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(ԵՐԵՎԱՆԻ ՖԻԶԻԿԱՅԻ ԻՆՍՏԻՏՈՒՏ)

Գագինյան Սուսանա Վարդանի

ԾԱՆՐ ՄԻՋՈՒԿՆԵՐՈՒՄ ԲԱՐՁՐ ԷՆԵՐԳԻԱՆԵՐՈՎ ԹԵԹԵՎ ՄԱՍՆԻԿՆԵՐԻ
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Ա.04.16 - "Միջուկի, տարրական մասնիկների և տիեզերական ճառագայթների
ֆիզիկա" մասնագիտությամբ ֆիզիկամաթեմատիկական գիտությունների թեկնածուի
գիտական աստիճանի հայցման ատենախոսության

ՍԵՂՄԱԳԻՐ

ԵՐԵՎԱՆ - 2026

A. I. ALIKHANYAN NATIONAL SCIENCE LABORATORY
(YEREVAN PHYSICS INSTITUTE)

Gaginyan Susanna

Study of Nuclear Reaction Mechanisms in Heavy Nuclei under High-Energy Light Particle
Irradiation

SYNOPSIS

of the dissertation in 01.04.16 - "Nuclear, elementary particles and cosmic ray physics" presented for
the degree of candidate in physical and mathematical sciences

Yerevan - 2026

Ատենախոսության թեման հաստատվել է Երևանի պետական համալսարանի ֆիզիկայի ինստիտուտի գիտական խորհրդում

Գիտական ղեկավար՝
Ֆիզ. մաթ. գիտ. դոկտոր

Անահիտ Ռաֆիկի Բալաբեկյան (ԵՊՀ)

Պաշտոնական ընդդիմախոսներ՝
քիմիական գիտ. թեկնածու Անի Պետրոսի Ապրահամյան (Նոթր Դամի համալսարան)
Ֆիզ. մաթ. գիտ.դոկտոր Ելենա Ալեքսանդրի Կոլգանովա (ՄՀՄԻ, Դուբնա)

Առաջատար կազմակերպություն՝ ՀՀ ԳԱԱ ՖՀԻ, Աշտարակ, Հայաստան

Ատենախոսության պաշտպանությունը կայանալու է 2026թ. մայիսի 8-ին ժամը 14:00-ին, ԱԱԳԼ-ում գործող ԲԿԳԿ-ի 024 «Ֆիզիկայի» մասնագիտական խորհրդում (Երևան, 0036, Ալիխանյան եղբայրների փ. 2):

Ատենախոսությանը կարելի է ծանոթանալ ԱԱԳԼ գրադարանում:
Սեղմագիրն առաքված է 2026թ. ապրիլի 8-ին:

Մասնագիտական խորհրդի գիտական քարտուղար՝
Ֆիզ. մաթ. գիտ. դոկտոր



Հրաչյա Մարուքյան

The dissertation topic was approved by the Scientific Council of the Institute of Physics of Yerevan State University.

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Leading organization:

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The defense will take place on May 8, 2026, at 14:00 during the “Physics” professional council session of HESC 024 acting within AANL (2 Alikhanyan brothers str., 0036, Yerevan).

The dissertation is available at the AANL Library.
The synopsis is sent out on April 8, 2026.

Scientific Secretary of the Special Council:
Doctor of Physical and Mathematical Sciences



Hrachya Marukyan

GENERAL CHARACTERISTICS OF THE WORK

Relevance of the Research. Nuclear reactions with high energies are a paradigm of contemporary experimental nuclear physics, providing a unique opportunity to study the properties of nuclear matter in extreme states of excitation. At projectile energies ranging from a few hundred MeV to the GeV domain, nuclear reactions are characterized by a complex interplay of reaction mechanisms such as spallation, fission, fragmentation, and multifragmentation. These phenomena are not only of interest for the fundamental properties of nuclear matter but also provide the basis for a broad range of applications in advanced nuclear technologies, such as ADS (Accelerator-driven systems), radioactive waste transmutation, lead-cooled small modular reactors and high-intensity neutron sources [1].

In accelerator-driven systems, high-energy spallation reactions on heavy targets such as lead or lead-bismuth eutectic provide an external neutron source required for subcritical reactor operation [1]. In radioactive waste transmutation, high-energy irradiation is used to reduce the long-term radiotoxicity of spent nuclear fuel by transforming long-lived isotopes. In addition, lead-cooled small modular reactors rely on accurate knowledge of spallation and fragmentation processes to describe neutron spectra and energy deposition in the reactor core and coolant [2, 3]. In all these systems, reliable predictions of residual nuclide production and reaction yields are essential for ensuring safety, efficiency, and long-term performance.

A key factor governing the dynamics of high-energy nuclear reactions is the nature of the projectile. Proton-induced reactions provide a well-established reference framework and have been extensively studied both experimentally and theoretically [4, 5]. However, deuteron-induced reactions introduce an additional level of complexity due to the weak binding energy of the deuteron. The deuteron can easily break up into its constituent nucleons, leading to correlated nucleon dynamics that significantly alter the reaction mechanism [6]. Processes such as breakup, stripping, and incomplete fusion contribute to a more distributed energy deposition within the target nucleus, resulting in higher excitation energies and an enhanced production of light and intermediate-mass fragments [6]. As a result, deuteron-induced reactions cannot be treated as a simple superposition of proton- and neutron-induced interactions.

The role of isotopic composition is another critical aspect of high-energy nuclear reactions. The use of isotopically enriched targets, such as ^{204}Pb , ^{206}Pb , ^{207}Pb , and ^{208}Pb , allows for a systematic investigation of isospin-dependent effects by varying the neutron-to-proton ratio of the system. One of the most important manifestations of isotopic sensitivity is the phenomenon of isoscaling, which describes the exponential dependence of isotopic yield ratios on neutron and proton numbers [7]. Isoscaling has been observed over a wide range of reaction mechanisms, from evaporation to multifragmentation, and provides a direct connection to the symmetry energy term of the nuclear Equation of State [8]. Through this relationship, experimental studies of isotopic effects offer valuable constraints on the properties of nuclear matter under highly excited and low-density conditions [9].

