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SPECTROSCOPY OF ^{13}Be

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Five quasi-stationary states of ^{13}Be populated in the reaction ^{14}C(^{11}B, ^{12}N)^{13}Be at E_{lab} = 190 MeV are reported. A Q-value, Q_0 = -39.60(9) MeV, and a mass excess, M.E. = 33.95(9) MeV, have been found for the lowest observed spectral line. The ground state is therefore unstable with respect to one-neutron emission by 0.80(9) MeV. Excitation energies of 1.22(10), 2.1(2), 4.3(2) and 7.0(2) MeV have been obtained for the observed spectral lines.

The investigation has been performed at the Laboratory of Nuclear Reactions, JINR.

Спектроскопия ^{13}Be

А.В.Белозеров и др.

Наблюдены пять квазистационарных уровней ядра ^{13}Be, заселенных в реакции ^{14}C(^{11}B, ^{12}N)^{13}Be при энергии E_{lab} = 190 МэВ. Измерено значение Q-реакции равным Q_0 = 39.60(9) МэВ и определен дефект массы ядра ^{13}Be М.Е. = 33.95(9) МэВ, соответствующий наиболее низколежащей спектральной линии. Сделан вывод, что основное состояние ядра ^{13}Be нестабильно по отношению к испусканию одного нейтрона на 0.80(9) МэВ. Определены также энергии возбужденных состояний 1.22(10), 2.1(2), 4.3(2) и 7.0(2) МэВ.

Работа выполнена в Лаборатории ядерных реакций ОИЯИ.

Recently the double-charge-exchange reaction ^{13}C(^{14}C, ^{14}O)^{13}Be at E_{lab} = 337.3 MeV was used to populate the states of ^{13}Be [1]. A precise mass measurement of ^{13}Be was performed for the first time, but low statistics prevented the conclusion that the ground state

was observed, and therefore the actual mass of ^{13}Be in its ground state remained an open question.

The present paper is devoted to the investigation of ^{13}Be with the reaction ^{14}C(^{11}B, ^{12}N)^{13}Be at E_{lab} = 190 MeV. The self-supporting 360 μg/cm^2 carbon foil enriched to 70% in ^{14}C was used as the target. With the goal to take into account background contributions arising from the admixtures of ^{12}C and ^{16}O in the ^{14}C target, the reactions ^{12}C(^{11}B, ^{12}N)^{11}Be and ^{16}O(^{11}B, ^{12}N)^{15}C were measured using a natural carbon target of 400 μg/cm^2 and an oxygen target consisting of a 1.1 mg/cm^2 thick layer of $W O_3$ on a 270 μg/cm^2 gold backing, respectively. The experiments were performed at the JINR cyclotron U-400, Dubna, using the MSP-144 spectrograph [2] placed at the reaction angle $\theta_{lab} = 4.6°$. The opening of the entrance slits was 1.0° horizontally and 1.5° vertically. The focal-plane detector [3] consisted of a four-section ionization chamber (ΔE_1, ΔE_2, E_{res}, veto) and of two proportional counters as position sensitive detectors (x_1, x_2). The distance between the two resistive wire anodes was 60 mm. The particular exit reaction channel, viz ^{12}N, was selected unambiguously by using the standard off-line procedure [4] consisting in applying successively contour gates to defferent two-dimensional plots of events in the parameter space (ΔE_1, x_1, ΔE_2, x_2, E_{res}). Details concerning the absolute device calibration, the coordinate linearization, the run calibration and other data processing procedures will be presented elsewhere [5].

All runs were calibrated using the reaction ^{14}C(^{11}B, ^{13}N)^{12}Be and/or ^{12}C(^{11}B, ^{13}N)^{10}Be and/or ^{16}O(^{11}B, ^{13}N)^{14}C, performed before each run and/or afterwards, with the ^{14}C and/or ^{12}C targets. A precise energy calibration in the present case relies on spectral lines of the most strongly populated states in the two-proton pickup reactions, i.e., the g.s. and excited states at 2.102 and 4.56 MeV of ^{12}Be [6], the g.s. and excited states at 3.36803 and 5.95839 MeV of ^{10}Be [7], and the g.s. and the 7.012 MeV excited state of ^{14}C [8].

The reaction products registered for a particular exit channel and collected in a calibrated run were processed event-by-event so that their x_1 and x_2 coordinates were used to reconstruct the particle trajectories in the spectrograph, and as a result the kinematical and the optical broadenings of spectral lines were taken into account and reduced [5]. This procedure allows one to construct the resulting spectra of any calibrated run in the frame of reference of excitation energies of the final nucleus of interest, say of ^{13}Be (or ^{12}Be) in runs with the ^{14}C target as well as in runs with ^{12}C or ^{16}O targets which have been used for background measurements. An obvious advantage of such a choice is the fact that the spectra become invariant with respect to experimental conditions in different runs, and therefore the background due to even large impurities in the target can be subtracted correctly. This can be seen in Figs.1—4.

