EPJ Web of Conferences **66**, 02026 (2014)
DOI: 10.1051/epjconf/20146602026

Spectroscopy of ^{9}Be and observation of neutron halo structure in the states of positive parity rotational band

A.S. Demyanova[1a], A.A. Ogloblin[1], A.N. Danilov[1], S.V. Dmitriev[1], S.A. Goncharov[2], N. Burtebaev[3], J. Burtebaeva[3], N. Saduev[4], T.L. Belyaeva[5], H. Suzuki[6], A. Ozawa[6], Y. Abe[6], S. Fukuoka[6], Y. Ishibashi[6], S. Ito[6], T. Komatsubara[6], T. Moriguchi[6], D. Nagae[6], R. Nishikiori[6], T. Niwa[6], K.Okumura[6], H. Ooishi[6], K. Yokoyama[6], S. Kubono[7]

[1]NRC Kurchatov Institute, Moscow, Russia,
[2]Lomonosov Moscow State University, Moscow, Russia
[3]Nuclear Physics Institute, Almaty, Kazakhstan
[4]Al-Farabi Kazakh National University, Kazakhstan
[5]Universidad Autonoma del Estado de Mexico, Mexico
[6]Institute of Physics, University of Tsukuba, Japan
[7]RIKEN, Wako, Saitama, Japan

Abstract. The differential cross sections of the ^{9}Be + α inelastic scattering at 30 MeV were measured at the tandem of Tsukuba University. All the known states of ^{9}Be up to energies ~ 12 MeV were observed and decomposed into three rotational bands, each of them having a cluster structure consisting of a ^{8}Be core plus a valence neutron in one of the sub-shells: $p_{3/2^-}$, $s_{1/2+}$ and $p_{1/2-}$. Existence of a neutron halo in the positive parity states was confirmed.

1 Introduction

^{9}Be is one of the most interesting light nuclei. Possessing a developed α + α + n quasimolecular structure ^{9}Be is an excellent object for studying clustering phenomena in nuclei. Moreover, as ^{9}Be is the only stable Borrowmean nucleus it is natural to expect in it the manifestation of some structural features typical to exotic nuclei near the drip-lines including the existence of a neutron halo. Though ^{9}Be structure was studied in numerous works (see, e.g. a review [1]) many important open questions remain.

There are known two well-developed rotational bands in ^{9}Be. One of them is based on the ground state 3/2‾ (π-band, K = 3/2‾) and is expected to have a strong cluster ^{5}He + ^{4}He configuration. The head of the second band is the first excited state $1/2^+$, 1.68 MeV (σ-band, K = $1/2^+$) located only 15 keV above the ^{8}Be + n threshold. This particular level was the object of intensive theoretical study and is considered to be either a virtual state [2] or a combination of ^{5}He + ^{4}He and ^{8}Be + n configurations [3]. Accordingly, both bands are characterized by large moments of inertia, which are either equal to that of ^{8}Be (the π-band) or even larger (the σ-band). Besides, there are some other states with the

[a] Corresponding author: a.s.demyanova@bk.ru

excitation energies less than 15 MeV with unknown structure and I^π assignment. Moreover, the very existence of some of them (e.g., 5.59 MeV [4]) requires confirmation.

Our analysis [5] of the data [6] done by the modified diffraction model, MDM [7] allowed determining the radii of some low lying excited states. The main result of these investigations was the observation of the abnormally large radius of the $1/2^+$, 1.68 MeV state and the conclusion that the latter has a neutron halo comparable with that of ^{11}Be. Earlier, a conception of a neutron halo was not applied to the states located in continuum.

In the present work we performed measurements 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 and continued the investigation of the halo effects in ^{9}Be. The experiment has two main aims: 1) determining the levels radii by use of the MDM and 2) getting new spectroscopic information. The measurements were done at the UTTAC (Tsukuba University tandem accelerator) by using EPS90 spectrograph. The single wire position sensitive proportional counter (SWPC) was installed in the spectrometer of E-course. Due to the specific properties of the magnetic spectrograph the spectra were measured in two steps: 1) up to excitation energy ~7 MeV and 2) from this value and higher. The target thickness was ~0.2 mg/cm^2 with impurities of ^{12}C and ^{16}O. The angular distributions were measured up to ~ 120° (Lab system).

