https://doi.org/10.52676/1729-7885-2025-1-175-178
УДК 539.14

PRELIMINARY RESULTS OF THE STUDY OF SHELL EFFECTS IN MASS AND ENERGY DISTRIBUTIONS OF FISSION FRAGMENTS OF ^{241}Am* IN ^{240}Pu(p,f) REACTION AT INCIDENT PROTON ENERGY OF 7 MeV

A. N. Pan[1,2*], D. K. Alimov[1,2], K. V. Kovalchuk[1], N. Burtebayev[1,2], D. M. Janseitov[1,2], R. K. Kosherbayeva[1]

[1] RSE "Institute of nuclear Physics" ME RK, Almaty, Kazakhstan
[2] Kazakh National University named after al-Farabi, Almaty, Kazakhstan

* *E-mail for contacts: a.pan@inp.kz*

Shell effects are most pronounced in mass and energy distributions of fission fragments at the lowest excitation energy of compound nucleus. To study shell effects the mass and energy distributions of fission fragments of ^{241}Am* compound nucleus in ^{240}Pu(p,f) reaction were measured at incident proton energy of 7 MeV. This energy is substantially lower than coulomb barrier for this reaction leading to very small reaction cross-section and low speed of data acquisition. Due to that the results we provide are only preliminary and final results will be provided later after acquisition of additional statistics. The measurement was carried out by 2E method on U-150M accelerator of Institute of Nuclear Physics, Almaty city, Kazakhstan. The acquired preliminary mass and energy distributions were decomposed into yields of separate fission shells assuming that the shape of mass yield of each fission mode is gauss distribution.

Keywords: *shell effects, fission fragments, plutonium-240, americium-241, fission fragments, fission mode.*

INTRODUCTION

Low excitation energy of fissile compound nuclei allows for very pronounced shell effects in mass and energy distributions of fission fragments [1]. This allows for better study different nuclear shells and their effects on the process of fission. Studies aimed at energies deep below coulomb barrier are rare due to one of the main features of low excitation energy nuclear fission which is small cross-section due to low incident particle energy. Small cross-section is a serious obstacle to acquisition of high statistics experimental data. Unlike the reactions with neutrons, light charged particles allow to study very wide ranges of both nucleon composition and excitation energy of compound nuclei. As a part of series of studies of fission of actinide nuclei by light charged particles we present the preliminary results of measurements of mass and energy distributions of fission fragments of ^{241}Am* compound nucleus in ^{240}Pu(p,f) reaction at incident proton energy of 7 MeV. The results are preliminary due to incident proton energy being around the half of coulomb barrier for this reaction (~13.6 MeV) leading to acquired statistic being only around 150 thousands events. ^{241}Am* compound nucleus can hardly be studied by other types of nuclear reactions as it is itself radioactive or requires even more exotic target materiel like even more radioactive ^{240}Am for reactions with neutrons.

Besides shell effects the mass and energy distributions are also affected by the charged liquid droplet effects. Their combined influence is described by random rapture model [2]. According to it there are several fission modes that influence mass and energy distributions: fission mode S formed by charged liquid droplet effects and maximum mass yield at $A_{CN}/2$, asymmetric fission mode S1 formed by closed nuclear shells Z50 and N82, asymmetric fission mode S2 formed by deformed nuclear shell N88 and asymmetric fission mode S3 formed by closed nuclear shell N50. Newer researches predict the presence of influence of additional deformed shell N84 and deformed shell Z52 [3, 4]. Said researches have given a new impulse to studies of deformed nuclear shells [5–9] which delve into theoretical calculations, experimental mass and gamma photon distributions. Since nuclear shells first and foremost are determined by energy of their formation it is most fitting to also study the energy distributions of fission fragments. The novelty of our research stems from experimental study of mass and total kinetic energy distributions of fission fragments together. To find influence of different deformed and spherical nuclear shells and to separate them from each other and liquid droplet effects new and more sensitive method of decomposition of mass and energy distributions into yields of separate fission modes was used [10]. The sensitivity of that method to smaller separate yields is increased due to usage of assumption of form of mass yield being gauss-like and due to inclusion of variance of average total kinetic energy of fission fragments into the analysis.

In this work we present preliminary results of the study of mass and energy of fission fragments of ^{241}Am* compound nucleus in ^{240}Pu(p,f) reaction at incident proton energy of 7 MeV. Acquired preliminary mass and energy distributions of fission fragments were decomposed into yields of separate fission modes including additional deformed shells and assuming the shape of mass yield being gauss-like. Possible presence of deformed shells N84, Z52 [3] and, probably, deformed shell Z38 [11, 12] was found.

