Exploring science education students' understanding of nuclear physics concepts through field study implementation with non-stationary calorimetry methods

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Abstract
This study explores the implementation of field studies using non-stationary calorimetric methods to understand the learning experience of science education students on the concept of nuclear physics. The study involved 72 science education S1 students who participated in an experiment to determine thermal power at the Kartini Reactor facility through a descriptive qualitative approach. The field study used reactor operation at a constant power of 100 kW by shutting down the cooling system to demonstrate the principle of heat accumulation. Students collected temperature data from three digital thermometers every 5 minutes for 35 minutes, then performed a linear regression analysis to calculate thermal power. Thematic analysis from student observations, interviews, and reflections reveals the development of conceptual understanding in four key areas. The students managed to calculate thermal power of 107.99 kW, 106.40 kW, and 109.08 kW with deviations in acceptable tolerances. The findings show that hands-on experience facilitates an understanding of energy conservation principles, heat transfer mechanisms, and experimental validation techniques. This study reveals students' ability to develop connections between theoretical concepts of nuclear physics and practical applications through authentic learning experiences.

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1. Introduction

Nuclear physics education in Indonesia faces significant challenges in bridging the gap between abstract theoretical concepts and practical applications (Mareta et al., 2024; Verawati & Nisrina, 2025). Science education students often have difficulty understanding fundamental nuclear processes such as fission reactions, energy conversion mechanisms, and the principles of reactor physics due to the abstract nature of the phenomenon and limited access to real nuclear facilities. Learning in the traditional classroom, while providing a theoretical foundation, fails to adequately demonstrate the practical significance of nuclear physics concepts in real-world applications (Al-Kamzari & Alias, 2025).

The integration of field study experiences in science education has been recognized as an effective pedagogical approach to improve student understanding and engagement (Bidarra & Rusman, 2017). Field studies provide an authentic learning environment where students can observe, measure, and analyze real phenomena, thus connecting theoretical knowledge with practical applications (Aji et al., 2024; Shaulskiy et al., 2022). In the context of nuclear physics education, access to real nuclear facilities offers unprecedented experiential learning opportunities that cannot be replicated in conventional laboratories (May, 2023).

BATAN (National Nuclear Energy Agency), which has now been reorganized into BRIN (National Research and Innovation Agency), operates several nuclear research facilities including the Kartini Reactor in Yogyakarta (Pramono et al., 2025). This TRIGA research reactor provides an ideal educational platform for learning nuclear physics due to its inherent safety characteristics and educational mission (Cagnazzo et al., 2012; Malec et al., 2025). The facility's Internet Reactor (IRL)

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Laboratory System allows remote monitoring and data collection, facilitating educational activities while maintaining strict safety protocols (Taxwim et al., 2020).

Previous research has shown the effectiveness of hands-on learning approaches in physics education, especially for abstract concepts that are difficult to visualize or experience directly. However, research that specifically examines the educational impact of nuclear reactor-based field experiences on the conceptual understanding of science education students is still limited. Most nuclear education research focuses on engineering or professional students, with less attention to the context of undergraduate science education (Rahma, 2025).

The non-stationary calorimetry method offers a pedagogically valuable approach to nuclear physics education because it utilizes fundamental thermodynamic principles familiar to undergraduate students while demonstrating advanced nuclear reactor physics concepts (Toplami, 2003). This method allows students to observe first-hand the principles of energy conservation through measured temperature changes resulting from nuclear fission reactions, providing tangible evidence of abstract nuclear processes.

Conceptual understanding in nuclear physics requires students to develop mental models that link atomic-scale fission events to macroscopic energy phenomena. Traditional learning often fails to build these relationships effectively, resulting in superficial memorization instead of deep understanding (Deslauriers et al., 2019). Field study experiences can overcome these limitations by providing opportunities for direct observation and hands-on measurement activities that reinforce theoretical concepts through practical application (Alon & Tal, 2015).

This research answers the need for an innovative pedagogical approach in nuclear physics education by describing the implementation of field studies using the non-stationary calorimetry method at BATAN and revealing the patterns of understanding of science education students about the concept of nuclear physics. This study aims to explore and describe students' learning experiences of particle and atomic reactions from field study experiences at BATAN's nuclear facility.

2. Method

This study uses a descriptive qualitative approach to explore students' learning experiences in the Particle and Atomic Reaction course. The lectures took place over 16 meetings, which integrated face-to-face lectures, virtual practicums, and field studies. A qualitative approach was chosen to explore students' conceptual understanding, involvement, and reflection throughout the learning process.