The interpretation of high-energy nuclear reactions relies on theoretical and transport models that combine microscopic descriptions of the intranuclear cascade with statistical approaches to nuclear de-excitation. Widely used tools such as MCNP, the Cascade-Exciton Model, and the Los Alamos Quark-Gluon String Model are capable of reproducing general trends in reaction observables [10, 11]. However, significant discrepancies remain between model predictions and experimental data, particularly for light and intermediate-mass fragments. These discrepancies are most pronounced in the mass region $A < 60$, where fragmentation and multifragmentation processes dominate and are not fully captured by existing models [12]. In addition, the accurate description of deuteron-induced reactions remains a challenge due to the complexity of breakup mechanisms and correlated nucleon interactions [6]. Uncertainties also persist in modeling the transition from evaporation and fission

to multifragmentation at high excitation energies [12]. This indicates fundamental limitations in the current description of energy deposition and de-excitation processes in highly excited nuclear systems.

These limitations highlight the need for high-quality experimental data obtained under well-controlled conditions, particularly for reactions involving isotopically enriched targets. Such data are essential for validating and improving theoretical models and for enhancing their predictive power in applications related to nuclear technology. Despite the extensive database available for proton-induced reactions, experimental information on deuteron-induced reactions at GeV energies remains limited, especially for heavy nuclei with well-defined isotopic composition. This lack of data restricts the ability to systematically study projectile-dependent effects and to accurately model isospin-dependent processes.

The present research is motivated by the need to address these challenges and to bridge the gap between well-established proton-induced reaction systematics and the relatively unexplored domain of deuteron-induced reactions on heavy isotopes. By focusing on isotopically enriched lead targets, the study provides new experimental benchmarks for understanding reaction mechanisms, isotopic effects, and the limitations of current theoretical models. Particular attention is given to the role of deuteron breakup in energy deposition, the behavior of fragment production in different mass regions, and the extraction of isoscaling parameters for constraining the symmetry energy. Through this approach, the work provides a reliable experimental basis for both fundamental nuclear physics and the development of advanced nuclear technologies.

Aim of the work. The aim of this dissertation is to perform a comprehensive experimental study of high-energy nuclear reactions induced by deuterons on isotopically enriched lead targets with a focus on reaction mechanisms, isotopic effects, and the evaluation of the predictive power of modern theoretical and transport models. The goal of this research is to contribute to the development of new experimental information and analyses required for improving our understanding of spallation, fission, fragmentation, and multifragmentation reactions in heavy nuclei, as well as for promoting applied nuclear technologies based on lead and lead-based systems.

Scientific novelty. The scientific novelty of the work is determined by the following results obtained and analyzed within the dissertation:

1. For the first time, high-energy deuteron-induced nuclear reactions on the isotopically enriched target ^{208}Pb have been studied experimentally.
2. A systematic comparison of the residual nucleus production cross sections for deuteron-induced reactions on isotopically enriched lead isotopes has been carried out under equal irradiation conditions.
3. New experimental results have been obtained, which can serve as strict tests for the validation and improvement of theoretical and transport models describing high-energy nuclear reactions in heavy nuclei.

Practical use. The practical application of the experimental results achieved in this dissertation is significant in terms of the development of nuclear technology as well as computational nuclear sciences. The determined production cross sections of residual nuclei in high-energy deuteron-induced reactions on isotopically enriched lead targets are significant as validation benchmarks for improving various nuclear reaction models. These include models such as MCNP, CEM, as well as LAQGSM, particularly in instances where discrepancies are identified in intermediate as well as light fragments. The experimental results are applicable in various instances, such as ADS, activation, as well as radiological studies on lead-based materials, and in developing advanced reactor technologies.

Results submitted for defense. The following results are submitted for defense:

- Experimental production cross sections of radioactive residual nuclei produced in high-energy deuteron-induced reactions on isotopically enriched lead targets.
- Systematic analysis of isotopic effects and reaction mechanisms in deuteron-induced nuclear reactions on heavy nuclei.
- Critical evaluation of the predictive capabilities of modern theoretical and transport models based on comparison with high-quality experimental data.

Approbation. The results of the dissertation were presented at international scientific conferences in the form of poster presentations as well as oral reports, including:

- *XVII International Conference "Symmetry Methods in Physics (SYMPHYS)"*, July 10-15, 2017, Yerevan, Armenia.
- *CERN-JINR European School of High-Energy Physics*, September 6-19, 2017, Évora, Portugal.
- *International School-Conference "Nuclear Physics and Applications" (NUCPHYS-SC&APPL)*, July 26-August 4, 2017, Braşov, Romania.
- *International Conference on Nuclear and Radiation Physics and Materials (NRPM 2019)*, June 17-21, 2019, Armenia.

Publications. Four papers have been published on the topic of the dissertation, the list of which is provided at the end of the abstract.

Structure of the dissertation. The dissertation consists of an introduction, three chapters, a conclusion, a List of Publications, and References. The total volume of the dissertation is 107 pages. It includes figures and tables presenting the experimental and analytical results and their interpretation.

The introduction presents the relevance of the topic, the aim of the work, scientific novelty, practical significance, and the main results of the dissertation.

Chapter 1 describes the experimental methodology and the experimental setup used for the measurement of production cross sections.

Chapter 2 presents the experimental results on production cross sections and discusses the mechanisms of deuteron-induced nuclear reactions.

Chapter 3 is devoted to the study of isotopic effects, isoscaling analysis, and the determination of the symmetry energy coefficient.

The conclusion summarizes the main results of the work.

CONTENT OF THE WORK

Chapter 1 (*Methodology and Experimental Setup*) is devoted to the experimental methodology used for determining production cross sections of residual nuclei formed in 4.4 GeV deuteron-induced reactions on isotopically enriched lead targets.

The chapter begins with a description of the induced-activity method, which constitutes the experimental basis of the present work. In contrast to on-line techniques, the off-line activation method makes it possible to register radioactive residual nuclei accumulated in the target after irradiation and to determine their production cross sections from measured γ -ray spectra [13]. At the same time, the method has an intrinsic limitation, since stable and very short-lived reaction products cannot be detected.

