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SHELL EFFECTS IN THE FISSION OF ^{236}U* NUCLEI, FORMED IN THE REACTION ^{232}Th(α,f) AT INCIDENT ALPHA PARTICLES ENERGY OF 29 MeV

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Mass and energy distribution of fission fragments of ^{236}U* nuclei, formed in the reaction ^{232}Th(α,f) at incident alpha energy of 29 MeV were studied to reveal the influence of shell effects. The experiment was carried out by 2E method at U-150M accelerator at Institute of Nuclear Physics, Almaty city. Acquired experimental data was decomposed into yields of separate shells, including deformed shells, assuming that the shell yield has the form of gauss distribution. The manifestation of deformed shells N84, Z52 and deformed shells Z36, Z38 was revealed.

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Keywords: *shell effects, nuclear fission, Uranium-236, fission fragments, fission mode.*

INTRODUCTION

Fission of nuclei by low energy light charged particles is of particular interest. It allows to study the process of fission and structure of nuclei, since it allows to probe composite nuclei in wide range of nucleon composition as well as wide range of excitation energies. Both of these ranges are inaccessible by neutron-induced or spontaneous fission. Previous research [1] has shown that shell effects are most pronounced at low excitation energies and vanish with the increase of excitation energies. This is the reason we chose incident alpha particle energy of 29 MeV as it corresponds to the coulomb barrier for α+^{232}Th reaction.

During the fission process the formation of fragments is influenced by liquid droplet effects and by shell effects in the composite nuclei while it evolves from the moment of formation to the scission point. The influence of these effects is described by the model proposed in [2]. According to this model there are several key fission modes: mode S which corresponds to liquid droplet effects with peak yield at $A_{cn}/2$, mode S1 which is formed by the influence of closed nuclear shells Z50 and N82, mode S2 which is formed by the influence of deformed nuclear shell N88, and mode S3 which is formed by the influence of closed nuclear shells of N50 and Z28. That model was used as a basis of modal analysis conducted in this paper, it was expanded by adding additional deformed shells N84 [3], Z36 [4, 5] and Z38 [5], Z52 [3]. To increase analysis sensitivity the shape of mass yield of a separate shell was assumed to be a gauss distribution, average total kinetic energy of fission fragment and variance of that average was included in the analysis.

In this work we show the results of study of ^{232}Th(α,f) reaction at incident alpha particle energy of 29 MeV. The measured mass and energy distributions were decomposed intro the yields of separate fission modes assuming the shape of each mass yield to be a gauss distribution. Manifestation of probable deformed shells N84, Z52 [3] and deformed shells Z36 [4, 5], Z38 [5] was found.

EXPERIMENTAL SETUP

The experiment was conducted at isochronous accelerator U-150M at the Institute of Nuclear Physics, Almaty city, using Dinode experimental chamber. The incident energy of alpha particles was 29 MeV. The measurements were carried out using a pair of PIPS semiconductor detectors, the detectors were located at 90° to the beam axis from both sides. The target consisted of a layer of ^{232}Th with 40 mcg/cm^2 with 50 mcg/cm^2 thick Al_2O_3 backing. "True" events selection was carried out by the pulse rise time and pulse length [6, 7]. The electronics setup was such that only fission fragments from the same fission event were counted. Fragment identification was carried out afterwards using the 2E method. The effects of neutron evaporation for the studied reaction were within the experimental errors and were not taken into account.

Since semiconductor detectors were used it is important to take into account Pulse Height Defect due to plasma effects in the detectors [8]. To compensate for it the methodic described in [9] was used.

EXPERIMENTAL RESULTS AND ANALYSIS

Experimental results are shown with black color on figure 1. Experimentally measured mass yield $Y(m)$ normalized to 200% is shown in linear and logarithmic scales, average total kinetic energy $<TKE>(m)$ and it's variance $\sigma_{<TKE>}(m)$ are shown in linear scales. It can be seen that asymmetric yields are a major part of the total mass yield, the yield of symmetric fragments is lower and the final shape of the mass yield is formed mostly by the influence of shell effects. The peak of measured mass yield is located near $M_H \approx 138$ a.m.u, the peak of measured average total kinetic energy is near $M_H \approx 132$ a.m.u. which corresponds to double magic nuclei ^{132}Sn, the peak of variance of measured average total kinetic energy is near $M_H \approx 130$ a.m.u.

