THE CONTINUUM OF ^{11}Be POPULATED BY THE (^{18}O,^{16}O) TWO-NEUTRON TRANSFER REACTION*

D. Carbone[a], A. Bonaccorso[b], C. Agodi[a], M. Bondì[a,c]
F. Cappuzzello[a,c], M. Cavallaro[a], A. Cunsolo[a], M. De Napoli[d]
A. Foti[d], D. Nicolosi[a,c], S. Tropea[a,c]

[a]INFN — Laboratori Nazionali del Sud, Catania, Italy
[b]INFN — Sezione di Pisa, Pisa, Italy
[c]Università degli Studi di Catania, Catania, Italy
[d]INFN — Sezione di Catania, Catania, Italy

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A study of the continuum of ^{11}Be populated by the ^{9}Be(^{18}O,^{16}O)^{11}Be reaction at 84 MeV incident energy has been performed. The ejectiles have been momentum analysed at forward angles by the MAGNEX magnetic spectrometer and ^{11}Be energy spectra have been obtained up to about 13 MeV. The scattering of two neutrons independently removed from the projectile as it passes the target nucleus has been described by means of an optical potential with a semiclassical approximation for the relative motion.

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1. Introduction

The importance of two-neutron transfer reactions in the understanding of the pairing force has been established for many years [1]. Among these, heavy-ion direct transfer reactions at bombarding energies not much above the Coulomb barrier, have proven to be valuable tools for getting precise spectroscopic information [2]. In this context, the right framework in which the reactions should be treated is a fully quantum-mechanical approach, such as Distorted Wave Born Approximation (DWBA) or Coupled Reaction Channel (CRC) methods [3], with the inclusion of the nuclear recoil. However, semi-classical approaches have proven to be accurate enough to explain integral properties such as the selectivity of the reaction, allowing also to treat the transfer to bound and unbound states in a coherent way. In

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particular, in Ref. [4] it has been shown that different contributions to the reaction, such as elastic break-up and absorption from target bound states and resonances can be distinguished, at least for the case of one-neutron transfer.

A systematic study, aiming at the investigation of two-neutrons excitations, has been recently started at the Catania INFN-LNS laboratories exploring the (^{18}O,^{16}O) two-neutron transfer reaction at 84 MeV incident energy on light targets. The ^{16}O ejectiles were momentum analyzed by the MAGNEX magnetic spectrometer [5]. Thanks to the spectrometer high resolution and large acceptance, it was possible to obtain high quality inclusive spectra, even in the largely unexplored region above the two-neutron emission threshold in the residual nucleus.

When dealing with transfer to the continuum, several angular momenta mix and thus the best observable to analyse is the energy distribution of the ejectile. As a first step, in Ref. [6] we made exploratory calculations for the ^{13}C(^{18}O,^{16}O)^{15}C reaction assuming an uncorrelated removal of the two neutrons. The used method extended the formalism of the transfer to bound states [7] to the case of unbound ones [8, 9]. Here, we report about the same calculations done for studying the ^{11}Be continuum.

2. Experiment and data analysis

The ^{18}O^{6+} beam at 84 MeV incident energy was produced and accelerated by the Tandem Van de Graaff facility of INFN-LNS. A 201 μg/cm^2 self-supporting ^{9}Be target was used. Supplementary runs with a 49 μg/cm^2 self-supporting ^{12}C target and a 258 μg/cm^2 WO$_3$ target were recorded in order to estimate the background in the ^{16}O energy spectra from ^{12}C and ^{16}O impurities in the ^{9}Be target. The ^{16}O ejectiles were momentum analysed by the MAGNEX spectrometer working in the full acceptance mode (solid angle $\Omega \sim 50$ msr and momentum range $\Delta p/p \sim 24\%$). The spectrometer optical axis was located at $\theta_{\rm lab}^{\rm opt} = 8^\circ$, which corresponds to a total covered angular range between 2.5° and 12° in the laboratory reference frame. The ejectiles were identified, event by event, by the simultaneous measurement of the position and angle at the focal plane, the energy loss in the gas section of the focal plane detector and the residual energy on the silicon hodoscope [10, 11]. Details about the technique can be found in Ref. [12]. The horizontal and vertical positions and angles at the focal plane were used as an input for a 10$^{\rm th}$ order reconstruction of the scattering angle and momentum modulus, based on the fully algebraic method implemented in MAGNEX [13]. This allows a compensation of the high order aberrations connected with the large acceptance of the spectrometer. The Q-values, or equivalently the excitation energy $E_x = Q_0 - Q$ (where Q_0 is the ground state Q-value), were extracted by the application of relativistic kinematic transformations. An overall energy and angular resolution of about 160 keV and 0.3° was obtained, mainly determined by the straggling introduced in the target.