The radioactive decay of the produced nuclei is described by

$$A(t) = A_0 \exp(-\lambda t), \quad \lambda = \ln 2/T_{1/2}, \quad (1)$$

where $T_{1/2}$ is the half-life of the radionuclide. The activity at the beginning of counting, after irradiation time t_1 and cooling time t_2 , is given by

$$A_x = \sigma \Phi N_x (1 - e^{-\lambda t_1}) e^{-\lambda t_2}, \quad (2)$$

where σ is the production cross section, Φ is the beam flux density, and N_x is the number of target nuclei.

The production cross section of a radioactive residual nucleus was determined from the full-energy photopeak area ΔN according to

$$\sigma = \frac{\Delta N \lambda \frac{t_{3r}}{t_{3l}}}{N_p N_x k \eta \epsilon (1 - e^{-\lambda t_1}) e^{-\lambda t_2} (1 - e^{-\lambda t_{3r}})}, \quad (3)$$

where N_p is the beam intensity, ϵ is the detector efficiency, η is the γ -ray intensity, t_{3r} and t_{3l} are the real and live times of the measurement, respectively. The ratio t_{3r}/t_{3l} accounts for the dead-time correction of the spectrometric system. In cases where the measured γ -line receives contributions from parent and daughter nuclei, cumulative and independent cross sections were determined using the corresponding decay relations [13]. For unresolved line overlaps, the cross sections were obtained by solving systems of linear equations.

The γ -ray spectra of the irradiated targets were measured using coaxial HPGe detectors with 28% relative efficiency and an energy resolution of about 2 keV at 1332 keV. The detectors were surrounded by thick lead shielding to reduce background radiation and improve the signal-to-noise ratio. The detector efficiency calibration was carried out using standard radioactive sources, and the resulting efficiency curve was used in the analysis of all measured spectra. The spectra were processed using the DEIMOS32 software package [14], while the nuclear data required for isotope identification were taken from standard reference tables [15].

The experimental setup is described in detail. Enriched lead targets ^{204}Pb (51%), ^{206}Pb (87.9%), ^{207}Pb (90.4%), and ^{208}Pb (98.7%) were irradiated by a 4.4 GeV deuteron beam from the Nuclotron of VBLHEP, JINR, Dubna (Fig. 1, right). The main target characteristics are listed in Table 1. Each lead foil was sandwiched between two 38 μm aluminium monitor foils of the same lateral dimensions. Beam intensity was monitored independently for each target via the reaction $^{27}\text{Al}(d, 3p2n)^{24}\text{Na}$ [16] with a cross section of 15.25 ± 1.5 mb. The total irradiation time was 73.37 h; the deuteron flux densities were $(2.39 \pm 0.3) \times 10^7 \text{ cm}^{-2}\text{s}^{-1}$ for ^{204}Pb , $(4.91 \pm 0.5) \times 10^7 \text{ cm}^{-2}\text{s}^{-1}$ for $^{206,207}\text{Pb}$, and $(4.56 \pm 0.5) \times 10^7 \text{ cm}^{-2}\text{s}^{-1}$ for ^{208}Pb .



Figure 1: Left and center: HPGe detector setup used for off-line γ -ray measurements. Right: General view of the Nuclotron accelerator at VBLHEP, JINR, Dubna.

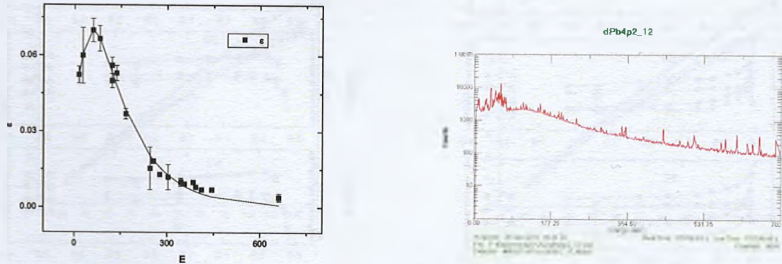


Figure 2: Left: Energy dependence of detector efficiency. Right: Example of a measured γ -ray spectrum of residual nuclei from an irradiated lead target processed with DEIMOS32.

| Target | Size (cm^2) | Weight (g) | Thickness (μm) |
|------------|--------------------|------------|-----------------------|
| ^{204}Pb | 1.05×0.72 | 0.0625 | 30 |
| ^{206}Pb | 1.85×3.15 | 0.325 | 50 |
| ^{207}Pb | 1.95×2.90 | 0.35 | 53 |
| ^{208}Pb | 1.8×1.6 | 0.193 | 55 |

Table 1: Main characteristics of the isotopically enriched lead targets.

Thus, Chapter 1 establishes the experimental and methodological basis of the dissertation and presents the formalism used for extracting reliable production cross sections of radioactive residual nuclei.

Chapter 2 (*Mechanisms of Reactions Induced by Deuterons on Lead Isotopes*) is devoted to the experimental study of production cross sections of residual nuclei formed in 4.4 GeV deuteron-induced reactions on isotopically enriched ^{204}Pb , ^{206}Pb , ^{207}Pb , and ^{208}Pb targets, as well as to the analysis of the reaction mechanisms contributing to the formation of residual nuclei in different mass regions.

From the four lead targets, production cross sections for 72, 87, 87, and 88 residual nuclei were determined, respectively. A general tendency of increasing fragment cross sections with increasing target mass number was observed for most identified isotopes. The measured cross sections are presented in the dissertation.

To identify the underlying reaction mechanisms, the excitation functions of representative product groups were compared with proton-induced data in the energy range 0.04-2.6 GeV [17] as a function of incident energy per nucleon. The products were grouped into spallation-evaporation, fission, and multifragmentation categories.

Spallation products (nuclides close to the target mass, such as $^{206,204}\text{Bi}$ and ^{200}Tl) show cross sections that decrease rapidly above ~ 1 GeV and fit smoothly onto the proton excitation functions (Fig. 3), consistent with peripheral reactions involving small energy transfer.