The top part of Fig.1 shows the complex spectrum of ^{13}N ions from the reaction (^{11}B, ^{13}N) performed with the ^{14}C target. It is a sum of 12 spectra acquired during different calibration runs. The bottom part of Fig.1 shows two background spectra displayed as negative. The first one is a spectrum of the reaction ^{12}C(^{11}B, ^{13}N)^{10}Be with the ^{12}C target (a sum of 10 calibration runs) and the second one is a spectrum of the reaction ^{16}O(^{11}B, ^{13}N)^{14}C with the ^{16}O target. Both background spectra were normalized to the amount of ^{12}C and ^{16}O admixtures in the ^{14}C target.

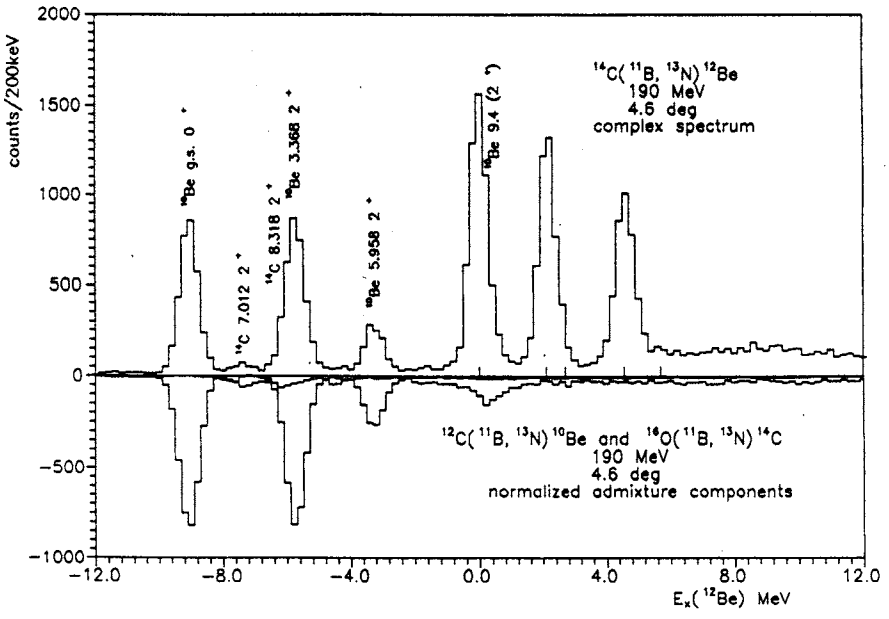

Fig.1. ^{13}N-spectra of the (^{11}B,^{13}N) reaction measured at E_{lab} = 190 MeV and θ_{lab} = 4.6° on the ^{14}C target (upper part), which contains also ^{12}C and ^{16}O and of the reactions ^{12}C(^{11}B, ^{13}N)^{10}Be and ^{16}O(^{11}B, ^{13}N)^{14}C on the ^{12}C and ^{16}O target, respectively (lower part). The background spectra (lower part) were taken under equivalent experimental conditions as the upper part spectrum and were normalized to the amount of ^{12}C and ^{16}O admixtures in the ^{14}C target. All spectra are displayed in the frame of excitation energy of ^{12}Be

Figure 2 displays the ^{13}N-spectrum of the reaction ^{14}C(^{11}B, ^{13}N)^{12}Be after subtraction of the background spectra of Fig.1. It illustrates the reliability of the applied data processing procedure, as the final spectrum exhibits small and randomly distributed residual counts in spite of the considerably high level of subtracted admixture spectra.

The spectral lines of the complex spectrum in Fig.1 were fitted with Gaussians (not shown) with the width of 680 keV. Taking into account the energy loss difference for the entrance and exit channels (e.g., 348 keV for the g.s. of ^{12}Be) we find a beam energy spread of about 580 keV.

In analogy to Fig.1 the upper part of Fig.3 shows the complex spectrum of ^{12}N ions of the reaction (^{11}B, ^{12}N) performed with the ^{14}C target. It is a sum of 22 spectra collected at different times in calibrated runs. The lower part of Fig.3 shows two background spectra, one from the reaction ^{12}C(^{11}B, ^{12}N)^{11}Be as a sum of 10 calibrated runs with the ^{12}C target and the other from the reaction ^{16}O(^{11}B, ^{12}N)^{15}C with the ^{16}O target. Both background spectra were normalized to the amount of ^{12}C and ^{16}O admixtures in the ^{14}C target.

