Conference Paper

# Nuclear states with abnormal radii

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## Abstract

The radius of a nuclear state is one of the most important its characteristics. Presently there were developed some methods exploiting special features of the nuclear reactions leading to short – lived excited states and allowing determination of their radii. Evidence of existing nuclear excited states with enhanced radii (size isomers) was obtained.

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## 1. Introduction

The size of a nucleus defined by the radius of its nucleon (proton and neutron) density distribution and the proton charge distribution is one of the most fundamental and important nuclear characteristics. Nuclear radius determines the basic properties of nuclei and is a consequence of the fundamental features of the strong interaction. Even a moderate deviation from its standard value may be connected with a radical change of nuclear structure. Our analysis of some nuclear reactions provided evidence that there exist several excited states in $^{9}$Be, $^{11}$Be, $^{11}$B, $^{12}$C, $^{13}$C whose radii exceed the radii of their ground states by ~20-30%. We specified these dilute states by name nuclear size isomers [1].

In this review, we summarize the results of measuring and analysis of the radii of the short-lived excited states by applying three direct methods: a recently developed modified diffraction model (MDM), the inelastic nuclear rainbow scattering method (INRS) and the asymptotic normalization coefficients method (ANC).

## 2. Results and discussion

## 2.1. Methods

A diffraction scattering model [2], a fairly rough approximation for calculating the differential cross sections, is quite adequate to determine nuclear radii from experiments on inelastic and elastic scattering. MDM operates only with a single parameter having the dimension of length, the diffraction radius $R_{dif}$, which is directly determined from the positions of the minima (maxima) of the experimental angular distributions. This means that the radius of the state is obtained from the radial distribution of absorption (imaginary part of the interaction potential) because the latter mostly determines the diffraction patterns. Due to this the real part of the potential cannot be extracted from diffraction scattering because it is screened by absorption. The radius enhancement exhibit itself from the shift of the minima (maxima) to smaller angles (Fig.1). The main assumption of the model is that the root-mean-square radius $<R^* >$ of a nucleus in the excited state is determined by the difference of the diffraction radii of the excited and the ground states. In Fig.1 the diffraction radius of the 7.65 MeV state (so-called Hoyle state) occurred to be $\sim$ 0.5 fm larger than those of the ground and the first excited states and, according to the MDM the same difference takes place also for the rms radii.

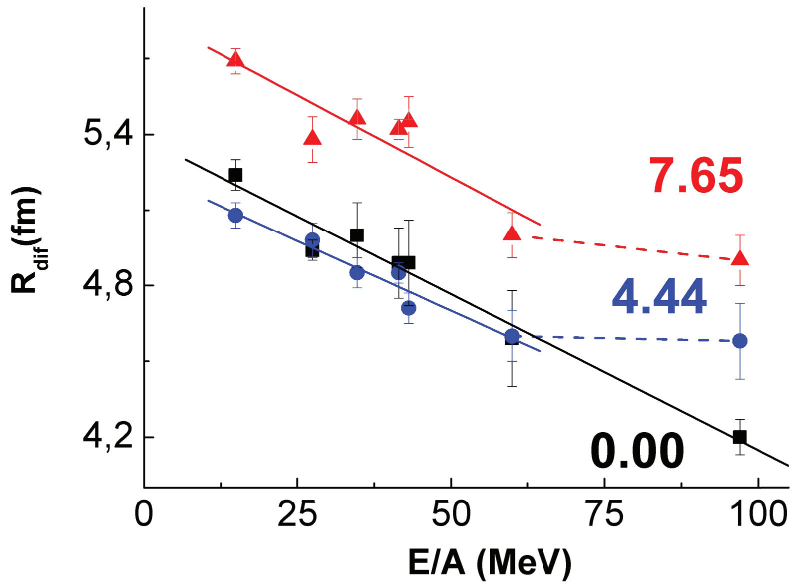


**Figure** 1: Energy dependence of the diffraction radii for the α + $^{12}C$ system determined from elastic scattering (filled squares) and inelastic scattering to the 4.44-MeV $2^+$ state (rhombuses), the 7.65-MeV $0^+$ state (triangles).