Deep spallation products ($^{194,196}\text{Au}$, $^{189,191}\text{Pt}$) exhibit a peak near 0.5 GeV followed by a smooth decrease with energy (Fig. 3), consistent with the trend reported by Kaufman and Steinberg [18].

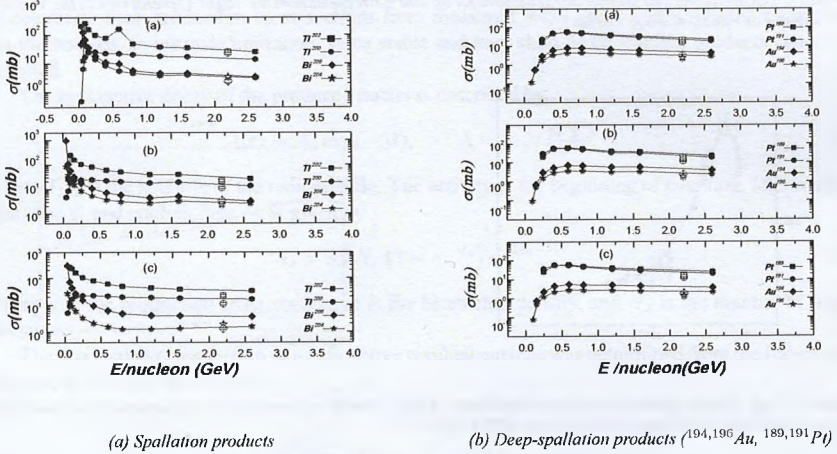


Figure 3: Cross sections for spallation (left) and deep-spallation (right) products from proton-induced reactions (solid symbols) and 4.4 GeV deuteron reactions (open symbols) on $^{206,207,208}\text{Pb}$ targets.

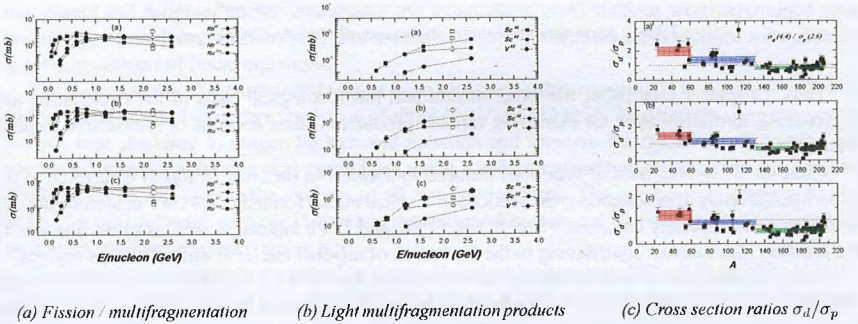


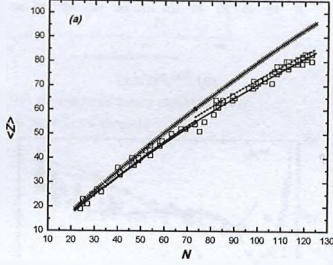
Figure 4: (a) Excitation functions for fission/multifragmentation products (^{103}Ru , ^{95}Nb , ^{88}Y , ^{83}Rb). (b) Light multifragmentation products ($^{16,48}\text{Sc}$, ^{48}V); note the monotonically rising excitation function with no peak. (c) Ratios σ_d/σ_p for 4.4 GeV deuteron- and 2.6 GeV proton-induced reactions on $^{206,207,208}\text{Pb}$. Shaded bands indicate mass regions $A < 60$ (red), $60 \leq A \leq 130$ (blue), $A > 130$ (green). Proton data: solid symbols; deuteron data: open symbols.

Charge distributions within each isobaric chain were analyzed using the three-parameter empirical

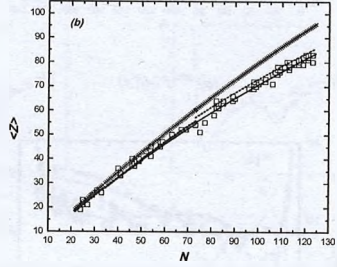
formula

$$\sigma(Z, A) = \sigma(Z_p, A) \exp\left(-R|Z - SA + TA^2|^{3/2}\right), \quad (4)$$

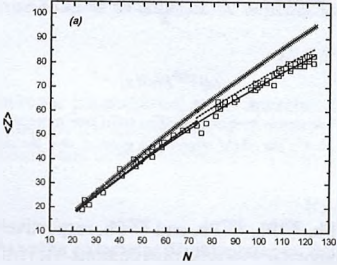
which allowed the determination of the most probable charge Z_p and the construction of total isobaric cross sections. The extracted mass-yield distributions reveal three clearly distinguished regions: a spallation-evaporation region near the target mass, a broad fission maximum around $A \sim 100$, and an enhanced light-fragment region at $A < 60$ associated with multifragmentation.



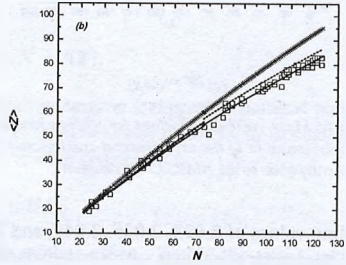
(a) ^{208}Pb



(b) ^{207}Pb



(c) ^{206}Pb



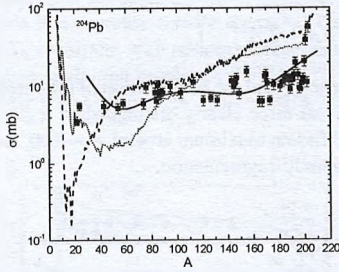
(d) ^{204}Pb

Figure 5: Average atomic number vs. neutron number for observed nuclides from all four lead targets. Crosses-EAL; solid line-stability valley; dotted-dashed lines- Z_p for $A < 130$ and $A \geq 130$; open squares-present data.