2 Results

A sample linear momentum spectrum covering the excitation energies E* ~ 12 MeV is shown in Fig.1 (the left part). Contrary to many works the $1/2^+$, 1.68 MeV state was well resolved (Fig.1, the right part). The predicted [2] shape of the corresponding line well reproduces the data. The spectra were decomposed into separate groups corresponding to the known levels of ^{9}Be with the widths taken from Ref. [8]. All the known states belonging to both rotational bands: $3/2^-$ (0.00) - $5/2^-$ (2.43) - $7/2^-$ (6.38 MeV) and $1/2^+$ (1.68) - $5/2^+$ (3.05) - $3/2^+$ (4.70) - $9/2^+$ (6.76 MeV), were identified.

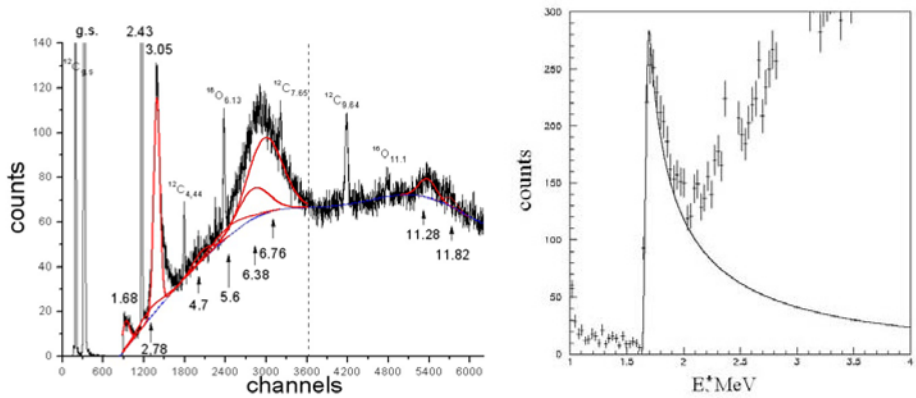

Figure 1. Left: A sample spectrum for α + ^{9}Be scattering at E_α=30MeV, θ_{lab}=20°. Vertical dashed line shows place of the connection of two spectrum parts measured separately. Dashed-dotted blue line represents the estimated background. States of ^{9}Be are denoted by arrows. Right: The part of the spectrum at θ_{lab}=7.5° near the threshold. The predicted [2] shape of the line corresponding to the 1.68 MeV state is shown.

The known level $1/2^-$ at 2.78 MeV manifests itself only 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 state which was observed until now only in a single work [4]. A bump at the excitation energy ~ 11 – 12 MeV was decomposed into two known states at 11.28 MeV and 11.82 MeV. A known broad state at 7.94 MeV could not be identified in our measurements because it got to the place of joining of both parts of the spectra measured separately. Moreover, the original aim of our experiment was not connected with the search of the third rotational band.

The angular distributions of the ^{9}Be + α inelastic scattering at 30 MeV were measured and shown in Fig. 2 together with the results of the DWBA calculations. Some disagreements may be connected with the influence of the ^{5}He transfer reaction reflecting the predicted [1, 3] contribution of the ^{5}He + ^{4}He configuration in the ^{9}Be structure. The latter one possibly manifests itself in the strong oscillation structure at the backward angles (Fig.3), as observed at E (α) = 50 MeV [9].