The research participants were 72 S1 Science Education students at Sebelas Maret University who took the course of Particle and Atomic Reaction. Participants were divided into 3 different class groups (Class A, B, and C). The selection of participants is carried out purposively with the following criteria: have completed prerequisite courses (A: 26, B: 26, C: 20), are willing to participate in the entire learning series, and actively participate in virtual practicum activities and field studies. This field study was conducted at the Kartini Reactor facility, BATAN Indonesia.

The main instrument of the research is the researcher himself, with auxiliary instruments in the form of:

a. Observation guide to record student activities

b. Student's Written Reflection Sheet

c. Semi-structured interviews with selected students

d. Documentation in the form of practicum reports, lecture recordings, and field notes

The data was analyzed by thematic analysis through the stages of reduction, coding, categorization, and interpretation to find patterns related to concept understanding, engagement, and learning challenges (Mindo, 2025). The validity of the data was maintained by triangulating sources, peer discussions, and confirming results (member checking) to participants (Carter et al., 2014).

The data collection techniques used in the study were obtained through classroom and field observations, students' written reflections, semi-structured interviews with selected participants, and documentation in the form of reports, recordings, and field notes shown through Figure 1. These four techniques complement each other to produce comprehensive information and improve the validity of the data.

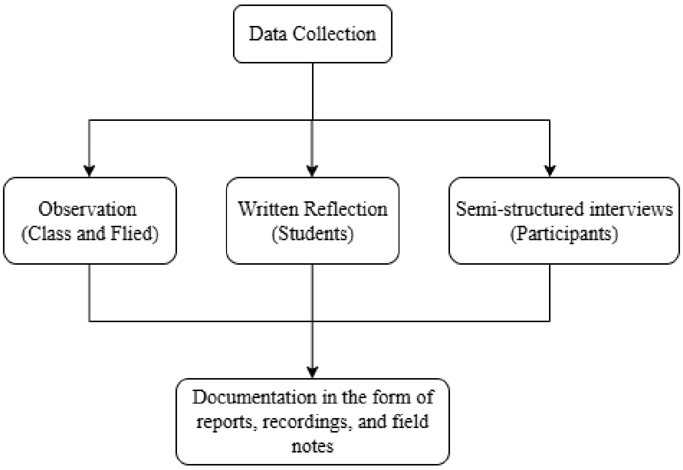

Figure 1.Data Collection Techniques

3. Results and Discussion

3.1. Results of Field Study Implementation

The field study at the Kartini Reactor facility was successfully carried out with all 72 students participating in the thermal power determination experiment. Students are divided into three groups for effective safety management and supervision. The experimental procedure follows a pre-established reactor operating protocol with modifications for educational purposes. Table 1 is an example of the observation results of one of the class B groups.

Table 1. Temperature Observation Results from Three Thermometers

Time (minutes)	Thermometer 1 (°C)	Thermometer 2 (°C)	Thermometer 3 (°C)
0	27.75	28.06	27.81
5	28.13	28.44	28.19
10	28.69	28.94	28.63
15	29.25	29.63	29.31
20	29.81	30.13	29.88
25	30.13	30.44	30.19
30	30.63	30.88	30.69
35	30.94	31.19	31.00

The students managed to collect temperature data that showed a consistent linear rise pattern across all thermometers. A temperature rises of about 3°C for 35 minutes demonstrates effective heat accumulation after the cooling system is turned off.

Thermometer Analysis 1:

Linear regression equation: y = 0.0945x + 27.76

Constanta (H): $m \, . \, C$ → 19.0476 kWh/°C

Rate of temperature rise $\frac{dT}{dt}$ → y = 0.0945x → 0.0945 °C/m = 0.0945 × 60 (s) → 5.67 °C/s

Thermal power ($P = H.\frac{dT}{dt}$) → P = 19.0476 × 5.67 = 107.99 kW

Percentage Difference = $(\frac{Thermal\ power - Reactor\ instrument\ power)}{Reactor\ Instrument\ power}) \ x\ 100\%$

$$(\frac{107.99 - 100)}{100}) \ x\ 100\% \ = \ 7.99\%$$

Thermometer Analysis 2:

Linear regression equation: y = 0.0931x + 28.027

Constanta (H): $m\ .\ C$ → 19.0476 kWh/°C

Rate of temperature rise $\frac{dT}{dt}$ → y = 0.0931x → 0.0931 °C/m = 0.0931 × 60 (s) → 5.586 °C/s