The ^{9}Be(^{18}O,^{16}O)^{11}Be reaction is interpreted as a two-step mechanism: $^{18}\mathrm{O} + {}^{9}\mathrm{Be} \to {}^{17}\mathrm{O} + {}^{10}\mathrm{Be}_{\mathrm{gs}} \to {}^{16}\mathrm{O} + {}^{10}\mathrm{Be}_{\mathrm{gs}} + n$ starting from the one-neutron separation energy ($S_n = 0.501$ MeV) and $^{18}\mathrm{O} + {}^{9}\mathrm{Be} \to {}^{17}\mathrm{O} + {}^{9}\mathrm{Be}_{\mathrm{gs}} + n \to {}^{16}\mathrm{O} + {}^{9}\mathrm{Be}_{\mathrm{gs}} + n + n$ starting from the two-neutron separation energy ($S_{2n} = 7.313$ MeV). The continuum spectrum of ^{11}Be, given in Fig. 1, can be divided in three region bounded by S_n and S_{2n}. Below S_n, the ground state and the 0.32 MeV bound state of ^{11}Be are populated. At higher E_x, resonances of ^{11}Be are excited up to S_{2n}. Crossing this threshold, the transfer to the continuum of $^{10}\mathrm{Be} + n$ and the transfer to the continuum of $^{9}\mathrm{Be} + n + n$, originated in the first step, merge together.

According to the model described in Refs. [6, 9], the cross section is calculated within a semi-classical model by integrating over the core-target distances of closest approach

$$\frac{d\sigma_{1n}}{d\varepsilon_{\mathrm{f}}} = C^2 S \int_0^{\infty} b db \frac{dP(b)}{d\varepsilon_{\mathrm{f}}} P_{\mathrm{el}}(b) \tag{1}$$

and the total break-up cross section is obtained by integrating over the neutron final continuum energy ε_{f}, calculated with respect to the target. C^2S is the spectroscopic factor of the neutron single particle initial state. The factor $P_{\mathrm{el}}(b) = |S_{c\mathrm{T}}|^2 = \exp(-\ln 2 \exp[(R_{\mathrm{S}} - b)/\Delta])$ is the core survival probability in the elastic channel [14] written in terms of the parameterised S-matrix for the core-target scattering. The strong absorption radius is defined as $R_{\mathrm{S}} = 1.4(A_{\mathrm{P}}^{1/3} + A_{\mathrm{T}}^{1/3})$ in fm and $\Delta = 0.6$ fm is a diffuseness-like parameter. Equation (1) gives the final neutron energy distribution, which is related by energy conservation to the measured ejectile energy distribution [9]. The transfer probability from an initial bound state of definite energy ε_{i}, angular momentum l_{i}, and spin j_{i} to a final continuum states of positive energy ε_{f} is given by

$$\frac{dP}{d\varepsilon_{\mathrm{f}}}(j_{\mathrm{f}}, j_{\mathrm{i}}) = \sum_{j_{\mathrm{f}}} \left(\left|1 - \bar{S}_{j_{\mathrm{f}}}\right|^2 + 1 - \left|\bar{S}_{j_{\mathrm{f}}}\right|^2 \right) B(j_{\mathrm{f}}, j_{\mathrm{i}}) \,, \tag{2}$$