Using the Modified diffraction model (MDM) [7] 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; Fig.2, right) have the radii significantly larger than the radii of the members of the ground state band (0.00 – 2.43 – 6.38 MeV; Fig.2, left). Thus, the radii enhancement was observed not only for $1/2^+$, 1.68 MeV state as it was claimed in Ref. [5] but in all members of the σ band indicating to its neutron halo structure (Table 1). As it was suggested in Ref. [5] K = $1/2^+$ band in ^{9}Be is similar to the K = $1/2^+$ one in ^{11}Be based on the ground state having a well-known neutron halo.

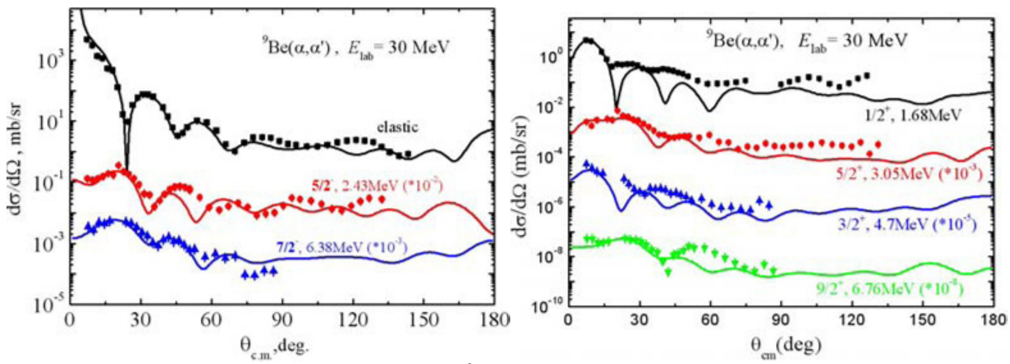

Figure 2. Differential cross-section of the α + ^{9}Be scattering at E (α) = 30 MeV corresponding to the excitation of the states of π – band (left) and σ – band (right) together with the DWBA calculations (solid lines).

Table 1. Transferred angular moments and diffraction radii obtained for π-band, K = $3/2^-$ and σ-band, K = $1/2^+$

E*, MeV, I^π	**g.s., $3/2^-$**	**2.43, $5/2^-$**	**6.38, $7/2^-$**	**1.68, $1/2^+$**	**3.05, $5/2^+$**	**4.7, $3/2^+$**	**6.76, $9/2^+$**
R_{dif}, fm	5.60±0.07	5.69±0.15	5.91±0.12	7.10±0.11	6.17±0.34	7.50±0.40	6.29±0.25
L	1	2, 4	2, 4	1	1, 3	1, 3	3, 5

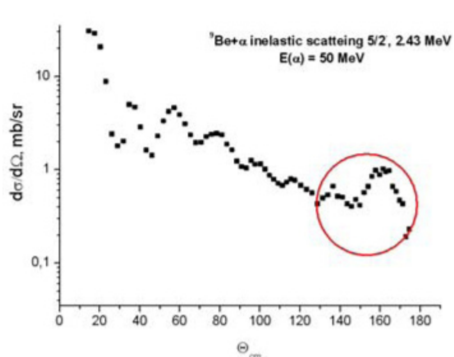

Figure 3. Differential cross section of the inelastic scattering to 2.43 MeV ($5/2^-$) state of the ^{9}Be + α at E (α) = 50 MeV [9]. Strong backward oscillations are seen.

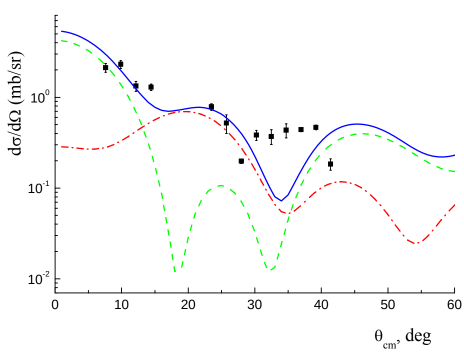

Figure 4. Differential cross-section of the α + ^{9}Be inelastic scattering to 5.59 MeV ($3/2^-$) state at E_α = 30 MeV with the DWBA calculations. The green curve corresponds to angular momentum transfer L =0, the red curve – L = 2, blue curve – the sum of both.