A similar result was obtained by the INRS. The nuclear rainbow angle depends on the trajectory of the particle passing through the target nucleus and, consequently from its real radius [3, 4]. MDM and INRS are complimentary because they reconstruct the same radius from different parts of the differential cross-section and uncertainties of both models could be, at least, partly to be eliminated. The enhancement of the radius of the excited state exhibits itself as a shift of the corresponding rainbow angle to the larger ones, contrary to behaviour of diffraction radii. Both effects are shown in Fig.2.

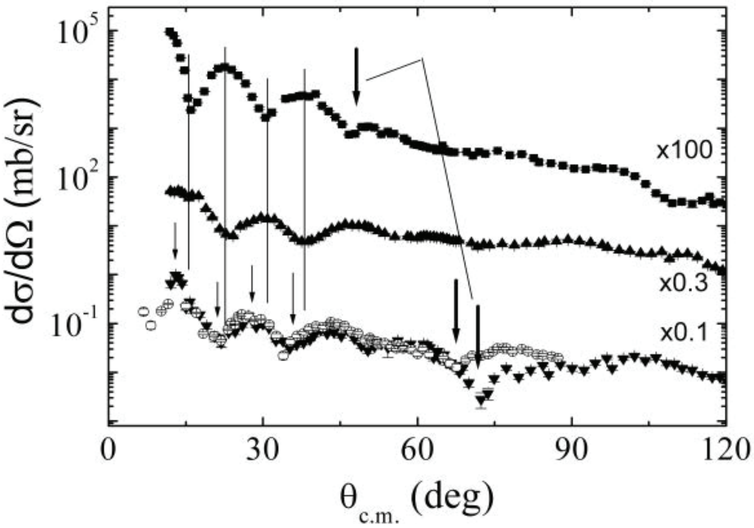


**Figure** 2: Differential cross sections of the α + $^{12}$C scattering. The upper and medium curves denote the elastic scattering and inelastic scattering to the $2^+$, 4.44 MeV at $E_\alpha$ = 60 MeV [5]. The lower curves refer to the inelastic scattering exciting the $0^+_2$, 7.65 MeV Hoyle state at $E_\alpha$ = 60 MeV (filled triangles) and 65 MeV (open circles). Thin arrows denote the diffraction minima (maxima), thick ones show the Airy minima. Small shift of the Airy minima with energy confirms the rainbow feature of the cross-sections.

In addition to the MDM and the INRS methods which deal with empirical systematic "angle – radius" and determining the rms radii, the ANCs may substitute the spectroscopic factors for the peripheral reactions [6, 7] and measure directly the radius of the valence neutron. As the model of ANC is theoretically proved this makes comparisons with its conclusions especially valid. Unfortunately, ANC method can be used only with transfer reactions contrary to the MDM and INRS models which are more universal. Due to this the ANC model can be adequately applied for determining the radii of the nuclei having neutron halos. Our recent studies [8] allowed performing a critical test of all three models by determining the radius of the 3.09-MeV $1/2^+_1$ state of $^{13}$C known to have a neutron halo. Comparison of the results obtained by the MDM, ANC, and INRS analysis, as well as some theoretical calculations orthogonal condition method, OCM) is presented in Table 1. One can see that a reasonable agreement was achieved providing both evidence of identity of all three methods and confirming capability of the MDM and INRS to get information of the radius of halos.