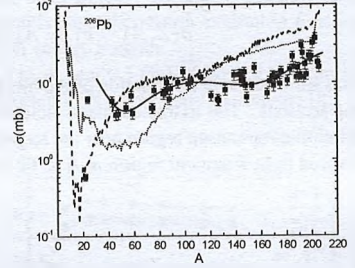
Total isobaric cross sections $\sigma(A)$ together with the SMM and MARS15 model [12, 19] calculations are presented as mass-yield distributions in Fig. 6. The distributions exhibit three characteristic regions common to all targets: a sharp decrease near the target mass (spallation-evaporation), a broad fission peak near $A \sim 100$, and a rising contribution at $A < 60$ from multifragmentation.

Total inelastic cross sections were estimated within the Glauber model:

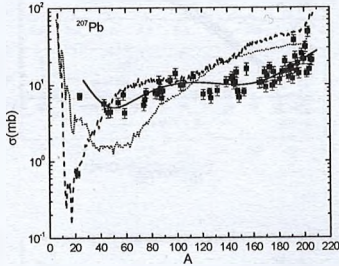
$$\sigma_{dA}^{\text{inel}} = \int d^2b \left[1 - \exp\left(-\sigma_{dN}^{\text{tot}} \int_{-\infty}^{\infty} \rho(\mathbf{b}, z) dz\right) \right], \quad (5)$$



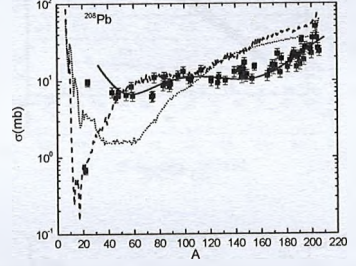
(a) $^{204}\text{Pb}(d,x)$



(b) $^{206}\text{Pb}(d,x)$



(c) $^{207}\text{Pb}(d,x)$



(d) $^{208}\text{Pb}(d,x)$

Figure 6: Mass-yield distributions for all four lead targets at 4.4 GeV deuteron irradiation. The solid line represents the best polynomial fit to the experimental cross sections, the dotted line shows the SMM model calculation, and the dashed line corresponds to the MARS15 calculation.

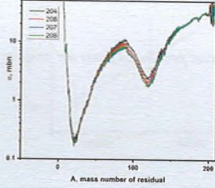
yielding values of 2.023, 2.035, 2.041, and 2.047 b for ^{204}Pb , ^{206}Pb , ^{207}Pb , and ^{208}Pb , respectively.

The chapter concludes with a comparison of the experimental mass-yield distributions with MCNP transport-code calculations (Fig. 7). The best agreement is found for ^{204}Pb , where isotopic impurity contributions were fully accounted for. Although the general shape of the distributions is reproduced, significant discrepancies remain in the light- and intermediate-mass regions, indicating that the present theoretical description of deuteron-induced reactions requires further refinement [20].

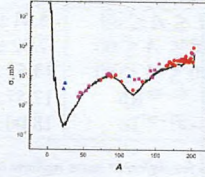
Chapter 3 (Isotope Effect) This chapter investigates the isospin-dependent properties of deuteron-induced nuclear reactions on enriched lead targets through the analysis of isotopic yield ratios and isoscaling phenomena. When reactions are induced on targets differing only in neutron content, the yields of fragments with fixed (N, Z) vary systematically due to the neutron-proton asymmetry of the emitting system and the symmetry-energy term of the nuclear equation of state.

The isotope effect is quantified through the cross section ratio

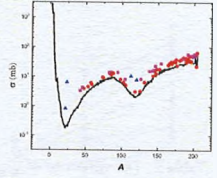
$$R_{21}(N, Z) = \frac{Y_2(N, Z)}{Y_1(N, Z)}, \quad (6)$$



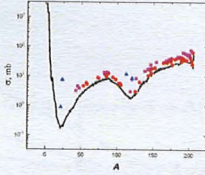
MCNP theoretical mass distributions for all four lead targets.



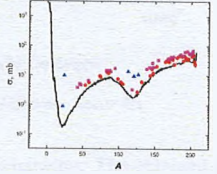
(a) $d + {}^{204}\text{Pb}$



(b) $d + {}^{206}\text{Pb}$



(c) $d + {}^{207}\text{Pb}$



(d) $d + {}^{208}\text{Pb}$

Figure 7: Left: Theoretical mass distributions computed with MCNP for all four lead targets. Right: Isobaric mass-yield distributions compared with experiment. Solid line---MCNP; circles---<40% experimental contribution; triangles--->70%; squares---40-70%.

which follows an exponential dependence

$$R_{21}(N, Z) = C \exp(\alpha N + \beta Z), \quad (7)$$

where the parameters α and β are related to the differences in neutron and proton chemical potentials divided by the temperature, $\alpha = \Delta\mu_n/T$ and $\beta = \Delta\mu_p/T$. This behavior is known as isoscaling. For medium and heavy fragments it is convenient to use the isospin projection $t_3 = (N - Z)/2$:

$$R_{21}(t_3) = \exp(C + B t_3), \quad (8)$$

where the parameter B characterizes the strength of the isotope effect. Within the statistical multi-fragmentation model, the isoscaling parameter α is related to the symmetry energy coefficient C_{sym} and the temperature T of the emitting source [21, 22]:

$$\alpha = 4 \frac{C_{\text{sym}}}{T} \left[\left(\frac{Z_1}{A_1} \right)^2 - \left(\frac{Z_2}{A_2} \right)^2 \right]. \quad (9)$$

Previous isoscaling studies on enriched tin isotopes (${}^{112,118,120,124}\text{Sn}$) from proton- and deuteron-induced reactions at 0.66-8.1 GeV [21, 22] established that the parameter B increases with fragment mass and with the neutron-number difference ΔN , between the target pair. Using the Fermi gas model temperature estimates, the symmetry energy coefficient was found to be about 13 MeV for light fragments and about 15.9 MeV for intermediate-mass fragments.

| Range of residues | Slope |
|---------------------|------------------|
| $7 \leq A \leq 30$ | 5.41 ± 1.22 |
| $40 \leq A \leq 60$ | 7.02 ± 2.55 |
| $70 \leq A \leq 80$ | 13.52 ± 3.47 |
| $^{81-86}\text{Rb}$ | 17.57 ± 1.34 |
| $^{93-96}\text{Tc}$ | 18.00 ± 3.43 |

Table 2: The values of $4C_{\text{sym}}/T$ (Slope) for different mass regions of residual nuclei produced from tin targets.

