系を考慮した結果、水素ターゲットに $^{11}$B を入射すること($^{1}$H($^{11}$B,n)$^{11}$C 反応)によって単色性の優れた中性子が得られることを見いだした。同じく測定が困難な 20～30MeV 領域の核データ測定のために $^{7}$Li(p,n)中性子場を整備した。これらの中性子源や、東北大、米国 ANL 等の中性子源施設を用いて多くの中性子断面積を測定し、さらには相補的な陽子入射反応断面積の測定も行った。これらのデータを用いて 40MeV 程度以下の核子入射反応機構の解明を行った。ここでの主な成果は分散関係による散乱状態と束縛状態の統一的理解、軟回転体模型＋チャンネル結合法(SRM-CC)による原子核の低励起集団準位構造、電磁遷移確率と核子入射反応の統一的記述を目指す模型の開発と検証、パラメータの系統性導出である。本研究の成果は核データ評価の最も進んだ方法として国際的に認知され、IAEA や中国のグループも導入している。

**2.2　核データ評価**

主として JENDL-3.3、JENDL-4、JENDL-5 と核融合炉用の核データファイル(JENDL Fusion File)の整備を行った。国内で測定された中性子入射中性子放出二重微分断面積(DDX)データを系統的に収集し、光学模型、半古典的励起子模型、統計模型に基づく計算を行い、DDX を再現する計算手法とパラメータの構築を行い、JENDL Fusion File を作成した。その成果の多くは国際競争を勝ち抜いて、IAEA が進めている国際核融合炉用核データライブラリーFENDL-2 に採用された。また JENDL-3.3、4、5 の整備においても理論計算の一部を担当した。これらの評価活動に際しては(1)で得られた知見が有効に利用された。さらに長年にわたって核データ分野を困らせてきたピールのパズルとして知られる最小二乗法において異常な解が現れる現象の原因がデータの非線形変換にあるこ

とを突き止め、この現象を避ける有効な方法を提案した。この方法は Chiba-Smith の方法(または GMAP)として知られるようになり、米国における核データ評価でも、特に精度が必要とされる標準断面積の評価で用いられた(M.B. Chadwick et al., Nuclear Data Sheets 107, Vol.12, 2931-3060(2006))。

### 2.3　中間エネルギー核子入射核反応機構の研究

当時開始した JENDL 高エネルギーファイル整備のために、ここでも実験及び理論の両面にわたる研究を行った。実験においては九大グループが KEK で行った 0.8～3GeV 陽子及びパイ中間子を数種類のターゲットに入射して生成する二次中性子及び光子の測定に参加し、検出器の校正や回路系の一部を担当した。また、これらのデータを解析し反応機構を理解する新しい手法として量子分子動力学(QMD)手法開発の重要な一端を担った。この成果は原研版 QMD(JQMD)として結実した。さらには JQMD で取り扱いが困難なより高エネルギーを取り扱うため、リーダーを務めていたグループでストリング描像を組み込んだ模型 JAM を開発した。JQMD 及び JAM はその後 PHITS コードシステムに採用され、国産の高エネルギー放射線挙動解析プログラムとして広く世界に知られるようになった。米国滞在中にはロスアラモスで開発中の高エネルギー核データライブラリーLA150 評価の一部を担当し、その経験を国内に導入し、さらには SRM-CC, QMD 等の手法を用いて JENDL 高エネルギーファイルに含まれる多くの核種の評価に寄与した。

### 2.4　天体核物理の研究

それまでの研究で得られた成果を応用、発展させて、原子力基礎分野である核データと天体物理間での関連を見出し、複数分野を複数の視点から攻略することによりユニークで有機的に研究を展開している。その典型例が相対論的平均場理論(RMFT)から見た中性子星の性質と核子光学ポテンシャルの関連性についての成果で、中性子星の冷却と核子光学ポテンシャルのアイソベクター部のエネルギー依存性が相関を持つことを見出した。これは核データ計算で用いられる光学ポテンシャルの精密化により中性子星の構造に制限を付けうる可能性を示唆するもので非常に興味深い。さらに核データ計算の経験を生かして天体核反応率の計算手法の開発や実際の計算を行い、超新星爆発におけるニュートリノ反応による軽元素の生成量からニュートリノ振動のパラメータに制限を付けられることが分かった。また地上で最も希少な原子核である $^{180}$Ta の起源が超新星爆発時のニュートリノ反応であることを共同で見いだし、論文発表とともにプレス発表を行った（科学新聞 2010 年 5 月 28 日 1 面トップ、日刊工業新聞 2010 年 5 月 13 日、時事通信 2010 年 5 月 12 日）。この成果は日経サイエンスでも紹介された。

