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**A.S. Demyanova[1], A.N. Danilov[1], N. Burtebayev[2], D.M. Janseitov[2,3], Zh. Kerimkulov[2], D.K. Alimov[2], Y.S. Mukhamejanov[2]**

[1] NRC Kurcatov Institute, Moscow, Russia;
[2] Institute of Nuclear Physics, Almaty, Kazakhstan;
[3]Eurasian National University, Astana, Kazakhstan
e-mail: janseit.daniar@gmail.com

# EXOTIC STATES OF $^{13}$C NUCLEI WITH ABNORMAL RADII

**Abstract.** Differential cross-sections of the elastic and inelastic $\alpha+^{13}$C scattering were measured at E(α) = 90 MeV. The root mean-square radii (<$R_{rms}$>) of $^{13}$C nucleus in the states: 8.86 ($1/2^-$), 3.09 ($1/2^+$) and 9.90 ($3/2^-$) MeV were determined by the Modified diffraction model (MDM). The radii of the first two levels are enhanced compared to that of the ground state of $^{13}$C, confirming the suggestion that the 8.86 MeV state is an analogue of the Hoyle state in $^{12}$C and the 3.09 MeV state has a neutron halo. Some indications to the abnormally small size of the 9.90 MeV state were obtained.

**Key words:** radii of excited states, modified diffraction model, neutron halo.

**Introduction**. In the last few years evidences of the existence of nuclei with abnormally large radii of excited states were obtained were obtained. In our previous experiments on inelastic scattering $^{13}$C (α, α$^*$) at energies E(α) = 29 and 65 MeV [1,2], we have seen three of the excited state of 3.09 MeV ($1/2^+$), 8.86 MeV ($1/2^-$) and 9.90 MeV ($3/2^-$), radii of which differ from the ground state. Because of the importance of this result, a new dimension on the scattering of alpha particles $^{13}$C were carried out at the energy E(α) = 90 MeV.

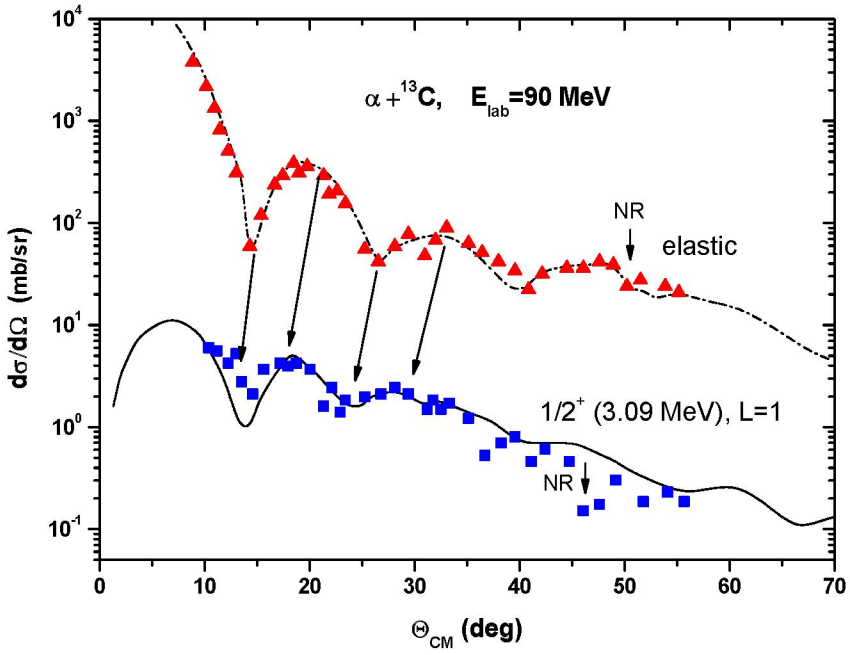


Figure 1 - The differential cross-sections $\alpha+^{13}$C of elastic and inelastic (1/2, 3.09 MeV) scattering at E(α)=90 MeV. Optical model calculation results are shown by the dashed curve. The solid line corresponds to calculations by DWBA (L=1). Positions rainbow lows are marked by vertical arrows