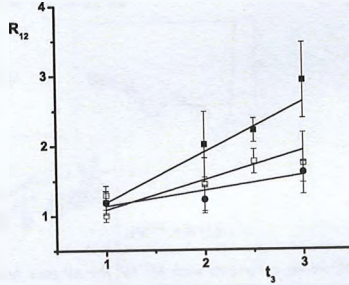


Figure 8: Dependence of the isobaric cross section ratio $R_{21}(t_3)$ on t_3 for fragments in the range $20 \leq A \leq 50$. Symbols: $^{208}\text{Pb}/^{204}\text{Pb}$, $^{208}\text{Pb}/^{206}\text{Pb}$, $^{208}\text{Pb}/^{207}\text{Pb}$; solid lines---linear fits.

The isoscaling formalism was then applied to enriched lead targets ^{201}Pb , ^{206}Pb , ^{207}Pb , and ^{208}Pb irradiated simultaneously under identical conditions, forming three independent target pairs with neutron-number differences $\Delta N = 4, 2$, and 1.

The extracted values are $B = 0.716 \pm 0.15$ for $^{208}\text{Pb}/^{204}\text{Pb}$, $B = 0.419 \pm 0.12$ for $^{208}\text{Pb}/^{206}\text{Pb}$, and $B = 0.21 \pm 0.08$ for $^{208}\text{Pb}/^{207}\text{Pb}$, demonstrating a linear dependence on the neutron-number difference of the target pair. The sign of B changes between mass regions: it is positive for $20 \leq A \leq 50$ and negative for heavier fragments, indicating a shift of the isobaric distributions. The values of B are presented in Table 3.

| Range of residues | $^{208}\text{Pb}/^{204}\text{Pb}$ | $^{208}\text{Pb}/^{206}\text{Pb}$ | $^{208}\text{Pb}/^{207}\text{Pb}$ |
|----------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| $20 \leq A \leq 50$ | 0.716 ± 0.15 | 0.419 ± 0.12 | 0.21 ± 0.08 |
| $50 \leq A \leq 80$ | -- | $-(0.017 \pm 0.004)$ | $-(0.046 \pm 0.002)$ |
| $80 \leq A \leq 100$ | $-(0.27 \pm 0.22)$ | $-(0.078 \pm 0.07)$ | -0.092 |

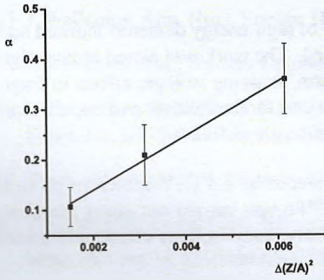
Table 3: The values of parameter B for different pairs of lead targets and different mass ranges.

From the slope of the dependence α versus $\Delta(Z/A)^2$, the symmetry energy coefficient was determined as

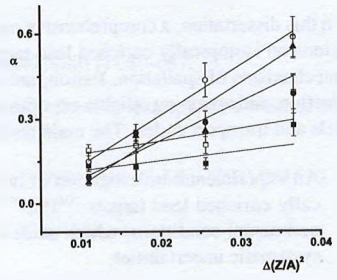
$$C_{\text{sym}} = 13.7 \pm 0.92 \text{ MeV} \quad (10)$$

for fragments in the mass range $20 \leq A \leq 50$.

Thus, isoscaling is a pronounced feature of 4.4 GeV deuteron-induced reactions on enriched lead isotopes. The parameter B depends on the neutron-number difference of the target pair and changes



(a) Lead targets



(b) Tin targets

Figure 9: Dependence of the isoscaling parameter α on $\Delta(Z/A)^2$. Solid lines - linear fits.

sign between light and heavy fragments, reflecting different reaction mechanisms. The obtained symmetry energy value indicates contributions from multifragmentation and fission processes in the formation of residual nuclei.

CONCLUSION

In this dissertation, a comprehensive experimental study of high-energy deuteron-induced nuclear reactions on isotopically enriched lead targets was performed. The work was aimed at investigating the mechanisms of spallation, fission, and multifragmentation, studying isotopic effects in fragment production, and obtaining reliable experimental cross-section data for the validation of nuclear reaction models and transport codes. The main results of the dissertation are as follows:

1. An experimental investigation of nuclear reactions induced by 4.4 GeV deuterons on isotopically enriched lead targets ^{204}Pb , ^{206}Pb , ^{207}Pb , and ^{208}Pb was carried out under identical experimental conditions, which made it possible to reliably study isotopic effects and minimize systematic uncertainties.
2. Production cross sections of a large number of residual radioactive nuclei were measured using the induced-activity method and high-resolution gamma-ray spectroscopy with HPGe detectors. In total, 72 residual nuclei were identified for ^{204}Pb , 87 for ^{206}Pb , 87 for ^{207}Pb , and 88 for ^{208}Pb .
3. It was demonstrated that spallation, fission, and multifragmentation mechanisms coexist and compete in deuteron-lead reactions at 4.4 GeV. The contribution of multifragmentation was found to be higher than in proton-induced reactions at comparable energy per nucleon.
4. A systematic enhancement of light fragment yields ($A < 60$) in deuteron-induced reactions compared with proton-induced reactions was observed, indicating a higher average excitation energy transferred to the target nucleus in deuteron interactions.
5. Isotopic effects in fragment production were investigated using four isotopically enriched lead targets. An isoscaling analysis was performed, and the symmetry energy coefficient was determined as $C_{\text{sym}} \approx 13.7 \pm 0.92$ MeV for fragments in the mass range $20 \leq A \leq 50$.
6. Experimental results were compared with calculations performed using the MCNP transport code. It was shown that the models reproduce general features of mass-yield distributions but significantly underestimate or overestimate yields of light and intermediate-mass fragments, indicating the need for further improvement of reaction models.
7. The obtained experimental cross-section data represent an important benchmark for testing and improving nuclear reaction models and transport codes such as MCNP, CEM, and LAQGSM.
8. The results of this work are important for applications in Accelerator-Driven Systems (ADS), where lead and lead-bismuth are used as spallation targets and coolant materials, and reliable nuclear data are required for system design and safety analysis[20, 23].
9. The present work represents the first experimental study of nuclear reactions induced by 4.4 GeV deuterons on an isotopically enriched ^{204}Pb target and the first consistent comparative study of fragment production for all four stable lead isotopes under identical irradiation conditions.

