NEUTRON HALO ROTATION IN ^{11}Be AND ^{9}Be AND MEASURING THE RADII OF NUCLEAR EXCITED STATES

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The results of the experiment performed by Kurchatov – Tsukuba – Almaty collaboration at the tandem of Tsukuba University are presented. All the known states of ^{9}Be up to the excitation energies ~ 12 MeV were observed. It is possible, all the low laying ^{9}Be states could be decomposed into three rotational bands, each having cluster structure ^{8}Be core plus a valence neutron in one of the orbits: $p_{3/2-}$, $s_{1/2+}$ and $p_{1/2-}$.

1. Introduction

^{9}Be belongs to the most interesting nuclei among the stable ones. It is characterized at least by two features typical to some exotic nuclei at the neutron drip line: low binding energy (1.67 MeV) and Borromean structure $\alpha + \alpha + n$ (each pair combination $\alpha + \alpha$ (^{8}Be) and $\alpha + n$ (^{5}He) is unstable). The cluster configuration of ^{8}Be + n dominates in the internal structure of ^{9}Be (see [1] and refs. there), however, the ^{5}He + ^{4}He one also can play some role [2]. Possessing very large deformation parameter ^{9}Be has two well developed rotational bands (π- band, $K = 3/2^{-}$) and (σ-band, $K = 1/2^{+}$) based on the ground and the first excited (1.68 MeV) states correspondingly. Accordingly, the both bands are characterized by large moments of inertia, which are either equal to that of ^{8}Be (the π-band) or even larger (σ-band).

All the members of the both bands except for the ground state lie in the continuum. The position of the σ-band head state (1.68 MeV) exceeds the neutron emission threshold only by 15 keV, making the study of its properties a problem of self-dependent interest (a virtual state [2], "dynamical" evolution of the structure [3]). Besides, 1.68 MeV state plays some role in the r-process of nucleosynthesis in the supernova explosions [4].

Though the ^{9}Be spectrum has been studied quite extensively some open questions concerning its level scheme still remain. Only few higher member-states are identified in each abovementioned rotational band ($5/2^-$ and $7/2^-$ in the π- band and $5/2^+$, $3/2^+$ and $7/2^+$ in the σ- one). The $9/2^-$ and $7/2^+$ states are not reliably identified. There are also some states at the excitation energies less than 10 MeV (2.78 MeV, ½- and 7.98 MeV,) which were not identified as the rotational ones. Existence of the 5.59 MeV ($3/2^-$) level reported only in one publication [5] requires confirmation.

The interest to ^{9}Be spectroscopic studies was recently renewed in view of observation [6] of strong enhancement of the radius of the $1/2^+$, 1.68 MeV state, which was interpreted as a manifestation of a neutron halo. Striking similarity between the positive parity rotational bands in ^{9}Be and ^{11}Be noted in Refs. [6] (the ground state of the latter is a standard of a one-neutron halo, and the radii of two higher member-states also occurred to be enhanced) confirmed this conclusion. Earlier, a conception of a neutron halo was not applied to the states located in continuum. It is interesting to note that basing on the criteria [7] one might expect the appearance of a neutron halo already in the ground state of ^{9}Be. However, the value of its *RMS* radius does not go out from the normal systematics.

The radius of the 1.68 MeV state was determined in Refs. [6] by the analysis of the inelastic scattering differential cross-sections in the diffraction angular region in the frame of the modified diffraction model, MDM [8]. However, the experimental data used in [6] were obtained before in a single work [9] in the ^{9}Be + α scattering at 35 MeV and only partly satisfied to the requirements of the MDM application. In particular, the radii of the higher members of the σ-band could not be extracted in Ref. [6]. Besides, the practice of the MDM use (see [6, 8] and refs. there) demonstrated that the analysis of the data obtained only at one energy could include quite large uncertainties.

In the present work we performed studying of the inelastic ^{9}Be + α scattering at E (α) = 30 MeV leading to the population of the ^{9}Be excited states up to the energies ~ 12 MeV. The experiment has two main aims: 1) to determine the levels radii by use of the MDM and 2) get new spectroscopic information. The measurements were done at the Tsukuba University tandem accelerator by the Enge type magnetic spectrograph.