where $\bar{S}_{j_{\mathrm{f}}}$ is the energy-averaged (due to the continuum conditions) and angular-momentum dependent optical model S-matrix, which describes the neutron-target interaction and $B(j_{\mathrm{f}}, j_{\mathrm{i}})$ is the elementary transfer probability. The latter depends on the details of the initial and final states, on the energy of relative motion and on the distance of closest approach between the two nuclei, as given in Ref. [9]. The calculation of the S-matrix, strongly related to the choice of the neutron target optical potential, is a key point of this formalism. The first term in Eq. (2), proportional to $|1-\bar{S}_{j_\mathrm{f}}|^2$, gives the neutron elastic break-up (or diffraction), while the second term proportional to $1-|\bar{S}_{j_\mathrm{f}}|^2$, gives the neutron absorption (or stripping) by the target.

For the calculation starting from S_n, which describes the $^{10}\mathrm{Be}+n$ interaction, the l-dependent optical potential from Ref. [15] was adopted, while for that starting from S_{2n}, describing the $^{9}\mathrm{Be}+n$ interaction, the energy-dependent optical potential from Ref. [16] was used. The used potentials have a Woods–Saxon real volume plus a spin–orbit and surface imaginary terms. The resulting calculations are superimposed to the continuum spectrum of ^{11}Be in Fig. 1. Between S_n and S_{2n} the elastic break-up (dark grey/red dashed curve) and the absorption (light grey/green dashed curve) are shown, as given by the first and the second term of Eq. (2), respectively. Similarly, above the S_{2n} threshold both elastic (grey/green dashed-dotted curve) and absorption (light grey/orange dashed-dotted curve) terms are shown.

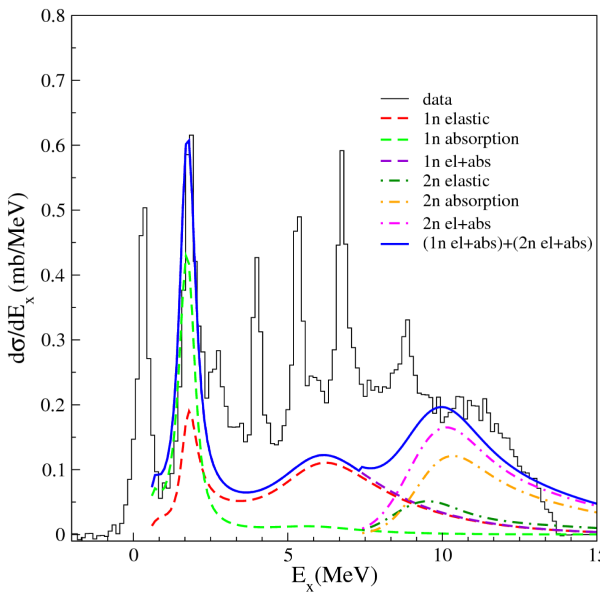

Fig. 1. (Colour on-line) Inclusive energy spectrum of the reaction $^{9}\mathrm{Be}(^{18}\mathrm{O},^{16}\mathrm{O})^{11}\mathrm{Be}$ at $3^\circ<\theta_\mathrm{lab}<10^\circ$ obtained after the subtraction of the background due to the contaminants in the target. Theoretical calculations of various break-up components (see the text): the one- and two-neutron elastic break-up; the one- and two-neutron absorption term; the sum of the one- and two-neutron elastic and absorption terms; the sum of all the contributions.

The calculation is able to reproduce the 1.78 MeV ^{11}Be resonance, since it is mainly built as a single-particle state $|(^{10}\mathrm{Be}_{\mathrm{gs}})(0^{+})\otimes(1d_{(5/2)})_{\upsilon}>$. There are many other resonances in the region between S_n and S_{2n}, mainly built by two neutrons plus the ^{9}Be ground state. This kind of structure is not included in the adopted approach and thus such resonances cannot be reproduced. In the region just above S_{2n}, the calculations show an enhancement of the cross section mainly coming from the absorption of the two neutrons (light grey/orange dot-dashed line in Fig. 1). This means that a $^{9}\mathrm{Be}+n+n$ resonant configuration can be present in this energy region.