**Discussion and results.** The differential cross-sections of elastic and inelastic scattering of $\alpha+^{13}C$ were measured in the K-130 cyclotron of the University of Jyväskylä, Finland. The data for the elastic and inelastic scattering (3.09 MeV), one of the most interesting of the excited state of $^{13}C$ nucleus), are presented in Figure 1. The diffraction minima and maxima (connected by straight lines) must be in phase if the elastic and inelastic diffraction radii are equal. The observed shift of the diffraction minima and maxima in the scattering cross-section in the direction of smaller angles in the inelastic scattering points to the increase in the radius of 3.09 MeV excited state as compared with the ground state. Estimation of the mean square radius was carried out by three independent methods: the modified diffraction model (MDM) [2], the method of the nuclear rainbow (MNR) [3, 4] and the method of using the asymptotic normalization coefficients (ANC) [5, 6]. Of the three approaches similar values, confirming the validity of the used methods, were obtained (Table 1) and confirm the existence of the neutron halo in the first excited states of the $^{13}C$ nucleus [1, 5].

Table 1 - $R_{rms}$ mean square radii for different state of $^{13}C$ nucleus

| $E^*$, MeV, $J^\pi$ | Structure | MDM, 65 MeV | MNR, 65 MeV | ANC , 65 MeV | MDM , 90 MeV | MNR , 90 MeV |
|---|---|---|---|---|---|---|
| 0.00, $1/2^-$ | Shell model | | | | | |
| 3.09, $1/2^+$ | Neutron halo | 2.98±0.09 * | ≥2.7 [1] | 2.62±0.10 [5]<br>2.68 [7], теория | 2.882.62±0.19 * | ≥2.6 * |
| 8.86, $1/2^-$ | Diluted cluster | 2.68±0.12 [1] | ≥2.5 * | | 2.632.62±0.16 * | ≥2.5 * |
| 9.90, $3/2^-$ | Compressed cluster | 2.02±0.14 [1] | | | 1.76±0.23 [8] | |
| *this work | | | | | | |

The differential cross-section of inelastic scattering of $\alpha+^{13}C$ excited state $1/2^-$ (8.86 MeV) at E(α) = 65 and 90 MeV are shown in Figure 2. As can be seen from this figure, the observed identity of the structure of the front angles (up to 45 degrees) confirms diffraction origin of the oscillations and the similarity of the diffraction radii measured at different energies. Minima at q≈2.5 $fm^{-1}$ in the experimental data at 65 MeV and q≈2,0 $fm^{-1}$ data at 90 MeV were identified as rainbow minimum (Airy). The use of MDM and MNR methods in the state of 8.86 MeV showed that the latter has increased radius (Table 1), close to the mean square radius of the Hoyle state ($0^+$, 7.65 MeV) in the $^{12}C$ nucleus [2].

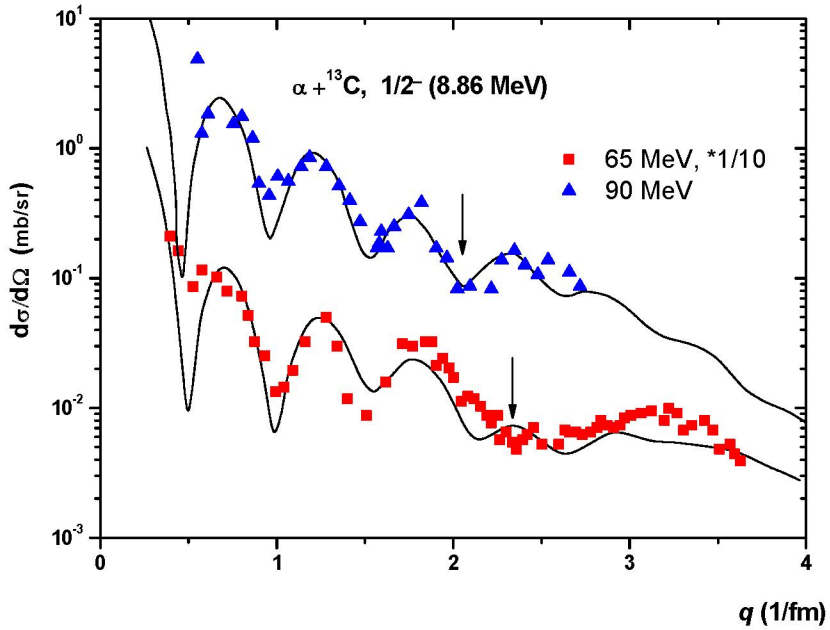


Figure 2 - the differential cross-section of inelastic scattering of $\alpha+^{13}C$ excited state $1/2^-$ (8.86 MeV) at energies 65 and 90 MeV, depending on the q momentum transfer. Rainbow lows items are marked with arrows

