The spectrum of ^{6}Be populated in the charge-exchange ^{1}H(^{6}Li,^{6}Be)n reaction

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Abstract.
^{6}Be spectrum populated in the charge-exchange ^{1}H(^{6}Li,^{6}Be)n reaction was studied experimentally. The known 0^+ ground state (g.s.) and excited 2^+ state were observed. Above the 2^+ state a broad energy hump extending up to 15 MeV is present in the spectrum. This hump is apparently composed of negative parity states and its interpretation as the isovector soft dipole mode connected to the ^{6}Li g.s. is suggested.

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INTRODUCTION

The ^{6}Be isotope has been for a long time the subject of experimental study. Out of the first series of experimental works the last one [1] was published far ago and only very recently two new experimental works [2], [3] were carried out. One should emphasize the two aspects of interest of this nucleus.
(i) The g.s. of ^{6}Be is particle unstable and this nucleus is the lightest ground state true two-proton ($2p$) emitter. $2p$ radioactivity is an exclusive quantum-mechanical phenomenon when a sequential decay is not possible and the three final-state fragments are emitted simultaneously [4].
(ii) The ^{6}Be nucleus is an isobaric partner of ^{6}He which is a classical halo nucleus. Enormous efforts has been invested in the recent two decades in the studies of the halo aspect of the ^{6}He structure. To examine the correlation in the neutron halo one has to excite or destroy the ^{6}He nucleus. This embarrasses the interpretation of experimental data because one has to take into account the reaction mechanism. Recently it has been demonstrated in Ref. [2] that a valuable alternative to study of ^{6}He itself could be a

precision study of correlations in the decay of ^{6}Be states.

This work is aimed at the study of the properties of the ^{6}Be continuum above the first excited state (2^+ state at $E_T = 3.03$ MeV; E_T is energy above the two-proton breakup threshold [6]). This part of ^{6}Be spectrum will be explained by the population of negative parity states. We will interpret such an exclusive population as a novel effect: the isovector soft dipole excitation mode. Having in mind the interest attracted by soft dipole mode studies in exotic dripline halo nuclei as a tool for nuclear structure and nuclear astrophysics we dedicate this work to prove the existence of such a new phenomenon.

EXPERIMENTAL SETUP

The experiment was carried out at the U400M cyclotron in the Flerov Laboratory of Nuclear Reactions, JINR (Dubna, Russia). The ^{6}Be spectrum was populated in the charge-exchange ^{1}H(^{6}Li,^{6}Be)n reaction. On one hand, this reaction was chosen because of its presumably simple mechanism. On the other hand, in this inverse kinematic case, the ^{6}Be decay products (α + p + p) fly out in relatively narrow cone in the forward direction in laboratory frame. The latter makes possible to detect all decay products with reasonable efficiency in a wide range of ^{6}Be excitation energy. Such condition allowed us to study the reaction in the whole angular range.

The 32 MeV/A ^{6}Li beam was delivered by the cyclotron and transported by the ACCULINNA fragment separator [5] into an experimental chamber. The beam with typical intensity of 3×10^7 s^{-1} was focused in an area of diameter 5 mm in the center of the cryogenic hydrogen target. 4 mm thick gas cell was filled with hydrogen at pressure of 3 bar and cooled down to a temperature of 35 K.