To decompose experimental yields into yields from separate fission modes the shape of a mass yield of a separate shell was assumed to be a gauss distribution. To evaluate goodness of the decomposition a χ^2 criteria was chosen and minimized to improve the accuracy of decomposition:

$$\chi^2 = \sum_m \frac{\left(Y_{exp}(m) - Y_{tot}(m)\right)^2}{Y_{err}(m)^2} + \sum_m \frac{\left(\langle TKE\rangle_{exp}(m) - \langle TKE\rangle_{tot}(m)\right)^2}{\langle TKE\rangle_{err}(m)^2} + \sum_m \frac{\left(\sigma^2_{\langle TKE\rangle_{exp}}(m) - \sigma^2_{\langle TKE\rangle_{tot}}(m)\right)^2}{\sigma^2_{\langle TKE\rangle_{err}}(m)^2};$$

$$Y_i(m) = A_{im} \cdot e^{-\frac{(m-m_i)^2}{2\cdot\sigma^2_{im}}};$$

$$\langle TKE\rangle_i(m) = A_{iTKE} \cdot \left(1 - \left(1 - 2\cdot\frac{m}{A_{cn}}\right)^2\right) \cdot \left(1 + b_i \cdot \left(1 - 2\cdot\frac{m}{A_{cn}}\right)^2\right);$$

$$\sigma^2_{\langle TKE\rangle_i}(m) = p_i \cdot \langle TKE\rangle_i^2(m);$$

$$Y_{tot}(m) = \sum_i Y_i(m);$$

$$\langle TKE\rangle_{tot}(m) = \sum_i \langle TKE\rangle_i(m) \cdot \frac{Y_i(m)}{Y_{tot}(m)};$$

$$\sigma^2_{\langle TKE\rangle_{tot}}(m) = \sum_i \frac{Y_i(m)}{Y_{tot}(m)} \cdot \sigma^2_{\langle TKE\rangle_i}(m) + \sum_{i,j} \frac{Y_i(m)\cdot Y_j(m)}{Y^2_{tot}(m)} \cdot \left(\langle TKE\rangle_i(m) - \langle TKE\rangle_j(m)\right)^2, \; i < j;$$

where m – mass number, $Y_{exp}(m)$ – experimentally measured mass yield, $Y_{err}(m)$ – error in measurement mass yield, $Y_{tot}(m)$ – mass yield from decomposition, $<TKE>_{exp}(m)$ – experimentally measured average total kinetic energy of fission fragments, $<TKE>_{err}(m)$ – error in measurement of average total kinetic energy, $<TKE>_{tot}(m)$ – average total kinetic energy from decomposition, $\sigma^2_{<TKE>exp}(m)$ – variance of experimentally measured average total kinetic energy of fission fragments, $\sigma^2_{<TKE>err}(m)$ – error in variance of experimentally measured average total kinetic energy of fission fragments, $\sigma^2_{<TKE>tot}(m)$ – variance of experimentally measured average total kinetic energy from decomposition, $Y_i(m)$ – mass yield of a separate fission mode, A_{im} – height of a peak of mass yield of a separate fission mode, m_i – position of a peak of mass yield of a separate fission mode, σ^2_{im} – width of peak of mass yield of a separate fission mode, $<TKE>_i(m)$ – peak average total kinetic energy of a separate fission mode, A_{iTKE} – height of a peak of an average total kinetic energy of a separate mode, A_{cn} – mass number of a composite nuclei, b_i – coefficient of deviation from quadratic dependency due to shell effects, at $b_i = 0$ – the dependency is quadratic, $\sigma^2_{<TKE>i}(m)$ – variance of average total kinetic energy of a separate fission mode, p_i – coefficient of proportionality between an average total kinetic energy of a separate mode and its variance.

The use of an assumption of a shape of mass yield allows to decrease the number of parameters for decomposition (in contrast to the methodic proposed in [7]). The usage of average total kinetic energy and of its variance allows the methodic proposed in this paper to be very sensitive to the difference in values of average total kinetic energies of separate fission modes. This sensitivity stems from a quadratic dependence of variance on a difference between average total kinetic energies of separate fission modes. Such sensitivity allows to reveal yields from different shells which were not taken into account prior due to their low yield.