In order to understand the origin of the strength distribution in the spectrum, an estimate of the contribution of each single partial wave to the total sum was also done. This is possible since Eq. (2) contains an incoherent sum over final angular momenta. The partial wave decompositions of the n–^{10}Be and n–^{9}Be break-up cross sections are shown in Fig. 2 starting from $S_n =$ 0.501 MeV and $S_{2n} =$ 7.313 MeV, respectively. The resonance at 1.78 MeV corresponds to the $d_{5/2}$ orbital and above S_{2n} the main contribution comes from configurations where both neutrons are transferred to the $d_{3/2}$ continuum orbital, differently to what was found for the ^{15}C case [6], where also

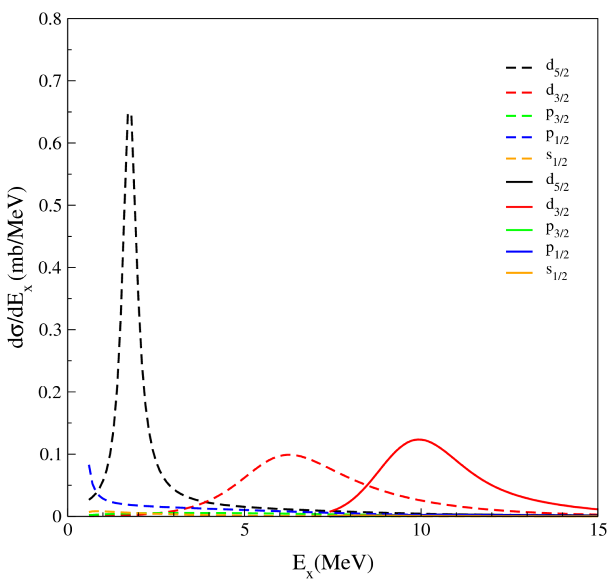

Fig. 2. (Colour on-line) Dominant contributions to the partial wave decomposition of the theoretical energy spectrum. The legend indicates the single particle angular momentum of each individual strength distribution. The lines starting at $E_x =$ 0.501 MeV refer to the $^{10}\mathrm{Be}+n$ system, while those starting at 7.313 MeV to the $^{9}\mathrm{Be}+n+n$ one (see the text).

the $d_{5/2}$ one gave strong contribution. The damping of $d_{5/2}$ at high excitation energy in ^{11}Be is an interesting consequence of the well-known $2s_{1/2}$ $1d_{5/2}$ collapse in this exotic nucleus [17].

3. Conclusions

In this work, some results obtained studying the ^{9}Be(^{18}O,^{16}O)^{11}Be reaction at 84 MeV incident energy have been reported. The ^{16}O ejectiles were measured by the MAGNEX and the excitation energy spectra of ^{11}Be were extracted. Both the elastic break-up and absorption channel have been analysed considering an independent removal of the two neutrons from the projectile. The calculations give a good account for the continuum background in the ^{11}Be excitation energy spectrum and show that the elastic break-up represents a minor part of the continuous spectra, which are, in fact, dominated by the absorption of both neutrons. In particular, an enhanced probability of exciting $^{9}\mathrm{Be} + n + n$ configurations near the S_{2n} threshold is obtained. Moreover, the calculation is able to reproduce a single particle resonance at 1.78 MeV. However, the model cannot account for the strong population of the narrow resonances built mainly by two neutrons plus the target observed between S_n and S_{2n}, because of the lack of core polarization excitations. An explicit treatment of the full $^{9}\mathrm{Be} + n + n$ interaction, including the n–n pairing, would be required to understand the remaining details of the energy spectra.

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