EXPERIMENTAL SETUP

The experiment was carried out at U-150M isochronous cyclotron of Institute of Nuclear Physics, Almaty City using Dinode experimental chamber. Proton beam energy was 7 MeV. The target was a layer of ^{240}Pu of

~50 mcg/cm^2 thickness on ~50 mcg/cm^2 thick aluminum backing. Methodology of the experiment was described in [10].

RESULTS OF THE MEASUREMENTS AND ANALYSIS OF EXPERIMENTAL DATA

Experimental results are presented on Figure 1 with black color. Measured mass yield Y(m) is shown in linear and logarithm scales, both normalized at 200%. Average total kinetic energy of fission fragments <TKE>(m) is shown in linear scale. In mass and energy distributions it could be seen that the yield of asymmetric fission fragments is much higher than the yield of symmetric fission fragments. Due to low excitation energy of compound nuclei the shape of mass and energy distributions are mainly formed by shell effects. Peak of mass yield of fission fragments is at M_H≈138 a.m.u. Peak of average of total kinetic energy is at M_H≈132 a.m.u., which is corresponding to double magic ^{132}Sn nucleus.

Methodology of decomposition of mass and energy distributions into yields of separate fission modes and its advantages were described in [10].

The results of decomposition of mass and energy distributions are shown in Figure 1. For mass distribution in the area of S1 fission mode 3 gauss shapes have been used. For Z50 closed shell position of the peak of gauss was M_H≈128.5 a.m.u., amplitude was A_{im}=0.45%. For Z52 deformed shell position of the peak of gauss was M_H≈132.5 a.m.u., amplitude was A_{im}=0.7%. For N82 closed shell position of the peak was M_H≈135.8 a.m.u. and amplitude was A_{im}=0.55%. Widths of all abovementioned gausses were equal and taken as σ^2_{im}=3 a.m.u., the basis of such approach was shown in [13]. For energy distributions, due to close proximity by mass of deformed nuclear shell Z52 and closed nuclear shell N82, they were described by the one shared distribution of average of total kinetic energy of fission fragments with peak value <TKE>$_i$≈190 MeV. For Z50 closed nuclear shell separate distribution of average of total kinetic energy of fission fragments was used with peak value <TKE>$_i$≈177.5 MeV. For all abovementioned shells coefficients of b_i=0 were used. Deformed nuclear shell N88 (fission mode S2) by unchanged charge density hypothesis should have its peak around M_H≈145.2 a.m.u. for $^{241}Am^*$ nucleus, but in experimentally measured distribution position of the peak of heavy fragment is at M_H≈137–138 a.m.u. This position corresponds to deformed nuclear shell N84 in heavy fragment [3]. Due to it S2 fission mode was assumed to be a sum of two gausses: 1) first one corresponding to deformed nuclear shell N84 [3] with position at M_H=139 a.m.u., amplitude of A_{im}=3.8 % and width of σ^2_{im}=6 a.m.u.; 2) second one corresponding to deformed nuclear shell N88 with position at M_H≈146 a.m.u., amplitude of A_{im}=1.335% and width of σ^2_{im}=5.7 a.m.u. Both deformed shells are described by the same distribution of average of total kinetic energies with peak value <TKE>$_i$≈181 MeV, coefficient b_i=0.05. Fission mode S3 was described by one gauss corresponding to N50 shell with position at M_L≈84 a.m.u., amplitude of A_{im}=0.215% and width of σ^2_{im}=3.5 a.m.u., distribution of average of total kinetic energies with peak value <TKE>$_i$≈188.2 MeV, coefficient b_i=0. Mode S which is formed by charged liquid droplet effects is described by one wide gauss with position at M=120.5 a.m.u., amplitude of A_{im}=0.505 %, and width of σ^2_{im}=12.9 a.m.u., distribution of average of total kinetic energies with peak value <TKE>$_i$≈168 MeV, coefficient b_i=0.