An evaluation by MDM has given the state radius value of $3/2^-$ (9.90 MeV), which proved to be less than that of the ground state of $^{13}C$ nucleus (Table 1). This conclusion is confirmed by comparing the various inelastic scattering cross-sections with the transfer of angular momentum L=2 (Figure 3). The diffraction structure for the differential cross-section of the $3/2^-$ (9.90 MeV) is shifted to larger angles, indicating its smaller radius. This result contradicts the predictions that have been proposed in [9], according to which the state $3/2^-$ (9.90 MeV) must have a radius comparable to the Hoyle state. The physical reason for this decrease of the nuclei size is not yet clear.

Thus, the dilute state at 3.09 and 8.86 MeV and compact at 9.90 MeV coexist in a $^{13}C$ nucleus with other normal radii states.

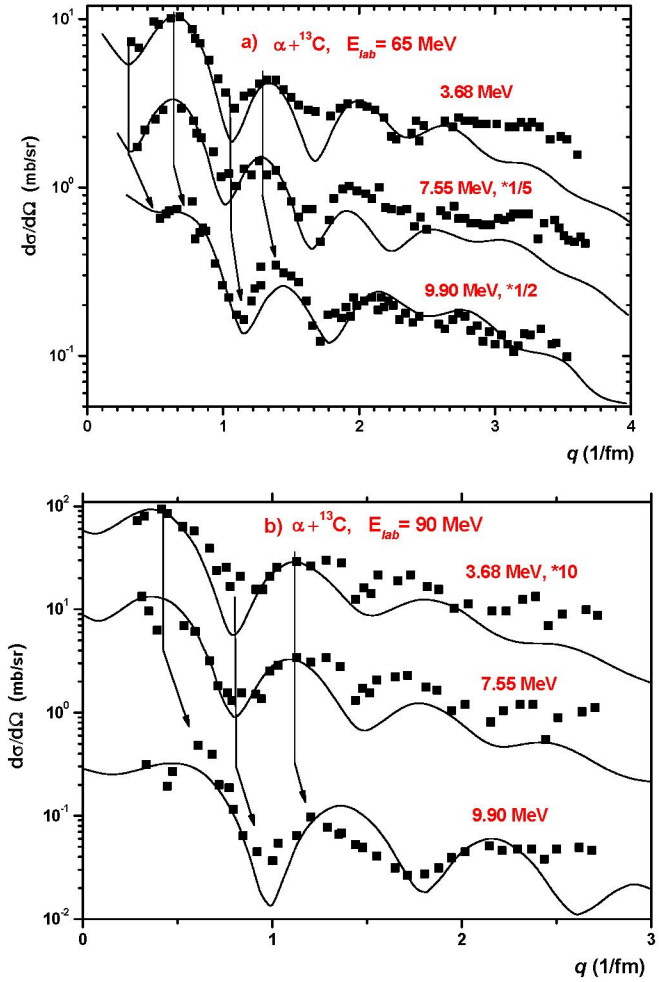


Figure 3 - the differential cross-section of inelastic scattering $^{13}C(\alpha,\alpha)^{13}C^*$ at energies 65 and 90 MeV, at L=2 for states 3.68 MeV, 7.55 MeV and 9.9 MeV of $^{13}C$ nucleus depending on the q momentum transfer. The vertical line are drawn through the minima and maxima of the differential cross-sections of the excited levels of 3.68 and 7.55 MeV. The corresponding minima and maxima of sections of 9.9 MeV state are indicated by the arrows. The solid curves correspond to calculations by DWBA (L=2). The data are taken from [8]

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## REFERENCES

[1] Demyanova A.S. et al., Spectroscopy of exotic states of $^{13}C$ // EPJ Web of Conferences 66, 02027 (2014).

[2] Danilov A.N. et al., Determination of nuclear radii for unstable states in $^{12}C$ with diffraction inelastic scattering // Phys. Rev. C 80, 054603 (2009).

[3] Ohkubo S. and Hirabayashi Y., Evidence for strong refraction of $^{3}$He in an α-particle condensate // Phys. Rev. C 75, 044609 (2007).