2. Results

A sample linear momentum spectrum covering the excitation energies E* ~ 12 MeV is shown in Fig.1. Only three relatively narrow groups corresponding to the excited states 1.68, 2.43 and 3.05 MeV are well distinguished. The other known levels at these excitation energies are quite broad (Γ = 0.7 – 1.3 MeV), and their separation from the background is not a completely unambiguous task. We approximated the background by a smooth curve described by a polynomial connecting the phase volume near the threshold with the minima in the regions of the channel numbers ~ 1700 and 3700. The unresolved bump centered at ~ 6.5 MeV was decomposed into two groups corresponding to the 6.38 MeV ($7/2^-$) and 6.76 MeV ($9/2^+$) states with the widths taken from Ref. [10]. Thus, all the known states belonging to both rotational bands: $3/2^-$(0.00) - $5/2^-$ (2.43) - $7/2^-$(6.38) and $1/2^+$ (1.68) - $5/2^+$ (3.05) - $3/2^+$ (4.70) - $9/2^+$ (6.76), were identified.

No well-formed group corresponding to the known level $1/2^-$, 2.78 MeV, Γ = 1.08 MeV[10] was clearly observed in our measurements. The latter manifests itself as some widening of the basement of a strong peak corresponding to the 3.05 MeV state. Our data confirm the existence of a broad 5.59 MeV which was seen until now only in a single work [5] and whose parameters were determined there as $I^\pi = 3/2^-$, Γ = 1.33 MeV.

At the excitation energies higher ~ 7 MeV a bump at 11 – 12 MeV was observed. Two states at 11.28 MeV (Γ = 575 keV) and 11.82 (Γ = 400 keV) MeV are known, and we performed the decomposition of the mentioned bump into the components corresponding to these particular levels. Their spin – parity assignments are contradictory. According to extrapolations based on the experimental moments of inertia they could correspond to $9/2^-$ or $7/2^+$ members of the rotational bands. However, a rather recent compilation [10] gives $7/2^-$ and $5/2^-$ assignments to the known 11.28 and 11.82 MeV levels correspondingly. On the other hand, it was suggested for the 11.28 MeV state $I^\pi = 9/2^-$ [9] or $7/2^+$ [5]. An attempt to determine their spin-parity assignments we performed by the analysis the corresponding angular distributions. A known broad state at 7.94 MeV was not observed in our measurements.

The differential cross-sections of the ^{9}Be + α inelastic scattering at 30 MeV were measured. Using the Modified diffraction model (MDM) [8] the estimates of the radii values of some states have been done. All four first states belonging to the positive parity rotational band (1.68 – 3.05 – 4.70 – 6.76 MeV) have the radii significantly larger than the radii of the members of the ground state band (0.00 – 2.43 – 6.38 MeV). This finding and the comparison with the positive parity rotational states of ^{11}Be whose parameters are quite similar to those of the ^{9}Be band, clearly indicate to their neutron halo structure as it was suggested in [6] on the basis of some limited data. The states 2.78 – 5.59 – 7.94 MeV ($1/2^-$ - $3/2^-$ - $5/2^-$) possibly form the third rotational band: extrapolation to the state $7/2^-$

predicts the excitation energy of the latter level to be ~13.8 MeV, the value which is consistent with the existing data (see refs. in [10]). If so, all the low laying ^{9}Be states could be decomposed into three rotational bands, each having cluster structure ^{8}Be core plus a valence neutron in one of the orbits: $p_{3/2-}$, $s_{1/2+}$ and $p_{1/2-}$.

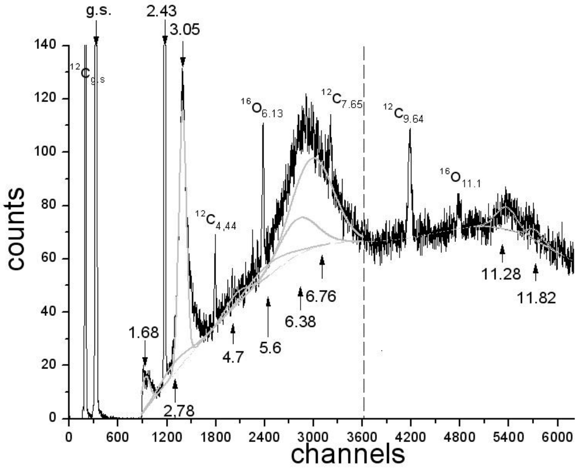

Figure 1. Typical spectrum for $\alpha+^{9}Be$ scattering at E_{α}=30MeV, θ_{lab}=20˚. Vertical dashed line shows place of connection of two spectrum parts after measurements by the magnetic spectrometer. Dashed-dotted line represents background. States of ^{9}Be are shown by arrows.

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