The model proposed in [2] was used as a ground for this analysis. Said model includes the following fission modes: mode S which corresponds to liquid droplet effects with peak yield at $A_{cn}/2$, mode S1 which is formed by the influence of closed nuclear shells Z50 and N82, mode S2 which is formed by the influence of deformed nuclear shell N88, and mode S3 which is formed by the influence of closed nuclear shells of N50 and Z28. In the paper [10] it was shown that often instead of a closed shell Z50 a deformed shell Z52 takes its place. However, using the current assumption about the shape of mass yield of a separate shell it is not possible to fit the experimental results using this standard model. This is especially true with the variance of average total kinetic energy which is the source of increased sensitivity pointing to the role of additional shells in the formation mass and energy yields of fission fragments. This is the reason for the inclusion of additional shells in the decomposition of experimentally measured mass and energy yields. After the finish of the decomposition analysis the literature review allowed to link these additional shells to some theoretically predicted deformed shells and to some previously found in other reactions deformed shells.

The results of decomposition analysis is shown in figure 1. In the area of fission mode S1 three gauss shapes were used to describe the experimental results: for closed shell Z50 – position at $M_H \approx 129$ a.m.u. and peak height of A_{im}=0.255%, for deformed shell Z52 – position at $M_H \approx 133$ a.m.u. and peak height of A_{im}=0.215%, for closed shell N82 – position at $M_H \approx 135.3$ a.m.u. and peak height of A_{im}=0.105%. Widths of peaks for shells Z50 and Z52 were equal σ^2_{im}=3 a.m.u., width of a peak for shell N82 was σ^2_{im}=2.5 a.m.u. Close by position in mass shells

Z52 and N82 were described by the same yield of peak average total kinetic energy of $<TKE>_i\approx197.2$ MeV, separate peak average total kinetic energy value was used for Z50 shell equal to $<TKE>_i\approx180.2$ MeV. For all these shells $b_i=0$. For Z50 $p_i=0.0016$, for Z52 and N82 both $p_i=0.0018$. Variance of average total kinetic energy is higher for shells Z52 and N82 than for shell Z50. Deformed shell N88 (fission mode S2), using unchanged charge density hypothesis should be around $M_H\approx144.2$ a.m.u. for $^{232}Th(\alpha,f)$ reaction, however the peak yield of heavy fragments is located near $M_H\approx137$–138 a.m.u. Using the same hypothesis this position corresponds to deformed shell N84[3] in heavy fragment and deformed shell Z38 in light fragment [5]. This is why fission mode S2 is described as the sum of two gauss shapes: 1st shape with position at $M_H=138$ a.m.u., peak height of $A_{im}=3.555\%$ and width of a peak $\sigma^2_{im}=6.55$ a.m.u. corresponding to deformed shell N84[3] in heavy fragment and deformed shell Z38 in light fragment [5], 2nd shape with position at $M_H\approx144$ a.m.u., peak height of $A_{im}=0.83\%$ and width of a peak $\sigma^2_{im}=5.25$ a.m.u. corresponding to deformed shell N88 in heavy fragment [2] and deformed shell Z36 in light fragment [4, 5]. Both shapes of deformed shells were described by the same values of peak average total kinetic energies $<TKE>_i\approx176.45$ MeV, $b_i=0$, $p_i=0.00295$. Fission mode S3 was also described as sum of two gauss shapes: 1st shape with position at $M_L\approx83.4$ a.m.u., peak height of $A_{im}=0.075\%$, width of a peak $\sigma^2_{im}=4.1$ a.m.u., peak average total kinetic energy $<TKE>_i\approx180.5$ MeV, $b_i=0$, $p_i=0.0025$ corresponding to closed shell N50 in light fragment [2], 2nd shape with position at $M_L\approx76.9$ a.m.u., peak height of $A_{im}=0.018\%$ and width of a peak $\sigma^2_{im}=3.9$ a.m.u., peak average total kinetic energy $<TKE>_i\approx173.4$ MeV, $b_i=0$, $p_i=0.0022$. The difference between position of Z28 in decomposition ($M_L\approx76.9$) and position of Z28 from unchanged charge density hypothesis ($M_L\approx71.8$) could be explained by the location of this shell at the edge of range of sensitivity of experiment. Liquid droplet effects which are described by fission mode S were described by a single gauss shape with position at M=118 a.m.u., peak height of $A_{im}=1.66\%$, peak width of $\sigma^2_{im}=12.3$ a.m.u., peak average total kinetic energy $<TKE>_i\approx160.9$ MэB, $b_i=0$, $p_i=0.0042$.