Table 1: Summary of rms matter and halo radii for the 3.09-MeV 1/2$^+$ state of $^{13}$C.

| Method | $R_{rms}$ (fm) | $R_h$ (fm) |
|---|---|---|
| MDM [9] | 2.74 ± 0.06 | 5.88 ± 0.40 |
| MDM [10] | 2.92 ± 0.07 | 6.99 ± 0.41 |
| ANC [7] | 2.62 ± 0.20 | 5.04 ± 0.75 |
| ANC [8] | 2.72 ± 0.10 | 5.72 ± 0.16 |
| INRS [10] | 3.0 ± 0.1 | 7.4 ± 0.6 |
| OCM [11] | 2.68 | 5.47 |
| $R(^{12}C)+\hbar(\mu\varepsilon)^{-1/2}$ | 2.7 | |

## 2.2. Neutron and proton halos

We focused our attention on two types of size isomers: the excited states in light nuclei possessing neutron halos and α-cluster structure.

Neutron halos were studied in a numerous number of works and some myths about their properties seem to be established. Among them are:

# Halos are the immanent property exclusively of the drip-line nuclei;

# Halos are formed only in the ground states of nuclei;

# Halos exist only in particle-stable states due to the “long tail” of the valence neutron wave function;

# Studying of halos always requires use of radioactive nuclear beams.

New investigations using the methods describing above showed that all these statements should be seriously corrected. This is well demonstrated by comparison of the level schemes of the typical one-neutron halo nucleus $^{11}$Be and $^{9}$Be (Fig. 3).

Both nuclei have similar positive parity rotational bands with almost the same moment of inertia, and Fig. 3 clearly shows that there is no difference between both bands. The radii of the excited states were measured by application of MDM to the α-scattering. Those in the case of $^{9}$Be are significantly larger than that of the ground state indicating to a halo structure. However, $^{9}$Be is stable and locates quite far from the drip-line. Its positive parity rotational band completely belongs to the continuum, while that of $^{11}$Be lies only partly in discreet spectrum. Thus, the presented pair of nuclei demonstrates conditional character of previous ideas about halo. Moreover, the obtained result provides evidence for a new type of a halo, the rotating one.

Our very recent results showed that MDM possibly can be applied to the analysis of a more wide scope of nuclear reactions. The analogy between inelastic scattering

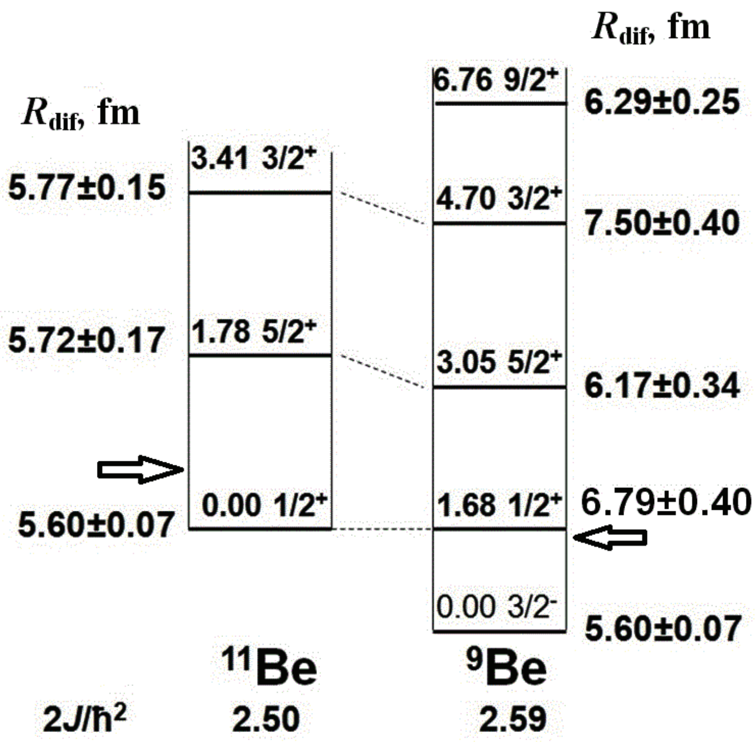


**Figure** 3: Plot of the energy levels of $^{11}$Be and $^{9}$Be belonging to the positive parity rotational bands. The moments of inertia are indicated in the bottom line. The diffraction radii from $^{11}$Be + $^{12}$C scattering at $E(^{11}$Be) = 737 MeV and α + $^{9}$Be at $E$(α) = 30 MeV are shown in the left and right columns. Neutron emission thresholds are specified by arrows.