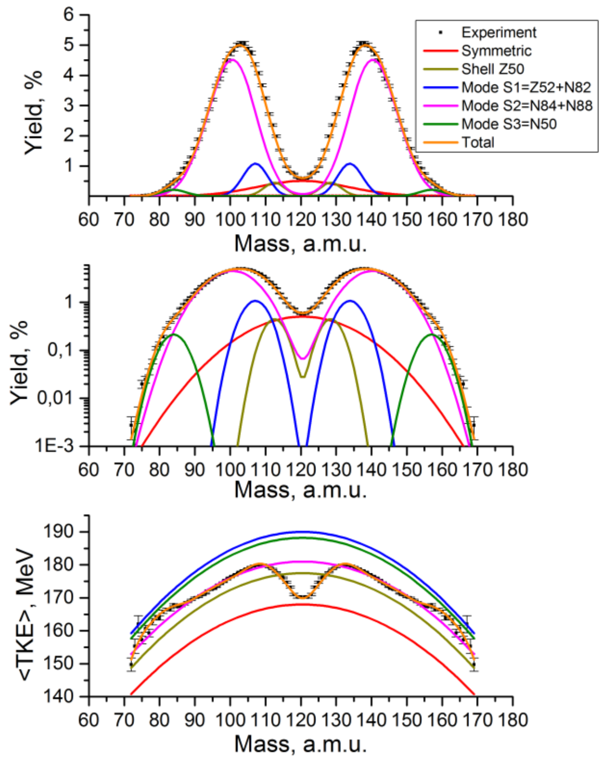

Figure 1. Experimentally measured mass and energy distributions of fission fragments of $^{241}Am^*$ compound nucleus formed in $^{240}Pu(p,f)$ reaction with incident proton energy of 7 MeV (black) and decomposition into yields of separate fission modes (in colors)

CONCLUSION

Measurements of mass and energy distributions of fission fragments of $^{241}Am^*$ compound nucleus formed in $^{240}Pu(p,f)$ reaction at incident proton energy of 7 MeV were conducted. Proton incident energy is almost 2 times lower than the coulomb barrier for said reaction. Acquired preliminary data was decomposed into yields of separate fission modes assuming the shape of mass yield of each mode to be gauss. That allowed seeing the presence of previously predicted deformed nuclear shells. In the future, after collecting additional statistics, the final results will be published.

Acknowledgments

The work was carried out with the support of the Ministry of Energy of the Republic of Kazakhstan, within the framework of the program BR23891530 «Development of complex scientific research in the field of nuclear and radiation physics based on Kazakhstan's accelerator complexes».

REFERENCES

1. K.B. Gikal et al., Proton induced fission of ^{232}Th at intermediate energies // Physics of Atomic Nuclei. – 2016. – Vol. 79, No. 9–10. – Pp. 1367–1374.
2. U. Brosa et al., Nuclear Scission // Phys. Rep. – 1990. – Vol. 197. – P. 167.
3. G. Scamps & C. Simenel, Impact of pear-shaped fission fragments on mass-asymmetric fission in actinides // Nature. – 2018. – Vol. 564. – P. 382.
4. G. Scamps & C. Simenel, Effect of shell structure on the fission of sub-lead nuclei // Phys. Rev. C. – 2019. – Vol. 100. – P. 041602(R).
5. E. Prasad et. al., Systematics of the mass-asymmetric fission of excited nuclei from ^{176}Os to ^{206}Pb // Phys. Lett. B. – 2020. – Vol. 811. – P. 135941.
6. B. M. A. Swinton-Bland et. al., Mass-asymmetric fission of ^{205,207,209}Bi at energies close to the fission barrier using proton bombardment of ^{204,206,208}Pb // Phys. Rev. C. – 2020. – Vol. 102. – P. 054611.
7. K. Nomura et. al., Microscopic description of octupole collective excitations near N = 56 and N = 88 // Phys. Rev. C. – 2021. – Vol. 103. – P. 054301.
8. A. Chatillon et. al., Influence of proton and neutron deformed shells on the asymmetric fission of thorium isotopes // Phys. Rev. C. – 2022. – Vol. 106. – P. 024618.
9. Shivani Jain et. al., Investigation of octupole deformed fragments decaying from even-even isotopes of $^{222–230Th}$ // Phys. Rev. C. – 2022. – Vol. 105. – P. 034605.
10. A.N. Pan et al., Shell effects in the fission of ^{236}U* nuclei, formed in the reaction ^{232}Th(α,f) at incident alpha particle energy of 29 MeV // NNC RK Bulletin. – 2023. – Vol. 2. – P. 4–8. https://doi.org/10.52676/1729-7885-2023-2-4-8.
11. E.M. Kozulin et al., Fission of ^{180,182,183}Hg* and ^{178}Pt* nuclei at intermediate excitation energies // Phys. Rev. C. – 2022. – Vol. 105. – P. 014607.
12. A.A. Bogachev et al., Asymmetric and symmetric fission of excited nuclei of ^{180,190}Hg and ^{184,192,202}Pb formed in the reactions with ^{36}Ar and ^{40,48}Ca ions // Phys. Rev. C. – 2021. – Vol. 104. – P. 024623.
13. T. Banerjee et al., Search for possible fission modes at high excitation energies in ^{254}Fm // Phys. Rev. C. – 2022. – Vol. 105. – P. 044614.