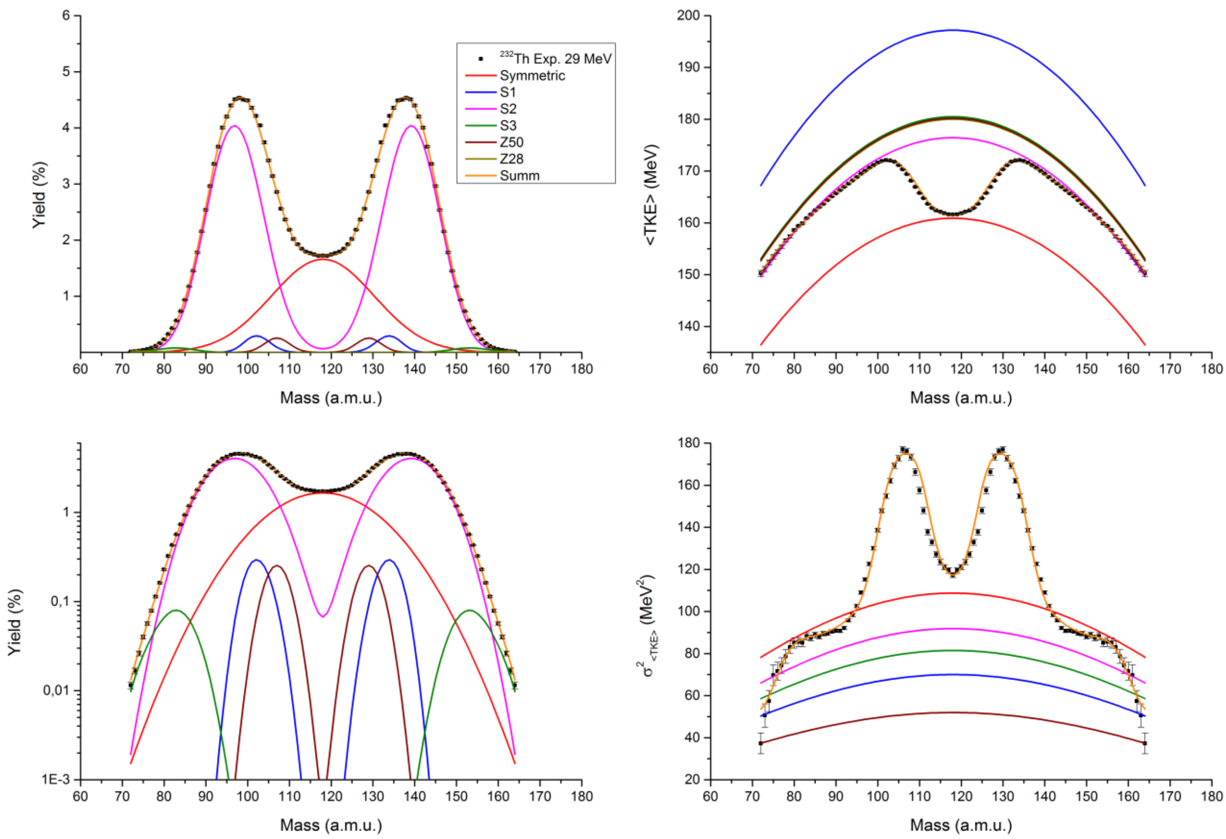

Figure 1. Experimentally measured mass and energy distributions of fission fragments of composite nuclei $^{236}U^*$, formed in $^{232}Th(\alpha,f)$ reaction at incident alpha particle energy of 29 MeV (in black) and decomposed into yields from separate fission modes

CONCLUSION

Mass and energy distributions of fission mass and energy distributions of fission fragments of composite nuclei ^{236}U*, formed in ^{232}Th(α,f) reaction at incident alpha particle energy of 29 MeV, which is equal to the coulomb barrier of that reaction, were measured. The experimental data was decomposed into yields from separate fission modes using the assumption that mass yield of each shell has a gauss shape. That assumption and the usage of average total kinetic energy and its variance allowed to increase sensitivity of the analysis and reveal the manifestation of previously predicted deformed shell. This method could be used in the future for the analysis of other reactions.