and charge-exchange reactions is known for a long time. If so, some of reactions of this type, say ($^{3}$He,t)-reactions, would provide a new tool for studying halos in isobar-analog states. Comparison of the $^{13}$C($^{3}$He,t)$^{13}$N-reactions, inelastic and elastic scattering $^{13}$C+ $^{3}$He [12] allowed identification of a proton halo in the 2.37 MeV state of $^{13}$N which is a mirror one to the 3.09 MeV state in $^{13}$C. It is interesting to note that the radii of both states practically coincide, though the wave functions of the valence proton and neutron nucleons are different due to location of them above and under the threshold (Fig. 4).

Observation of halos in nuclei located not only in discreet spectra, but also in continuum and isobar-analogs considerably widen the existing conceptions on nuclear structure and require more both experimental and theoretical studies.

### 2.3. Alpha-clusters

Alpha-particle scattering experiments (e.g., [13]) led to observation of quite a number of states with enhanced radii. A good example is shown in Fig. 5. The Hoyle state of $^{12}$C became as a key object for testing some modern cluster theories. This state plays extremely important role in Nature because it is responsible for the existence of

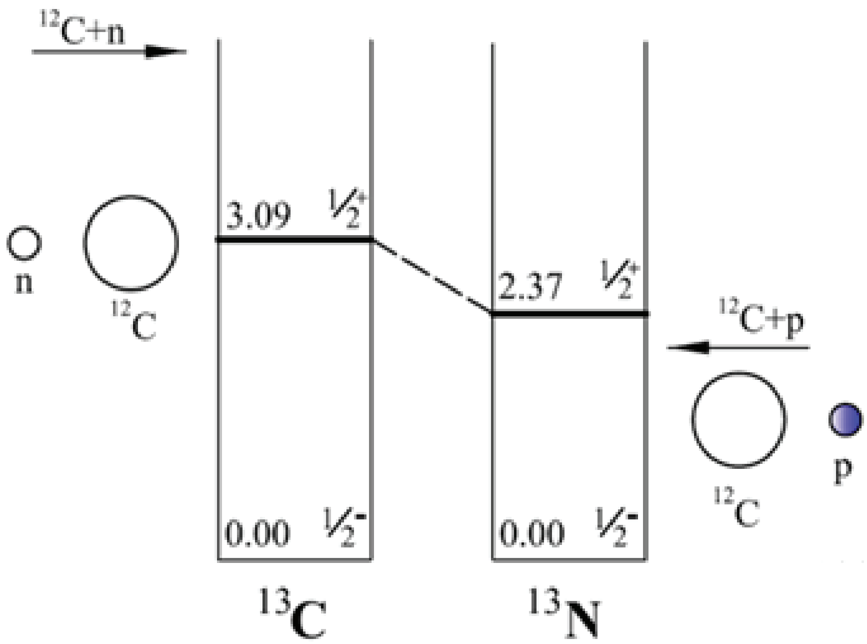


**Figure** 4: Halos in mirror states of $^{13}$C and $^{13}$N.

Table 2: Summary of the rms matter radii of the $0^+_2$, 7.65-MeV Hoyle state in $^{12}$C.