[4] Demyanova A.S. et al., Radii of cluster states in $^{11}$B and $^{13}$C // Int. J. Mod. Phys. E 20, No 4, 915 (2011).

[5] Liu Z.H. et al., Asymptotic normalization coefficients and neutron halo of the excited states in $^{12}$B and $^{13}$C // Phys. Rev. C 64, 034312 (2001).

[6] Belyaeva T.L. et al., Determination of neutron halo radii in the first excited states of $^{13}$C and $^{11}$Be with the asymptotic normalization coefficients method // Phys. Rev. C 90, 064610-1 (2014).

[7] Yamada T. and Funaki Y. Cluster states and alpha particle condensation in $^{13}$C // Int. J. Mod. Phys. E 17, 2101 (2008).

[8] Оглоблин А.А. и др., Возможное наблюдение в ядре $^{13}$C возбужденного состояния с аномально малым радиусом // Письма в ЖЭТФ, V. 102, No 4, 199 (2015).

[9] Furutachi N., Kimura M. Bent three-α linear-chain structure of $^{13}$C // Phys. Rev. C 83, 021303 (2011).

**А.С. Демьянова[1], А.Н.Данилов[1], Н. Буртебаев[2], Д.М. Джансейтов[2,3], Ж. Керимкулов[2], Д.К. Алимов[2], Е.С. Мухамеджанов[2]**

[1] ҰЗО Курчатов Институты, Мәскеу, Ресей;
[2]Ядролық Физика Институты, Алматы, Қазақстан;
[3] Еуразия Ұлттық Университеті, Астана, Қазақстан

## $^{13}$C ЯДРОСЫНЫҢ ЭКЗОТИКАЛЫҚ КҮЙЛЕРІНІҢ РАДИУСТАРЫ

**Аннотация.** Осы жұмыста 90 МэВ энергияларда α–бөлшектердің $^{13}$C ядроларында серпімді және серпімсіз шашырауының дифференциалды қималарының нәтижелері көрсетілген. Модификацияланған дифракциялық модел шеңберінде $^{13}$C ядросының 8.86 (1/2$^{-}$), 3.09 (1/2 $^{+}$) және 9.90 (3/2$^{-}$) МэВ қозған күйлерінің орташа квадратталған радиустары (<Rrms>) есептелді. $^{13}$C ядросының қозған бірінші екі күйлердің радиустары, негізгі күй радиусымен салыстырғанда, анағұрлым үлкен. Қосымша, қозған 9.90 МэВ күйінің радиусы үшін аномальды кіші шамасы алынды.

**Тірек сөздер:** қозған күйлердің радиустары, модификацияланған дифракциялық модель, нейтрондық гало.

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**А.С. Демьянова[1], А.Н.Данилов[1], Н. Буртебаев[2], Д.М. Джансейтов[2,3], Ж. Керимкулов[2], Д.К. Алимов[2], Е.С. Мухамеджанов[2]**

[1]НИЦ Курчатовский Институт, Москва, Россия;
[2]Институт Ядерной Физики, Алматы, Казахстан;
[3]Евразийский Национальный Университет, Астана, Казахстан

## ЭКЗОТИЧЕСКИЕ СОСТОЯНИЯ ЯДРА $^{13}$C С АНОМАЛЬНЫМИ РАДИУСАМИ

**Аннотация.** В данной работе представлены результаты измерения дифференциальных сечении упругого и неупругого рассеяния α+$^{13}$C при E(α) = 90 МэВ. В рамках модифицированной дифракционной модели (МДМ) определены среднеквадратичные радиусы (<Rrms>) возбужденных состояний: 8.86 (1/2$^{-}$), 3.09 (1/2 $^{+}$) и 9.90 (3/2$^{-}$) МэВ ядра $^{13}$C. Радиусы первых двух уровней увеличены по сравнению с радиусом основного состояния ядра $^{13}$C, что подтверждает предположение, что состояние 8.86 МэВ является аналогом состояния Хойла в ядре $^{12}$C и состояние 3.09 МэВ имеет нейтронное гало. Дополнительно, получены аномально небольшие размеры для состояния 9.90 МэВ.

**Ключевые слова:** радиусы возбужденных уровней, модифицированная дифракционная модель, нейтронное гало.