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REFERENCES

1. Gikal K.B. [et al.] Proton induced fission of ^{232}Th at intermediate energies // Physics of Atomic Nuclei. – 2016. – No. 9–10. – Vol. 79. – pp. 1367–1374.
2. Brosa U. [et al.] Nuclear Scission // Phys. Rep. – 1990. – Vol. 197, Is. 4. – P. 167–262.
3. Scamps G. & Simenel C. Impact of pear-shaped fission fragments on mass-asymmetric fission in actinides // Nature. – 2018. – Vol. 564. – P. 382–285.
4. Kozulin E.M. [et al.] Fisiion of ^{180,182,183}Hg* and ^{178}Pt* nuclei at intermediate excitation energies // Phys. Rev. – 2022. – C. 105.014607.
5. Bogachev A.A. [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. – 2021. – C. 104.024623.
6. Kondratiev N.A., Mulgin S.I., Okolovich V.N., Rusanov A.Ya. Metod bystroy spektrometrii parnykh oskolkov deleniya s otborom sobytiy po vremeni proleta // Sov. J.: Prib. Tekh. Eksp. – 1990. – 62, 2.
7. Mulgin S.I. [et al.] The modal structure of fragment mass and energy yields from the 10.3-30.0 MeV proton induced fission of ^{232}Th and ^{235}U // Nucl. Phys. A. – 2009. – Vol. 824, Is. 1–4. – P. 1–23.
8. Schmitt H.W. [et al.] Precision Measurements of Correlated Energies and Velocities of ^{252}Cf Fission Fragments // Phys. Rev. – 1965. – 137, B837.
9. Mulgin S.I. [et al.] Two-parametric method for silicon detector calibration in heavy ion and fission fragment spectrometry // Nucl. Instrum. Methods A. – 1997. – Vol. 388, Is. 1–2. – P. 254–259.
10. Bockstiegel C. [et al.] Nuclear-fission studies with relativistic secondary beams: Analysis of fission channels, Nucl. Phys. A. – 2008. – Vol. 802, Is. 1–4. – P. 12–25.

АЛЬФА БӨЛШЕКТЕРІНІҢ ЭНЕРГИЯСЫ 29 МэВ БОЛҒАН КЕЗДЕ ^{232}Th(α,f) РЕАКЦИЯСЫНДА АЛЫНҒАН ^{236}U* ЯДРОСЫНЫҢ БӨЛІНУІНДЕГІ ҚАБЫҚ ӘСЕРЛЕРІ

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Қабық әсерлерінің мінез-құлқын зерттеу үшін 29 МэВ Альфа бөлшектерінің энергиясында ^{232}Th(α,f) реакциясында алынған ^{236}U* ядросының бөліну фрагменттерінің массалық-энергетикалық таралуы өлшенді. Өлшеу Алматы қаласындағы Ядролық физика институтының У-150М үдеткішінде 2Е әдісімен жүргізілді. Алынған массалық-энергетикалық үлестіру жеке қабықшалардың, соның ішінде деформацияланған қабықшалардың үлестері бойынша ыдырап, қабықшаның үлес формасы гаусс деп болжайды. Деформацияланған N84, Z52 және деформацияланған Z36, Z38 қабықтарының көрінісі анықталды.

Жұмыс Қазақстан Республикасы Энергетика министрлігінің қолдауымен № BR09158499 гранты шеңберінде орындалды.

Түйін сөздер: *қабықша әсерлері, ядроның бөлінуі, уран-236, бөліну фрагменттері, бөлу мода*.

ОБОЛОЧЕЧНЫЕ ЭФФЕКТЫ В ДЕЛЕНИИ ЯДРА $^{236}U^*$, ПОЛУЧЕНОМ В РЕАКЦИИ $^{232}Th(\alpha,f)$ ПРИ ЭНЕРГИИ АЛЬФА ЧАСТИЦ 29 МэВ

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Для исследования поведения оболочечных эффектов было измерено массово-энергетическое распределение осколков деления ядра $^{236}U^*$, полученного в реакции $^{232}Th(\alpha,f)$ при энергии альфа частиц 29 МэВ. Измерение проводилось методом 2E на ускорителе У-150М Института ядерной физики, г. Алматы. Полученное массово-энергетическое распределение было разложено по вкладам отдельных оболочек, включая деформированные оболочки, предполагая, что форма вклада оболочки представляет собой гаусс. Обнаружено проявление деформированных оболочек N84, Z52 и деформированных оболочек Z36, Z38.

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Ключевые слова: *оболочечные эффекты, деление ядра, уран-236, осколки деления, мода деления.*