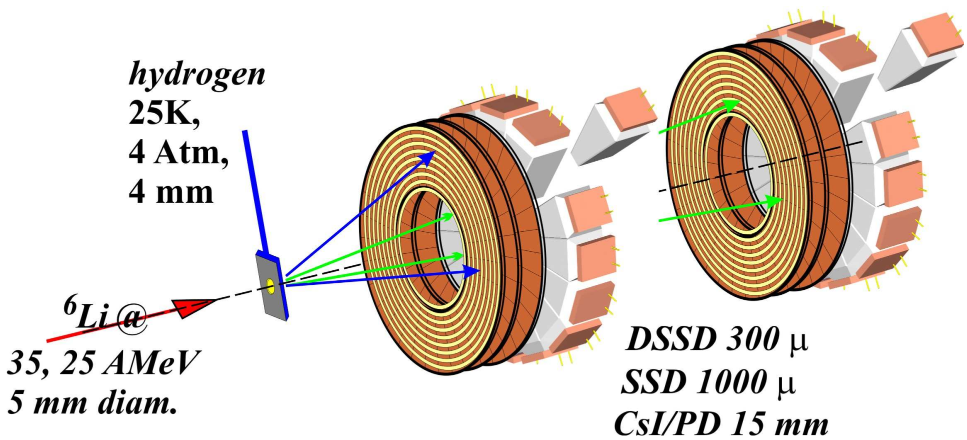

FIGURE 1. (color online) Detector system setup.

Reaction products were detected using two identical telescopes positioned 91 and 300 mm downstream of the target (see Fig. 1). Each telescope consisted of a 300 μm thick annular double side silicone strip detector (DSSD) and of a 1000 μm thick annular single side silicone strip detector (SSSD), both of them had an active area with the outer and inner diameters of 82 and 32 mm, respectively, and a 28 mm central hole. The silicon detectors were backed by 19 mm thick CsI(Tl) detectors forming an array with outer and inner diameters of 97 and 37 mm, respectively. The DSSD were segmented into 32 sectors on front side and 32 rings on back side providing position information of the measured particles. The SSSD and CsI(Tl) array were segmented into 16 sectors. Particle identification was performed by standard ΔE-E method. The angular ranges of the far and the near telescope were $3.2^\circ - 7.5^\circ$ and $10.9^\circ - 24.2^\circ$, respectively, in the laboratory system.

DATA ANALYSIS

In this work only the triple α + p + p coincidences, originating from the ^{6}Be decay, were analysed. Registration of the triple coincidences corresponded to the complete kinematical measurement for the ^{1}H(^{6}Li,^{6}Be)n reaction and allowed us to reconstruct all possible spectra and correlations.

Invariant mass spectrum

Invariant mass spectrum of ^{6}Be measured in the whole angular range is presented in Fig. 2. Two peaks in the spectrum at the energies E_T = 1.3 MeV and E_T = 3.0 MeV show the population of the known ground 0^+ and excited 2^+ states ([6] and Refs. therein). The width of the g.s. is 0.092 MeV [6]. Measured width of the ^{6}Be g.s. peak ($\sim$0.5 MeV) is determined by our experimental resolution.

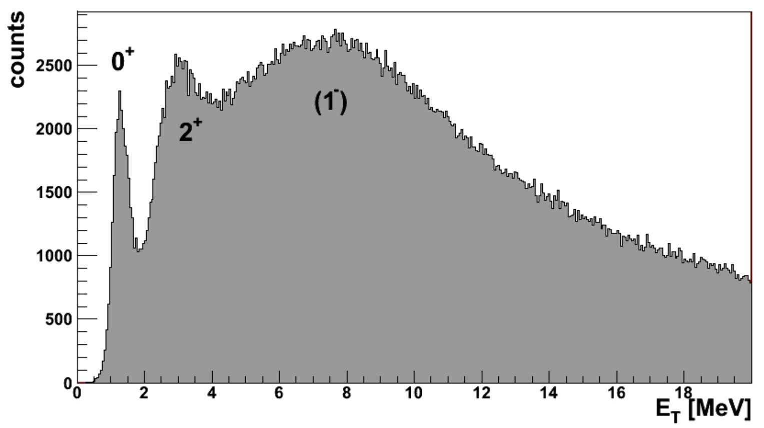

FIGURE 2. ^{6}Be invariant mass spectrum.

The main part of the counts in the spectrum comes from a broad hump centred at about 8 MeV. It should be noted that the shape of the spectrum shown in Fig. 2 is affected by the detection efficiency. In the case of triple coincidences the efficiency depends on many parameters. Generally, this function depends on the energy and angular correlations of the decay products. The calculations of efficiency were carried out on the basis of Monte Carlo simulations which take into account all details of the experimental setup.