Differential cross section of the α + ^{9}Be inelastic scattering to the 5.59 MeV ($3/2^{-}$) state is shown in Fig.4. DWBA calculations show the important contribution of the transferred L = 0 angular momentum what indicates to the spin - parity $I^{\pi} = 3/2^{-}$ in agreement with Ref. [4]. This finding allows suggesting the existence of the third (K = $1/2^{-}$) rotational band: 2.78 ($1/2^{-}$) – 5.59 ($3/2^{-}$) – 7.94 ($5/2^{-}$) – 13.79 (π = -) in ^{9}Be (see Fig.5). If the K = $1/2^{-}$ band really exist it would mean that all the low laying ^{9}Be states could be grouped into three rotational bands having cluster structure ^{8}Be core plus a valence neutron in one of the sub-shells $p_{3/2-}$, $s_{1/2+}$, $p_{1/2-}$. The similarity of the moments of the inertia of the all three bands of ^{9}Be and that of ^{8}Be testify in favour of this assumption. Preliminary analysis using MDM gave the value of the diffraction radius of the 5.59 MeV state equal ~ 6.5 fm, what is approximately 1 fm larger than those of the ground state band.

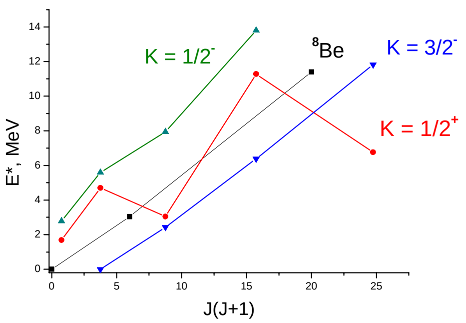

Figure 5. ^{9}Be rotational bands. K=$3/2^{-}$ corresponds to rotational band based on the ground state, K=$1/2^{+}$ — to rotational band based on the 1.68 MeV state, K=$1/2^{-}$ — to hypothetical rotational band based on the 2.78 MeV state.

3 Conclusions

Our high resolution experiment confirmed observation of the abnormally large radius of the $1/2^{+}$, 1.68 MeV state and the conclusion that the latter has a neutron halo comparable with that of ^{11}Be. Higher members of the positive parity band (3.05 – 4.70 – 6.76 MeV) also have enhanced radii relatively the states belonging to the negative parity band (0.00, $3/2^{-}$, 2.43, $5/2^{-}$ and 6.38 MeV, $7/2^{-}$). Some evidence of the existing of the third rotational band with K = $1/2^{-}$ based on the state $1/2^{-}$, 2.78 MeV was obtained.

The work was supported by the RFBR grant No 12-02-000927-a.

References

1. W. von Oertzen, M. Freer, Y. Kanada-En'yo, Phys. Rep. **432**, 43 (2006)
2. V.D. Efros, J.H. Bang, Eur. Phys. J. A **4**, 31 (1999)
3. E. Garrido, D.V. Fedorov and A.S. Jensen, Phys. Lett. B **684**, 132 (2010). I.J. Thompson, Comput. Phys. Rep. **7**, 167 (1988)
4. S. Dixit et al., Phys. Rev. C **43**, 1758 (1991)
5. A.A. Ogloblin, A.N. Danilov, T.L. Belyaeva, A.S. Demyanova, S.A. Goncharov and W. Trzaska, Phys. Rev. C **84,** 054601 (2011); Phys. of Atomic nuclei, **74,** 1581 (2011)
6. R.J.Peterson et al., Nucl. Phys. A **377**, 41 (1982)
7. A.N. Danilov et al., Phys. Rev. C **80**, 054603 (2009)
8. D.R. Tilley et al., Nucl. Phys. A **745**, 155 (2004)
9. N. Burtebaev et al., Jour.Voprocy Atomn. Nauki i Tekniki, Ser. Fiz.,Yad. Reak.v. **1/2**, 137 (2002)