Thermal power ($P = H.\frac{dT}{dt}$) → P = 19.0476 × 5.586 = 106.40 kW

Percentage deviation = $(\frac{Thermal\ power - Reactor\ instrument\ power)}{Reactor\ Instrument\ power}) \ x\ 100\%$

$$(\frac{106.40 - 100)}{100}) \ x\ 100\% \ = \ 6.40\%$$

Thermometer Analysis 3:

Linear regression equation: y = 0.0954x + 27.793

Constanta (H) = $m\ .\ C$ → 19.0476 kWh/°C

Rate of temperature rise $\frac{dT}{dt}$ → y = 0.0954x → 0.0954 °C/m = 0.0931 × 60 (s) → 5.724 °C/s

Thermal power ($P = H.\frac{dT}{dt}$) → P = 19.0476 × 5.724 = 109.03 kW

Percentage deviation = $(\frac{Thermal\ power - Reactor\ instrument\ power)}{Reactor\ Instrument\ power}) \ x\ 100\%$

$$(\frac{109.03 - 100)}{100}) \ x\ 100\% \ = \ 9.03\%$$

In this practicum, the results of the thermal power calculation of the three thermometers were 107.99 kW, 106.40 kW, and 109.08 kW respectively. When compared to the nominal power used when the reactor was operating, which was 100 kW, the results were 7.99%, 6.40%, 9.03%. These three difference values are within the maximum tolerance range of ±10% as set out in the reactor calibration procedure, which means that the difference between the calculation results and the instrument readings is still technically acceptable. Based on this quantitative evaluation, it can be concluded that adjustment or recalibration of the power meter instrumentation system is not necessary (Fatwasauri et al., 2021). The three power values calculated from each thermometer are consistent and show a low deviation from the reference value of 100 kW. In addition, the stability of the temperature linear pattern over time read on the graph of each thermometer indicates that the IRL system runs with reliable accuracy. This practicum proves that the non-stationary calorimetry method can be an effective and accurate approach in reactor power validation (Khusnarini, 2024).

3.2. Student Understanding Development

Reflection analysis and student interviews reveal conceptual understanding in several key areas:

3.2.1. The Principe of Energy Conservation

Students demonstrate a better understanding of energy conservation through direct observation of the conversion of nuclear fission energy into thermal energy. One student noted: "*Seeing the temperature of the reactor rise helped me understand how nuclear energy becomes the heat energy we learn about in theory*."

3.2.2. Nuclear fission process

Field experience provides a concrete context for understanding fission chain reactions and energy release mechanisms. Students can relate theoretical calculations to measurable temperature changes, reinforcing their mental models of nuclear processes.

3.2.3. Heat Transfer Mechanism

Students gain a practical understanding of heat transfer in a reactor system, observing how thermal energy accumulates when the cooling system is shut down. This hands-on experience strengthened theoretical knowledge of thermodynamic principles in nuclear applications (Mariati, 2013).

3.2.4. Experimental Validation Techniques

The multi-point measurement approach using three thermometers introduced the concepts of experimental reliability and uncertainty analysis. Students learn the importance of redundant measurements and validation of data consistency in nuclear operations.

3.3. Engagement and Attitude Change

Students' observations and reflections reveal a high level of engagement throughout the field study experience. Key themes identified include:

3.3.1. Authentic Context Connections

Students often mention how the experience of a reactor facility makes abstract concepts "real" and "perceptible". This authentic experience provides a meaningful context that increases motivation and interest in the topic of nuclear physics (Hayat, 2024).

3.3.2. Development of Safety Awareness

Exposure to reactor safety protocols and operational procedures significantly enhances students' understanding of nuclear safety principles. Students gain an appreciation of the engineering controls and regulatory requirements governing nuclear operations.

3.3.3. Technology Integration

IRL systems and modern instrumentation broaden students' understanding of contemporary nuclear technology applications. Students express an interest in instrumentation and nuclear control systems.

3.3.4. Collaborative Learning

Group work during data collection and analysis encourages peer-to-peer learning and scientific discussion. Students engage in explanatory discussions while interpreting the results, strengthening understanding through social interactions.

3.4. Learning Challenges and Outcomes

Some challenges arise during implementation that provide additional learning opportunities including:

3.4.1. Technical Complexity

Initial exposure to the reactor system required scaffolding and additional support. However, these challenges increase students' appreciation of the complexities of nuclear engineering and safety requirements. This kind of scaffolding approach has proven to be effective in helping students develop conceptual understanding gradually until they achieve learning independence (Eveline et al., 2019).

3.4.2. Data Analysis Skills

Students initially struggle with linear regression analysis and statistical interpretation. Through guided practice and collaboration between friends, all students successfully completed the calculation of thermal power. This suggests that a combination of instructor guidance and teamwork can overcome early barriers in quantitative learning, while strengthening critical thinking and problem-solving skills (Johnson et al., 2014; Mustoip et al., 2024).