The ^{12}N-spectrum shown in Fig.4 displays resonances of ^{13}Be from the binary reaction ^{14}C(^{11}B, ^{12}N)^{13}Be as well as a very complex continuum related to three- and more-body

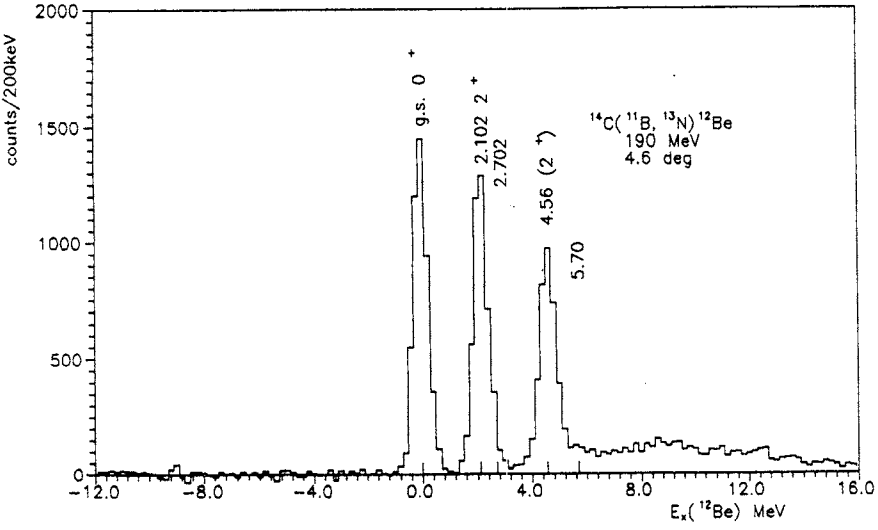

Fig.2. Spectrum of the $^{14}C(^{11}B, ^{13}N)^{12}Be$ reaction after subtraction of the background components originating from target impurities ^{12}C and ^{16}O

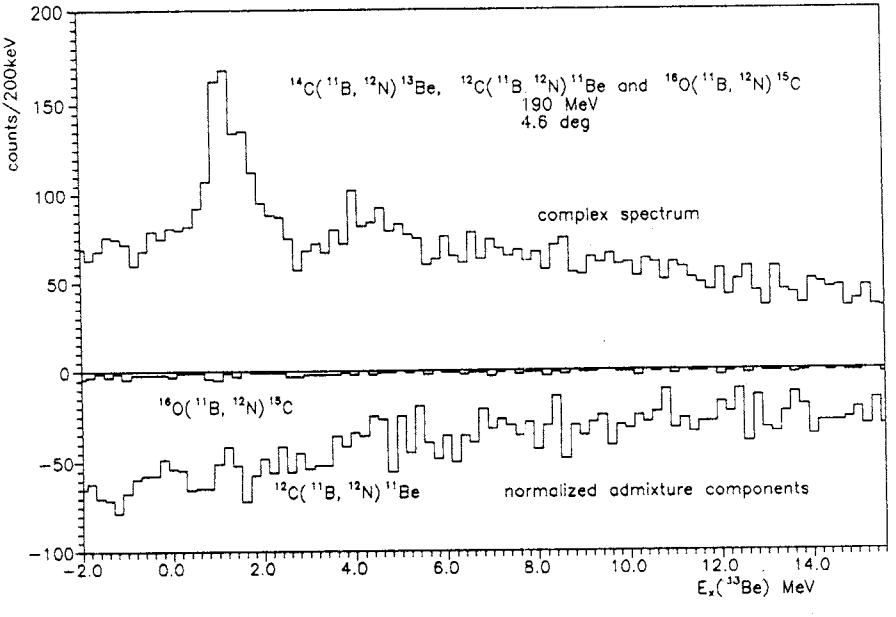

Fig.3. ^{12}N-spectra of the (^{11}B, ^{12}N) reaction measured at E_{lab} = 190 MeV and θ_{lab} = 4.6° on the ^{14}C target (upper part) and of the reactions $^{12}C(^{11}B, ^{12}N)^{11}Be$ and $^{16}O(^{11}B, ^{12}N)^{15}C$ on the ^{12}C and ^{16}O target, respectively (lower part). The background spectra were normalized to the amount of ^{12}C and ^{16}O admixtures in the ^{14}C target. All spectra are displayed in the frame of excitation energy of ^{13}Be