Angular distribution

Fig. 3 shows a two-dimensional plot of the invariant mass energy versus the CM angle of ^{6}Be from the ^{1}H(^{6}Li,^{6}Be)n reaction. The left panel presents the measured data, the right panel shows the same data after correction for efficiency. In the presented spectra there are well pronounced three regions saving the positions of its maxima at different angles θ_{Be}. This fact allowed us to assume that this peaks correspond to the population of separate states and allowed us proceed to the analysis of this phenomena. As the first step of analysis we made effort to clarify the angular behaviour of the measured spectra (see Fig. 3). The whole angular range of the invariant mass spectrum was divided into 18 equal bins and each bin was corrected for efficiency. The whole spectrum could be represented as a sum of three terms corresponding to the known 0+, 2+ states and the broad structure above 4 MeV:

$$\frac{d\sigma}{dE_T d\theta_{Be}} = \sum_{i=1}^{3} f_i(\theta_{Be}) F_i(E_T) \tag{1}$$

Peaks at energies about 1.3 and 3.0 MeV were fitted using the Breit-Wigner profiles. For the broad hump between E_T = 4 MeV and E_T = 14 MeV the function suited to approximate the experimental data was chosen as.

$$\begin{aligned} \sigma_{J\pi} &\sim \frac{\Gamma_{J\pi}(E)}{(E-E_r)^2 + \left(\frac{\Gamma_{J\pi}(E)}{2}\right)^2}, \\ \Gamma_{J\pi}(E) &\sim \alpha \left(\frac{E}{^{(J\pi)}E_r}\right)^2 + (1-\alpha)\left(\frac{E}{^{(J\pi)}E_r}\right)^4, \\ \alpha &\sim 0.65\,,\ J\pi = \ 0+,2+; \quad \Gamma_{1-} \sim E_r^{3/2} \end{aligned} \tag{2}$$

An example of such a decomposition for an angular range of $30° - 40°$ is given in Fig. 4. The integral of (2) gives the population cross section for each state in the invariant mass spectrum (see Fig. 4).

The most forward focused state is 0^+, the first excited state 2^+ cross section is shifted to backward angles. The broad hump has a maximum in between of the g.s. 0+ and first e.s. 2^+ maxima. Based on this feature of the observed angular distributions we assume it reasonable to attribute a ΔL = 1 angular momentum transfer to the origin of this hump. Such a momentum transfer corresponds to the population of states in ^{6}Be with the most probable spin-parity J^π = 1^-. It should be emphasised that the cross section for the population of these negative parity states highly exceeds the population of the known 0^+ and 2^+ states. So we are dealing here with the strong effect in the population of the ^{6}Be continuum.