3.4.3. Conceptual Integration

Connecting theoretical knowledge with practical measurement requires continuous effort, especially in areas of science that demand conceptual understanding as well as technical skills. The process of structured reflection helps students make explicit connections between theory and practice, as students can internalize abstract concepts while critically evaluating field experiences (Kolb, 1984).

3.5. Course Performance Correlation

The analysis of the final grades of the course revealed very satisfactory performance in all participants, with an overall average score of 86.26 which was in the A category (Excellent). The distribution of grades showed an extraordinary achievement where all 72 students from three parallel classes (A, B, and C) managed to achieve A- grades or higher, with a graduation rate of 100%. This indicates the successful integration of the field study experience with the overall learning objectives of the course.

Analysis per class showed interesting performance variations (Figure 2), class C showed the highest average (88.26) with 30% of students achieving excellent grades (≥90), class B had the best consistency with the lowest standard deviation (1.49), while class A showed a balanced distribution between the very good and good categories. Students demonstrate particular strengths in solving application-oriented problems that require the integration of theoretical knowledge with practical experience in the field. Class Profile Radar shown via the chart in Figure 2.

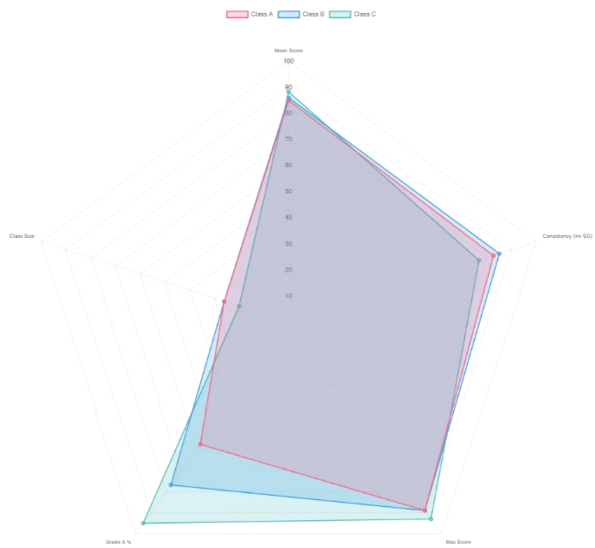

Figure 2. Class Profile Radar Chart

Based on Figure 2, the Class Profile Radar Chart displays a multi-dimensional comparison between the three classes based on five key metrics: grade point average, learning consistency (inverse standard deviation), maximum grade, percentage of grade A students, and class size.

This visualization reveals the unique profile of each class: Class C forms a pattern with the widest area in the performance dimension (high average, highest maximum value, highest percentage of A grade) but shows lower consistency. Class B features a balanced profile with the highest consistency, while Class A exhibits a relatively compact pattern with moderate but stable performance. The difference in radar shape for each class visualizes the trade-off between high achievement versus learning consistency

The superior performance on the topic of nuclear reactor physics is evident from the students' success in calculating thermal power (106.40-109.08 kW) with acceptable deviations (6.40-9.03%), demonstrating a deep understanding of the concept of non-stationary calorimetry. The 100% graduation rate with a compact distribution of scores (range 81.8-93.0) indicates the suitability of the field study learning method with the characteristics and learning needs of science education students. This data reinforces the argument that authentic experiences in nuclear facilities have a significant positive impact on students' academic achievement.

4. Conclusion

The findings of the study show that the implementation of field studies using non-stationary calorimetry methods provides a meaningful learning experience for science education students in understanding the concepts of nuclear physics. Students demonstrate good conceptual understanding and problem-solving skills, and a change in positive attitudes towards learning particle and atomic reaction courses. Hands-on experience successfully bridges theoretical knowledge with practical applications, providing an authentic context for abstract concepts of nuclear physics.

This study validates the pedagogical value of authentic field experiences in science education, especially for complex technical topics that require direct observation and measurement. The success of students in completing thermal power calculations shows the feasibility of involving S1 students in advanced nuclear measurements while maintaining safety standards. The integration of theoretical preparation, hands-on experimentation, and reflective analysis creates a comprehensive learning framework that effectively addresses diverse learning needs and preferences. Future research will need to investigate the scalability of nuclear facility-based field studies and explore similar approaches using other technical facilities. The development of virtual reality-based or simulation-based alternatives can extend these pedagogical benefits to institutions that do not have direct access to nuclear facilities, while maintaining the authentic characteristics and engagement that make these interventions successful.

Author Contributions

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