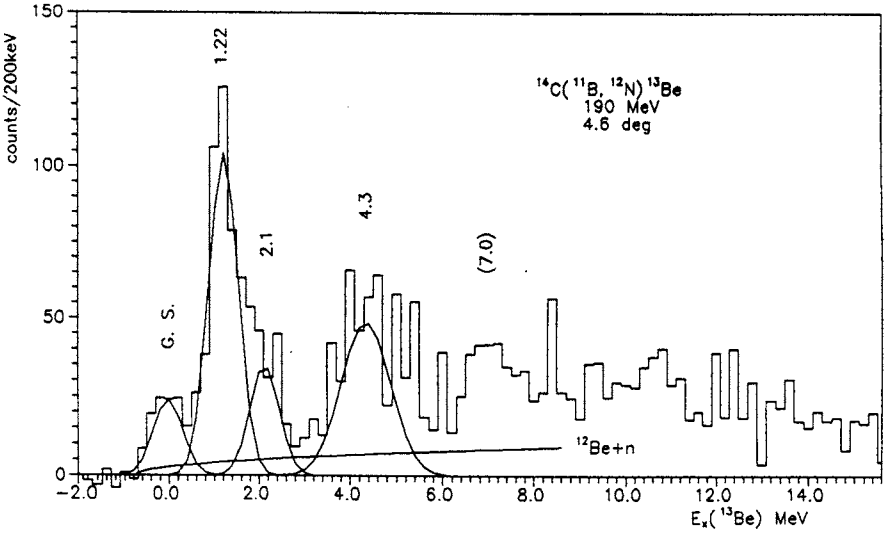

Fig.4. Spectrum of the $^{14}C(^{11}B, ^{12}N)^{13}Be$ reaction after subtraction of the background components from target impurities. The experimental spectrum is presented by the histogram. The fitted spectral components as well as a three-body continuum for $^{12}N+^{12}Be+n$ are shown by full lines

Table. ^{13}Be mass excess and excitation energies

E_{exc} (MeV) this work	M.E.[1] (MeV) this work	M.E.[1] (MeV) [1] exp.	M.E.[1] (MeV) [1] calc.	M.E.[1] (MeV) [11] calc.
0.0	33.95(9)[2]		34.05($1/2^+$)	34.31($1/2^-$)
			35.45($3/2^-$),	
1.22(10)	35.17(6)	35.16(5)	35.60($5/2^+$)	34.36($5/2^+$)
2.1(2)	36.05(15)	35.85($1/2^-$)	35.59($5/2^-$),	
			37.27($1/2^+$)	35.86($1/2^+$)
4.3(2)	38.25(18)	(38.28(9)	37.65($5/2^+$),	
7.0(2)	41.0(2)	41.66(20)	,	

[1] The identification of calculated levels with measured resonances is tentative only.
[2] With this mass excess ^{13}Be is unstable against one-neutron emission by 0.80(9) MeV.

processes. The resolution in the present experiment was about 2 times worse than in ref.[1], but the achieved statistics were about 26 times higher. It allowed us to see most probably the g.s. transition and therefore to measure the g.s. mass excess of ^{13}Be (Table). The ground

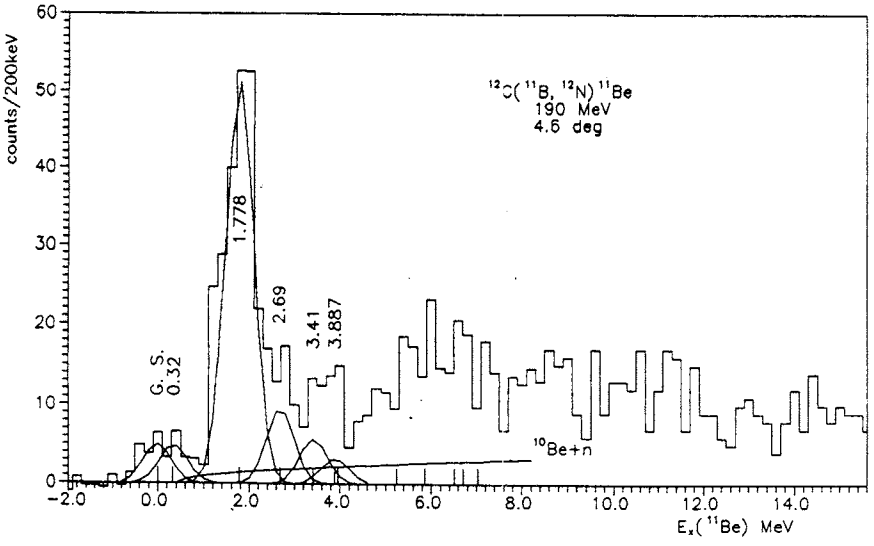

Fig.5. Spectrum of the $^{12}C(^{11}B, ^{12}N)^{11}Be$ reaction at E_{lab} = 190 MeV and θ_{lab} = 4.6°. The lines have the same meaning as in Fig.4. Numbers in the spectrum correspond to excitation energies of known levels of ^{11}Be in units of MeV