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LIST OF PUBLICATIONS

The research results presented in this dissertation are based on various scientific publications. Although the overall list of publications regarding the research activity of the author is broader, the following list is specific regarding those publications that directly correspond to the research results and conclusions presented in this dissertation.

1. A. R. Balabekyan, S. V. Gaginyan, J. R. Drnoyan, "Method of induced activity for studying nuclear reactions on Pb and Sn isotopes," *Journal of Contemporary Physics (Armenian Academy of Sciences)*, 2016, Vol. 51, No. 3, pp. 211 - 217.
2. A. R. Balabekyan, G. S. Karapetyan, N. A. Demekhina, S. V. Gaginyan, J. R. Drnoyan, V. I. Zhemenuk, J. Adam, L. Zavorka, A. A. Solnyshkin, V. M. Tsoupko-Sitnikov, "Spallation reactions induced by 4.4 GeV deuterons on lead isotopes." *Journal of Physics G: Nuclear and Particle Physics*, 2019, Vol. 46, No. 9, 095103.
3. A. R. Balabekyan, G. Karapetyan, N. A. Demekhina, S. V. Gaginyan, D. R. Drnoyan, V. I. Zhemenuk, J. Adam, L. Zavorka, A. A. Solnyshkin, V. M. Tsoupko-Sitnikov, "Isotopic dependence of fragment production cross sections in the reactions of deuterons on enriched lead and tin isotopes," *Physics of Atomic Nuclei*, 2018, Vol. 81, No. 6, pp. 804 - 809.
4. S. V. Gaginyan, "Comparative analysis of theoretical and experimental interaction cross-sections of deuterons with enriched ^{204}Pb , ^{206}Pb , ^{207}Pb , and ^{208}Pb ," *Journal of Contemporary Physics (Armenian Academy of Sciences)*, 2023, Vol. 58, No. 2, pp. 112 - 116.

Ծանր միջուկներում բարձր էներգիաներով թեթև մասնիկների ազդեցության տակ ընթացող ռեակցիաների մեխանիզմի ուսումնասիրությունը

ԱՄՓՈՓԱԳԻՐ

Ատենախոսությունը նվիրված է ծանր միջուկներում բարձր էներգիաներով թեթև մասնիկների ազդեցության տակ ընթացող ռեակցիաների մեխանիզմի ուսումնասիրությանը: Աշխատանքում ուսումնասիրվել են տրոհման, բաժանման և մուլտիֆրագմենտացիայի մեխանիզմները, մնացորդային միջուկների առաջացման իզոտոպային էֆեկտները, ինչպես նաև ստացվել են մնացորդային միջուկների առաջացման կտրվածքների փորձարարական տվյալներ՝ միջուկային ռեակցիաների մոդելների և մասնիկների տեղափոխման մոդելավորման կողերի ստուգման և կատարելագործման համար:

Աշխատանքի հիմնական արդյունքները հետևյալն են՝

1. Կատարվել է 4.4 ԳէՎ էներգիայի դեյտրոններով հարուցված միջուկային ռեակցիաների փորձարարական հետազոտություն հարստացված ^{204}Pb , ^{206}Pb , ^{207}Pb և ^{208}Pb թիրախների վրա նույն փորձարարական պայմաններում, ինչը հնարավորություն է տվել ուսումնասիրել իզոտոպային էֆեկտները և նվազեցնել համակարգային սխալները:
2. Մնացորդային ռադիոակտիվ միջուկների առաջացման կտրվածքները չափվել են ներմուծված ակտիվության մեթոդով և բարձր լուծողունակությամբ գամմա-սպեկտրոմետրիայի միջոցով (HPGe դետեկտորներով): Արդյունքում նույնակա-նացվել են 72 մնացորդային միջուկ ^{204}Pb -ի, 87^{*} ^{206}Pb -ի, 87^{*} ^{207}Pb -ի և 88^{*} ^{208}Pb -ի դեպքում:
3. Ցույց է տրվել, որ դեյտրոն-կապար ռեակցիաներում 4.4 ԳէՎ էներգիայի դեպքում միաժամանակ իրականանում և մրցակցում են տրոհման, բաժանման և մուլտիֆրագմենտացիայի մեխանիզմները, ընդ որում մուլտիֆրագմենտացիայի ներդրումը դեյտրոններով հարուցված ռեակցիաներում ավելի մեծ է, քան պրոտոններով հարուցված ռեակցիաներում մեկ նուկլոնի նույն էներգիայի դեպքում:
4. Նկատվել է թեթև ֆրագմենտների ($A < 60$) ելքերի համակարգված աճ դեյտրոններով հարուցված ռեակցիաներում՝ համեմատած պրոտոններով հարուցված ռեակցիաների հետ, ինչը վկայում է, որ դեյտրոնի փոխազդեցության դեպքում թիրախ միջուկին փոխանցվում է ավելի մեծ միջին զրգոման էներգիա:
5. Ուսումնասիրվել են չորս հարստացված կապարի թիրախներից ֆրագմենտների առաջացման իզոտոպային էֆեկտները: Կատարվել է isoscaling վերլուծություն և որոշվել է սիմետրիայի էներգիայի գործակիցը՝ $C_{\text{sym}} \approx 13.7 \pm 0.92 \text{ MeV}$, $20 \leq A \leq 50$ զանգվածային թվերով ֆրագմենտների համար:
6. Կատարվել է փորձարարական արդյունքների համեմատություն MCNP մասնիկնե-րի տեղափոխման մոդելավորման կողով կատարված հաշվարկների հետ: Ցույց է տրվել, որ մոդելները ընդհանուր առմամբ վերարտադրում են զանգվածային