| **$R_{rms}$ (fm)** | 4.31 | 3.83 | 3.53 | 3.47 | 3.38 | 3.22 | 3.27 | 2.93 | 2.90 | 2.4 | 2.89 ± 0.04 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ref.** | [14] | [15] | [16] | [17] | [18] | [19] | [20] | [21] | [22] | [23] | Exp. [2] |

nuclei heavier than Helium in Universe. A lot of theoretical models of its structure were proposed and plenty of attention in the two last decades was devoted to a hypothesis of existence of α-particle Bose-Einstein condensation (αBEC). According to the latter model, a dilute α -cluster structure resembling a gas of almost non-interacting α-particles was proposed for this state. Estimates of the αBEC model ($R_{rms}(0^+_2)$ = 4.31 fm) [14] is nearly twice as large as the radius of the ground state (2.34 fm). Thus, experimental determination of it became a challenge to experimental physics.

The experimental value of the Hoyle rms radius determined by the MDM from alpha-particle scattering at various energies was found to be $\langle R \rangle$ = 2.89 ± 0.04 fm [2]. The result was confirmed by INRS method [4]. Still, almost all theoretical models also predicted an enhanced radius of the Hoyle state, so it is not so easy to choice between them.

Attention focused on the exotic structure of the Hoyle state was than extended to the neighboring $^{11}$B and $^{13}$C nuclei which differ from $^{12}$C by a proton hole and an extra neutron, correspondingly. The positions and quantum numbers of the state 8.56MeV ($3/2^-$) in $^{11}$B and 8.86 ($1/2^-$) in $^{13}$C satisfy to the requirements of the Hoyle states

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analogs. The values of their rms radii being close to that of the Hoyle state confirmed this suggestion [1].

Study of $^{11}$B showed that the existence of states with enhanced radii is not too unusual situation. Fig. 5 shows that the states with "normal" radii are located at the excitation energies below ∼ 7 MeV. A whole group of size isomers appears at higher excitation energies mixed with the normal ones (only one of them is shown in Fig. 5). Most of them have alpha cluster structure and belong to rotational bands [1].

The most interesting prediction made by the αBEC model was a hypothesis that some of the states in $^{11}$B and $^{12}$C should have really gigantic sizes [14, 24], about $<R>$ ∼ 6 fm what is comparable with those of Uranium. Of course, such suggestion was a challenge to experimentalists. We analyzed the existing data and came to conclusion that the theory was confirmed in no case.