state transition corss section was estimated to be of the order of 1 μb/sr. Though the unbound states require the shape of Breit-Wigner resonances, the necessity to fold in a resolution of about 680 keV justifies probably the unfolding of the spectrum with Gaussians. The lowest three spectral lines of ^{13}Be in Fig.4 were fitted with the width of 770 keV. With about 300 keV for the intrinsic width of the most strongly populated state in ^{13}Be, as it was estimated in [1], and 378 keV energy-loss difference for the (^{11}B, ^{12}N) reaction on the ^{14}C target, we find a beam energy spread of about 600 keV. This means that the long-term energy spread of the beam, together with the cumulative error of the absolute beam energy due to the energy uncertainty of 22 particular runs, do not exceed significantly the above-mentioned value of 580 keV for short-term exposures.

The high probability that three- or more-body processes would result in a continuum at high excitation energy prevented to identify some bumps in the spectra as highly excited states (resonances) of ^{13}Be. No attempt was made to unfold the continuum with many-body components. Though the sequential decay of an excited ejectile into the detected particle and the residuum, i.e., the channel $^{13}N^* \rightarrow {}^{12}N + n$, should be important [9,10], only a three-body phase-space distribution corresponding to the three-body continuum $^{12}N + {}^{12}Be + n$ (normalized somewhat arbitrarily) is displayed in Fig.4.

Figure 5 shows the spectrum of ^{12}N ions from the reaction $^{12}C(^{11}B, ^{12}N)^{11}Be$ with the ^{12}C target. Two runs were performed at magnetic field settings that allowed us to see also the ^{11}Be g.s. transition. The achieved resolution of 716 keV did not allow us to distinguish clearly spectral lines corresponding to the lowest two states, namely to the non-normal-

parity g.s. ($J^\pi = 1/2^+$) and to the first excited state at 0.32 MeV ($J^\pi = 1/2^-$), but we see that they both are weakly populated with approximately equal strengths. The most strongly populated state in this reaction is the one with $J^\pi = 5/2^+$ at 1.78 MeV.

Comparing Fig.4 and Fig.5 we observe a strong resemblance between both spectra, especially concerning the low-lying excited states. It indicates that the state of ^{12}Be at 1.22 MeV, most strongly populated in the reaction ^{14}C(^{11}B, ^{12}N)^{13}Be, can be assigned tentatively as $J^\pi = 5/2^+$. The mass excess of this resonance (Table) and the tentative spin assignment are in perfect agreement with the lowest resonance found in [1] for ^{13}Be. However, in our measurement we find a resonance that lies lower at the mass excess of 33.95(9) MeV, and which we identify as the ground state of ^{13}Be. Supposing that this resonance corresponds to the single neutron configuration $\nu 2s1/2$, an intrinsic width of about 1 MeV is estimated from an *R*-matrix calculation with a decay energy of 0.8 MeV. The present experiment does not exclude strictly such a large width for the lowest observed spectral line of ^{13}Be, but a $\nu 1p1/2$ single neutron configuration for the g.s. of ^{13}Be cannot be excluded. Therefore no definite conclusion about the parity of the ^{13}Be ground state with the tentative assignment $J = 1/2$ can be made.

The results of the ^{13}Be mass measurement and of the excited states found in the present experiment are given in the Table (first two columns), together with experimental results of Ostrowski et al. [1] (third column), and values calculated within the shell model with a mean field of Woods-Saxon shape and a zero-range density-dependent pairing interaction [1] (fourth column). In the fifth column, $(0 + 1)\hbar\omega$ shell-model calculations of Poppelier et al. [11] with the realistic Reid soft core potential for deriving the two-body matrix elements are shown.

Detraz and Vieira [12] have pointed out that in the light mass region the measured masses are systematically about 1—2 MeV lower than those predicted by the Garvey-Kelson mass relationship [13]. In fact, Jänecke and Masson [14] and Comay et al. [14] give mass excess values of M.E. = 35.24 and 35.30 MeV, respectively, i.e., values which are about 1.3 MeV higher than our result. On the other hand, the microscopic-macroscopic model prediction of Tachibana et al. [14], namely M.E. = 34.20 MeV, is in good agreement with the value found in the present experiment.

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