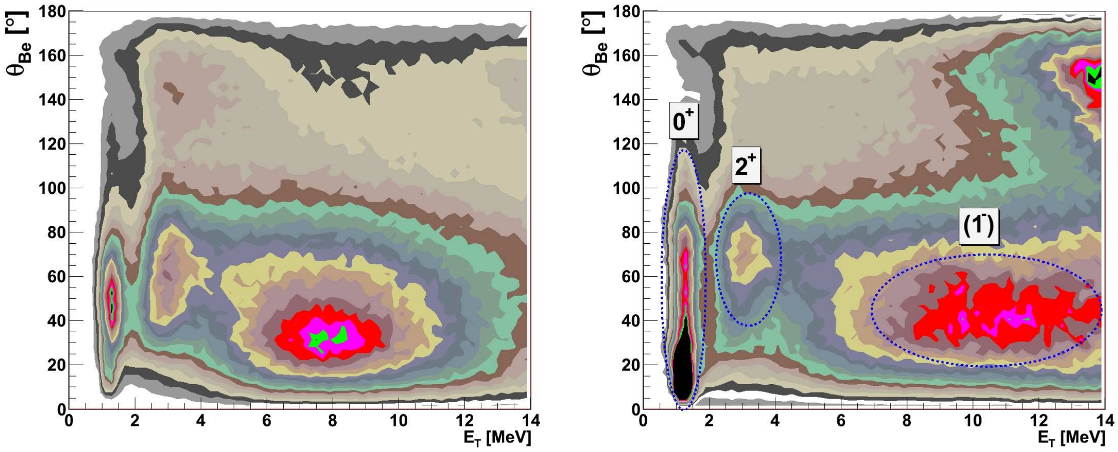

FIGURE 3. (color online) Invariant mass ^{6}Be energy versus θ_{Be}. The measured spectrum is shown in the left panel, the same data after correction for efficiency are shown in the right panel. In both spectra there are well visible three peaks depicted by dashed elipses. Position of these peaks does not depend on the angle θ_{Be}.

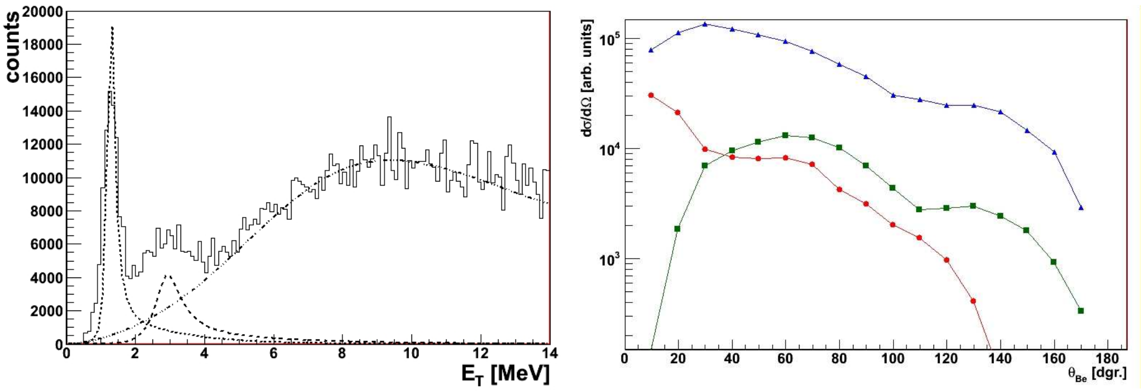

FIGURE 4. (color online) Left: Example of the decomposition of experimental spectrum measured in angular range $\theta_{Be} \in (30°, 40°)$ and corrected for efficiency (see explanation in the text). Right: Angular distribution for the ^{1}H(^{6}Li,^{6}Be)n reaction. Cross section is presented in arbitrary units. Circles and squares correspond to population of g.s. 0^+ and first e.s. 2^+. Triangles depict the population of the broad bump centered at energy of about 10 MeV.

CONCLUSION

The spectrum of ^{6}Be was studied experimentally in the charge-exchange ^{1}H(^{6}Li,^{6}Be)n reaction. The spectrum up to 15 MeV of excitation is completely described by population of three states 0^+ at 1.37 MeV, 2^+ at 3.05 and 1^- at $\sim 4-12$ MeV. The 1^- continuum is interpreted as a novel phenomenon – the isovector soft dipole excitation mode – opening qualitatively new opportunities of the nuclear structure studies. We expect that the further analysis will confirm our supposition and will give some additional information about the ^{6}Be structure.

REFERENCES

1. O. V. Bochkarev *et al.*, *Sov. J. Nucl. Phys.* **55**, 955 (1992).
2. L. V. Grigorenko *et al.*, *Phys. Rev. C* **80**, 034602 (2009).
3. P. Papka *et al.*, *Phys. Rev. C* **81**, 054308 (2010)
4. V. I. Goldansky *Nucl. Phys.* **19**, 482 (1960).
5. A. M. Rodin *et al.*, *Nucl. Instr. Meth.* **A391**, 228 (1997).
6. D. R. Tilley *et al.*, *Nucl. Phys.* **A708**, 3 (2002).