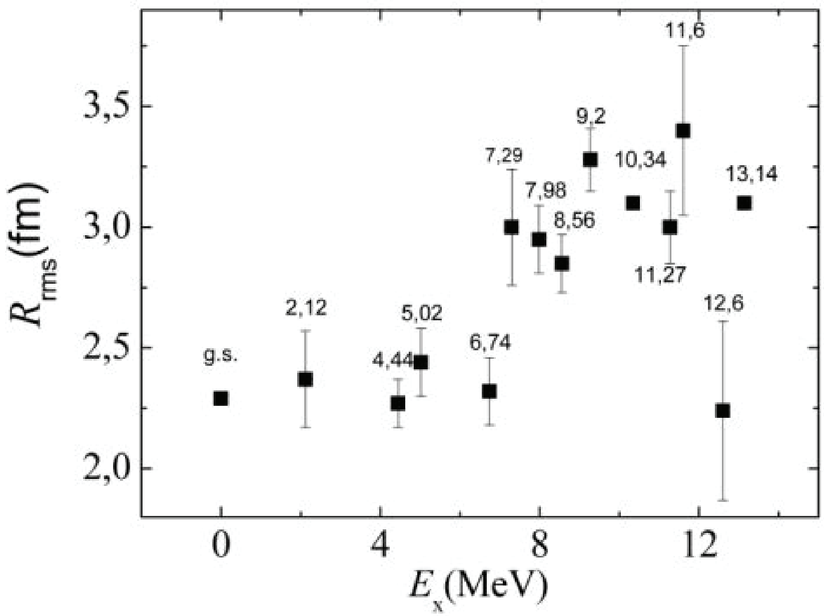


**Figure** 5: Radii of different states in $^{11}$B.

Especially important seems the result concerning the $^{16}$O [25]: the 15.1 MeV, $0^+$ state was considered by αBEC as a natural expansion of the model to heavier nuclei and be critical to the whole theory. The rms radius of the state was predicted to be $<R>$ = 5.6 fm. The theoretical prediction of the corresponding diffraction radius denoted by an open star lies far from the experimental value (filled star) whose position is undistinguishable from the radii of the state with different structures. Thus the result obtained by the MDM analysis (Fig. 6) demonstrates strong disagreement with the predictions of αBEC theory similarly to the result obtained for "gigantic" states of $^{11}$B

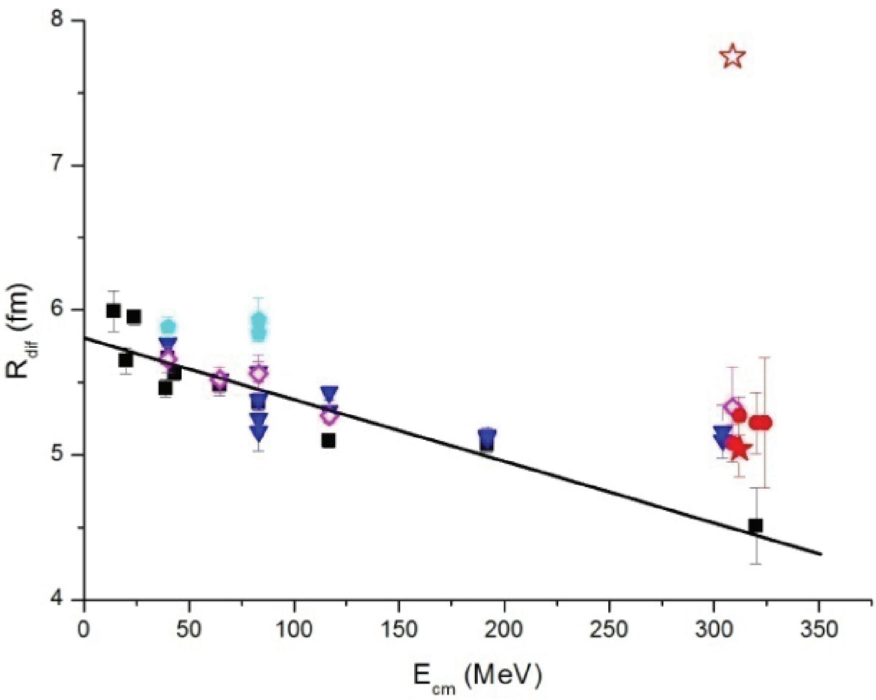


**Figure** 6: Energy dependence of diffraction radii extracted from the MDM analysis of α + $^{16}O$ elastic and inelastic scattering data. The solid line represents a linear approximation of the elastic scattering data. The diffraction radii for the elastic scattering, $1^-$, $2^+$, $3^-$, and $0^+$ states are denoted by filled squares, pentagons, triangles, rhombuses, and circles, correspondingly. The extracted diffraction radii for the 15.1-MeV $0^+_6$ state is marked by a filled star, while a prediction from [26] is pointed out by an open star. The radii of some states measured at 386 MeV are slightly shifted for convenience of observation.

and $^{12}C$. Besides, a good applicability of the MDM is seen. The states of $^{16}O$ of different structure and probably with similar radii locate approximately on the same line up to the energy ∼ 200 MeV. For the observed deviation from the line at about 300 MeV the inadequacy of diffraction mode seems to be responsible because the observed deviation at higher energies concerns all the states.

## 2.4. "Supercompact" size isomers: excited states with anomalously small radii

Recently we have revealed that even more exotic structure can exist [27]. The rms radius of $^{13}C$ in the 9.90-MeV $3/2^-$ state obtained by the MDM analysis of the inelastic α-scattering was found 1.89 ± 0.14 fm, i.e. noticeably smaller than the radius of $^{13}C$ in the ground state (2.33 fm).