բաշխումների ընդհանուր տեսքը, սակայն նկատվում են էական շեղումներ թեթև և միջին զանգվածային ֆրագմենտների համար, ինչը ցույց է տալիս ռեակցիայի մոդելների հետագա կատարելագործման անհրաժեշտությունը:

7. Ստացված կտրվածքների փորձարարական տվյալները հանդիսանում են կարևոր փորձարարական հիմք միջուկային ռեակցիաների մոդելների և մասնիկների տեղափոխման մոդելավորման կողերի (MCNP, CEM, LAQGSM) ստուգման և կատարելագործման համար:
8. Ստացված արդյունքները կարևոր նշանակություն ունեն Accelerator-Driven Systems (ADS) համակարգերի համար, որտեղ կապարը և կապար-բիսմութը օգտագործվում են որպես տրոհվող թիրախ և ջերմակիր, և պահանջվում են հուսալի տվյալներ համակարգերի նախագծման և անվտանգության հաշվարկների համար:
9. Սույն աշխատանքում առաջին անգամ փորձարարականորեն ուսումնասիրվել են 4.4 ԳէՎ էներգիայի դեյտրոններով հարուցված միջուկային ռեակցիաները հարստացված ^{20}Pb թիրախի վրա, ինչպես նաև առաջին անգամ իրականացվել է մնացորդային միջուկների առաջացման կտրվածքների համակարգված համեմատական ուսումնասիրություն կապարի բոլոր չորս կայուն իզոտոպների համար նույն ճառագայթման պայմաններում:

Ստացված արդյունքները ունեն ինչպես հիմնարար գիտական նշանակություն բարձր էներգիաների միջուկային ռեակցիաների մեխանիզմների ուսումնասիրման համար, այնպես էլ կիրառական նշանակություն՝ ժամանակակից միջուկային տեխնոլոգիաների և արագացուցիչներով կառավարվող համակարգերի (ADS) հաշվարկների և մոդելավորման համար:

Исследование механизмов ядерных реакций в тяжёлых ядрах при облучении высокоэнергетическими лёгкими частицами

ЗАКЛЮЧЕНИЕ

Настоящая диссертационная работа посвящена экспериментальному исследованию ядерных реакций, индуцированных дейтронами высоких энергий на изотопически обогащённых мишенях свинца. В работе изучены механизмы расщепления, деления и мультифрагментации, исследованы изотопические эффекты в образовании остаточных ядер, а также получены экспериментальные данные по сечениям образования, необходимые для валидации и совершенствования моделей ядерных реакций и транспортных кодов. Особое внимание уделено сравнительному анализу реакций на различных изотопах свинца и исследованию вкладов различных механизмов реакций при высоких энергиях возбуждения.

Основные результаты диссертационной работы следующие:

1. Проведено экспериментальное исследование ядерных реакций, индуцированных дейтронами энергии 4.4 ГэВ, на изотопически обогащённых мишенях ^{204}Pb , ^{206}Pb , ^{207}Pb и ^{208}Pb при одинаковых экспериментальных условиях, что позволило корректно исследовать изотопические эффекты и минимизировать систематические погрешности.
2. Измерены сечения образования большого числа остаточных радиоактивных ядер методом наведённой активности с использованием высокоразрешающей гамма-спектрометрии на детекторах HPGe. Идентифицировано 72 остаточных ядра для мишени ^{204}Pb , 87 — для ^{206}Pb , 87 — для ^{207}Pb и 88 — для ^{208}Pb .
3. Показано, что в реакциях дейтрон-свинец при энергии 4.4 ГэВ одновременно реализуются и конкурируют механизмы расщепления, деления и мультифрагментации, причём вклад мультифрагментации в дейтрон-индуцированных реакциях выше, чем в протон-индуцированных реакциях при сопоставимой энергии на нуклон.
4. Установлено систематическое увеличение выходов лёгких фрагментов ($A < 60$) в реакциях, индуцированных дейтронами, по сравнению с протон-индуцированными реакциями, что свидетельствует о передаче более высокой энергии возбуждения ядру-мишени в случае дейтронов.
5. Исследованы изотопические эффекты в образовании остаточных ядер с использованием четырёх изотопически обогащённых мишеней свинца. Выполнен изоскейлинговый анализ и определён коэффициент симметричной энергии $C_{\text{sym}} \approx 13.7 \pm 0.92$ МэВ для фрагментов с массовыми числами $20 \leq A \leq 50$.
6. Проведено сравнение экспериментальных результатов с расчётами по транспортному коду MCNP. Показано, что расчёты в целом воспроизводят форму массовых распределений, однако наблюдаются существенные расхождения для лёгких и промежуточных фрагментов, что указывает на необходимость дальнейшего совершенствования моделей ядерных реакций.

7. Получено, что экспериментальные данные по сечениям образования остаточных ядер могут быть использованы в качестве эталонных данных для тестирования и совершенствования транспортных кодов и моделей ядерных реакций (MCNP, CEM, LAQGSM).
8. Установлено, что полученные результаты имеют важное значение для расчётов и проектирования ускорительно-подкритических систем (ADS), в которых свинец и свинец-висмут используются в качестве спалляционных мишеней и теплоносителей.
9. Впервые проведено экспериментальное исследование реакций, индуцированных дейтронами энергии 4.4 ГэВ, на изотопически обогащённой мишени ^{204}Pb , а также выполнено систематическое сравнительное исследование сечений образования остаточных ядер для всех четырёх стабильных изотопов свинца при одинаковых условиях облучения.

Полученные результаты представляют интерес как для фундаментальной ядерной физики, так и для прикладных задач, связанных с разработкой ядерных технологий и ускорительно-подкритических систем, и могут быть использованы для совершенствования моделей ядерных реакций и библиотек ядерных данных.