ПРОТОНДАРДЫҢ 7 МэВ ЭНЕРГИЯСЫНДА ^{240}Pu(p, f) РЕАКЦИЯСЫНДА АЛЫНҒАН ^{241}Am* ҚҰРАМА ЯДРОСЫНЫҢ БӨЛІНУ ФРАГМЕНТТЕРІНІҢ МАССАЛЫҚ-ЭНЕРГЕТИКАЛЫҚ ТАРАЛУЫНДАҒЫ ҚАБЫҚША ӘСЕРЛЕРІН ЗЕРТТЕУДІҢ АЛДЫН АЛА НӘТИЖЕЛЕРІ

А. Н. Пан[1,2*], Д. К. Алимов[1,2], К. В. Ковальчук[1], Н. Буртебаев[1,2], Д. М. Джансеитов[1,2], Р. К. Кошербаева[1]

[1] ҚР Энергетика министрлігі «Ядролық физика институты» РМК, Алматы, Қазақстан
[2] Әл-Фараби атындағы Қазақ ұлттық университеті, Алматы, Қазақстан

* *Байланыс үшін e-mail: a.pan@inp.kz*

Қабықтың әсері бөлінетін құрама ядроның төмен қозу энергиялары кезінде бөліну фрагменттерінің массалық-энергетикалық таралуына айқын әсер етеді. Сондықтан қабық әсерлерінің әрекетін зерттеу үшін ^{240}Pu(p,f) реакциясында 7 МэВ атқыланатын протондардың энергиясымен алынған ^{241}Am* ядросының бөліну фрагменттерінің массалық энергиясының таралуы өлшенді. Бұл энергия берілген реакция үшін кулондық тосқауылдан едәуір төмен, нәтижесінде реакция қимасы төмен және деректер жиынының жылдамдығы төмен болады. Осыған байланысты біз зерттеудің алдын-ала нәтижелерін ұсынамыз, қосымша статистиканы жинағаннан кейін қорытынды жасауға болады. Өлшеу Алматы қаласындағы Ядролық физика институтының У-150М үдеткішінде 2E әдісімен жүргізілді. Алынған масса мен энергияның алдын-ала таралуы жеке қабықшалардың, соның ішінде деформацияланған қабықшалардың лобтарына ыдырайды, бұл қабық лобының пішіні Гаусс деп болжайды.

Түйін сөздер: *қабықша әсерлері, ядроның бөлінуі, плутоний-240, Америций-241, бөліну фрагменттері, бөліну режимі.*

ПРЕДВАРИТЕЛЬНЫЕ РЕЗУЛЬТАТЫ ИССЛЕДОВАНИЯ ОБОЛОЧЕЧНЫХ ЭФФЕКТОВ В МАССОВО-ЭНЕРГЕТИЧЕСКИХ РАСПРЕДЕЛЕНИЯХ ОСКОЛКОВ ДЕЛЕНИЯ СОСТАВНОГО ЯДРА ^{241}Am*, ПОЛУЧЕНОГО В РЕАКЦИИ ^{240}Pu(p,f) ПРИ ЭНЕРГИИ ПРОТОНОВ 7 МэВ

А. Н. Пан[1,2*], Д. К. Алимов[1,2], К. В. Ковальчук[1], Н. Буртебаев[1,2], Д. М. Джансеитов[1,2], Р. К. Кошербаева[1]

[1] РГП «Институт ядерной физики» МЭ РК, Алматы, Казахстан
[2] Казахский национальный университет имени аль-Фараби, Алматы, Казахстан

** E-mail для контактов: a.pan@inp.kz*

Оболочечные эффекты оказывают наиболее выраженное влияние на массово-энергетические распределения осколков деления при низких энергиях возбуждения делящегося составного ядра. Поэтому для исследования поведения оболочечных эффектов было измерено массово-энергетическое распределение осколков деления ядра ^{241}Am*, полученного в реакции ^{240}Pu(p,f) при энергии налетающих протонов 7 МэВ. Эта энергия значительно ниже кулоновского барьера для данной реакции, что ведет к низкому сечению реакции и малой скорости набора данных. Ввиду этого мы представляем предварительные результаты исследования, после набора дополнительной статистики возможно будет сделать окончательные выводы. Измерение проводилось методом 2Е на ускорителе У-150М Института ядерной физики, г. Алматы. Полученное предварительное массово-энергетическое распределение было разложено по вкладам отдельных оболочек, включая деформированные оболочки, предполагая, что форма вклада оболочки представляет собой гаусс.

Ключевые слова: *оболочечные эффекты, деление ядра, плутоний-240, америций-241, осколки деления, мода деления.*