An anomalously small radius of the 9.90-MeV state also follows from the comparison of the differential cross sections for the inelastic α + $^{13}C$ scattering populating three states of $^{13}C$ with the same transferred angular momentum $L$ = 2 and close excitation

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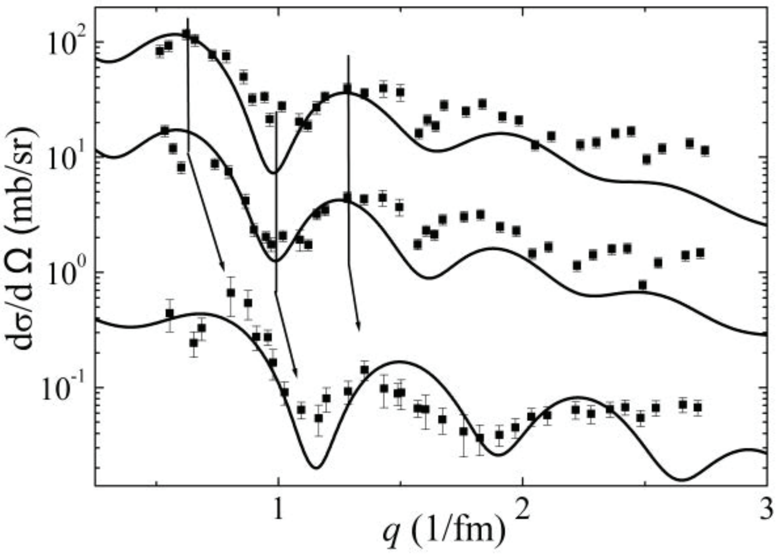


**Figure** 7: Differential cross sections of the inelastic α + $^{13}$C scattering populated the states with $E_x$ = 3.68 MeV (cross section is multiplied by a factor of 10), 7.55 MeV, and 9.90-MeV 3/2$^{--}$ at $E$(α) = 90 MeV. The DWBA calculations with the angular momentum transfer $L$ = 2 are shown by solid lines. The vertical lines are drawn through the diffraction minima and maxima of the cross sections leading to the excitation of the states with $E_x$ = 3.68 and 7.55 MeV. The arrows denote the positions of the extremes of angular distributions relating to the formation of the 9.90-MeV 3/2$^{--}$state.

energies (Fig. 7). If positions of the extremes had been in line in all angular distributions then the diffraction radii had to be identical. The shift toward larger momentum transfer, which is observed for the 9.90-MeV level, in fact indicates to a decrease of its radius. It is interesting to note that that normally this level was considered as a head of the rotational band 3/2$^{--}$(9.90 MeV) - 5/2$^{--}$(12.13 MeV) - 7/2$^{--}$(14.98 MeV), but having an enhanced radius.

These properties of the 9.90-MeV 3/2$^{-}$ state of $^{13}$C provide reason to consider this state as an example of a supercompact size isomer.

## 3. Conclusions

Measuring the radii of the short-lived nuclear excited states for a long time was considered as unachievable. Now there exist three methods that allow realizing such investigations: the modified diffraction model, inelastic nuclear rainbow scattering, and asymptotic normalization coefficient method. Though all the methods are model-dependent, and some their details and application areas require further refinement, unique information on nuclear structure was obtained.

The main result consists in discovery of nuclear states with abnormal radii, which we have named *nuclear size isomers*. Among them one may single out two groups of excited states: those with neutron halos and alpha-cluster states. Some of them were predicted by modern nuclear models, some not, providing a challenge to theory. An intriguing feature of these results is that most of these exotic structures were observed in stable nuclei $^{9}$Be, $^{11}$B, $^{12}$C, $^{13}$C in experiments with stable beams quite far from the modern mainstream.

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