### 2.5　重イオン代理反応の研究

原子炉では、燃料の燃焼に伴う中性子捕獲反応とβ崩壊の連鎖により、ウランより重い超ウラン元素(TRU)原子核が生成される。これらはすべてが不安定な核種であり、その核データを実験的に精度よく決定することは不可能である。特に短寿命の核種を標的として用意して中性子断面積を測定することは非常に困難であるため、重イオンからの多核子移行反応（例えば2中性子移行反応）を用いて、標的を準備できる核種から離れた核種を生成し、その反応特性を測定する手法を考案し、MEXT原子力システム研究開発事業に提案し資金を獲得した。JAEAのタンデム加速器を用いて $^{18}$O のビームを $^{238}$U や $^{237}$Np 等に照射して起きる多核子移行反応で生成する様々な核種を、中性子核反応で生成する複合核と見立てて、核分裂生成物の質量数分布や即発中性子数の測定を可能とするプロジェクトを遂行した。従来は基礎研究の手段としてしか認識されない重イオン核反応を原子力開発用核データの測定手法として適用可能であることを実証した。さらに、この方法の妥当性や適用範囲を検証できる理論を構築した。本テーマについて2件のプレスリリースを実施した。

### 2.6　核分裂の理論研究

核分裂は原子力の最も基礎となる物理現象でありながら、たかだか200個程度の核子が引き起こす大振幅集団運動として、その本質は未だに解明されていない。原子力開発上はデータを測定すれば原子炉の設計は可能となるが、測定が困難なエネルギーや核種に対しては理論的な推定が必要となるため、核分裂に関する理論研究を遂行した。それまで最大3次元で行われていたランジュバン模型計算を4次元に拡張した模型を作成し、様々な改良を加え、ウランを含むアクチノイド領域における核分裂片の質量数と全運動エネルギー(TKE)の相関を計算した。それによって、重い核分裂片の平均質量数が $^{132}$Sn の殻効果によってほぼ一定に保たれる実験データを理解できることを示した。また対称に分裂する成分の運動エネルギーが、ある質量数領域で相転移的に増加することと、主要な核分裂モードが非対称成分から対称成分に転移、さらに再度非対称成分に転移することを発見した。これによって核分裂片の質量数分布とTKEの系統的性質と特異性の両方を系統的に理解できることが分かり、当該分野における近年の重要な成果であると認識されている。さらには核分裂生成物のβ崩壊に伴って発生する反ニュートリノを用いて原子炉内の状態をリアルタイムで遠隔監視できる可能性に着目し、総和計算による原子炉ニュートリノ計算手法の開発を行った。また、これら核分裂に関する基礎研究の知見を駆使して国内で初となる核分裂収率核データの整備を実施した。核分裂研究においては2度に亘り原子力学会論文賞を受賞し、プレスリリースを4回実施した。

このように、複数の手法を統合し、複数分野における有機的な活動を行うことで、データを測定しフィッティングを行うという伝統的かつ正統的な手法を超えて、『課題解決型

基礎研究』として、原子力の基礎である核データ研究を深く、広がりのある分野とした。それにより核データ研究を革新的原子力システムの研究開発を主導する一分野として発展させたことに加えて、原子核物理、天体核物理、さらには医学を含む他分野にも原子力の知見が有効な貢献を与えうることを実証した。

## 3. おわりに

中性子散乱断面積の測定をテーマとした博士号取得と原研における初期の研究開始後、研究室のテーマ改変に伴う核データセンターへの移籍とその後の先端基礎研究センターへの移動、東工大への転職に伴い様々な研究に従事したが、それらはすべて原子核理工学の基礎として、また課題解決型基礎研究としての核データを基軸としたものである。退職した現在は東工大の名誉教授の称号をいただき、また研究員として後進の研究に微力ながら貢献をしたく思っている。核分裂のランジュバン理論計算も 5 次元への拡張がほぼ終了している。さらに、株式会社 NAT に NAT リサーチセンターを創設していただきそのセンター長として活動中である。

現役時代に専門誌に出版した論文（国際会議等を除く）一覧を参考文献に示す。Google Scholar Citations によると、2023 年 5 月 31 日時点での総引用数は 14,341、H 指標は 48 とのことである（https://scholar.google.co.jp/citations?user=bBpCh60AAAAJ&hl=ja）。現在も数本の論文を投稿中である。

現役時代は 3 件の原子力システム研究開発事業の大型プロジェクト（3 億円、2.3 億円、4 億円）獲得に加え、科研費、企業との共同研究、原子力規制庁の原子力規制人材育成事業等から、合計で 10 億円超の研究・教育資金を得ることができたが、原研・JAEA 時代の前半は外部資金を申請する権利がなく、これらはすべて 50 歳を過ぎてからの成果である。

40 年に亘って核データ研究を遂行するにあたって多くの方々のご協力、ご指導を仰ぎました。あまりにも多数であるため全員のお名前を挙げることは控えさせていただきますが、東北大学の馬場護名誉教授、小野章助教、理研・北大の木村真明主任研究員・教授、JAEA の岩本昭博士、菊池康之博士（故）、深堀智生博士、岩本修博士、西尾勝久博士、九州大学の渡辺幸信教授、ANL の A.B.Smith 博士（故）、D.L.Smith 博士、ベラルーシの Efrem Soukhovitsuki 博士（故）、キエフ原子核研究所の Fedir A. Ivanyuk 博士、IAEA の奥村森博士、大塚直彦博士、東工大の井頭政之名誉教授、石塚千香子助教と研究室に所属してくれた学生の皆さんには特に深く謝意を示させていただきます。その他の方々を含め、皆様、長い間ありがとうございました。ウクライナでの戦争が早く終結することと、皆様のご研究とご健康、核データ分野のますますの発展を祈念して本稿の終わりとさせていただきます。

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