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HIGHLY EXCITED ^{8}Be CORE IN THE CONFIGURATION OF THE ^{12}C AND ^{11}B GROUND STATES

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Abstract: Angular distributions of the ^{12}C(d, ^{6}Li)^{8}Be reaction at $E_{lab} = 78.0$ MeV and the ^{11}B(^{3}He, ^{6}Li)^{8}Be reaction at $E_{lab} = 71.8$ MeV were measured. Transitions leading to ^{8}Be in the ground state and the 3.04, 16.63, 16.92, 17.64 and 18.15 MeV excited states were observed. A DWBA analysis was performed regarding the (d, ^{6}Li) and (^{3}He, ^{6}Li) reactions as direct α particle or triton transfers, respectively.

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NUCLEAR REACTION ^{12}C(d, ^{6}Li), $E = 78$ MeV; ^{11}Be(^{3}He, ^{6}Li), $E = 71.8$ MeV; measured $\sigma(\theta)$; deduced reaction mechanism. ^{6}Li, ^{11}B, ^{12}C deduced three-, four nucleon cluster amplitudes. DWBA analysis.

1. Introduction

Direct transfer reactions constitute a well established tool for studying the structure of the nuclei involved. If the structure of final states of nuclei in the outgoing channel is well known, the investigation of complex transfer reactions will shed some light on the problem of wave functions of states of nuclei in the entrance channel. Reactions with ^{8}Be in the outgoing channel should be of special interest in this respect. This nucleus has a number of excited states with quite well established (for a survey see ref. [1])) and interesting structure.

The first excited states of ^{8}Be with excitation energies of 3.04 MeV ($J^{\pi} = 2^{+}$, $T = 0$) and 11.4 MeV (4^{+}, 0) are members of the ground state rotational band. The next two states at 16.63 MeV (2^{+}) and 16.92 MeV (2^{+}) are characterized by low widths and by a substantial $T = 0$ isospin mixing. According to ref. [2]) these two 2^{+} states could be written as a linear combination of the pure isospin configurations

$$|A\rangle = |16.63\rangle = \alpha|T=0\rangle + \beta|T=1\rangle\,,$$
$$|B\rangle = |16.92\rangle = \beta|T=0\rangle - \alpha|T=1\rangle\,, \qquad (1)$$

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with amplitudes α and β real and normalized by $\alpha^2+\beta^2=1$. The isospin mixing α^2/β^2 may be determined from the widths Γ_A and Γ_B for isospin allowed α-decay through the $T=0$ components of the wave function, or from cross sections of transfer reactions which proceed selectively through the $T=0$ components. The results of ref. [3]) led to $\alpha^2/\beta^2=1.45$ with $\alpha=0.769$ and $\beta=0.639$. Taking into account also a strong single particle character of these states Marion [4]) suggested configurations (^{7}Li+p) and (^{7}Be+n) for the 16.63 MeV and 16.92 MeV states, respectively. The next excited states of ^{8}Be 17.64 MeV (1^+) and 18.16 MeV (1^+) are pure isospin $T=1$ and $T=0$ states, respectively.

The aim of the present work is to investigate via the ^{12}C(d, ^{6}Li)^{8}Be and the ^{11}B(^{3}He, ^{6}Li)^{8}Be reactions to what extent the configurations of the highly excited ^{8}Be core plus an α or t cluster overlap with the ground states of ^{12}C or ^{11}B. For this purpose the angular distributions for the transitions to the ground and the first excited states as well as to the 2^+ and 1^+ states have been measured. Theoretical predictions of these angular distributions were obtained in the framework of DWBA calculation under assumption of a single-step-cluster transfer between the interacting nuclei.

2. Experimental procedure and results

The experiments were performed using deuteron and α-beams of $E_{lab}=78.0$ MeV and $E_{lab}=71.8$ MeV, respectively, from the cyclotron JULIC of the Kernforschungsanlage Jülich. As ^{12}C target a self-supporting foil of natural carbon with a thickness of 100 μg/cm^2 was used. As ^{11}B target a self-supporting foil with 160 μg/cm^2 was prepared with an enrichment of 98.55%. The thicknesses of the targets were determined from the comparison of the measured elastic scattering angular distributions with the cross sections calculated with optical model potentials obtained from investigations of elastic scattering of d+^{12}C at $E_{lab}=77.3$ MeV [ref. [5])] and of ^{3}He+^{11}B at $E_{lab}=74.0$ MeV [ref. [6])].

Two kinds of measurements were carried out. In scattering chamber experiments the outgoing ^{6}Li particles were detected with solid state $\Delta E-E$ counter telescopes. The energy resolution was about 400 keV. The obtained data provide an overview of the entire energy spectrum and sufficient resolution to resolve the two low-lying states. In order to resolve the highly excited states high resolution measurements were performed using the QQDDQ magnetic spectrometer BIG KARL [7]). Horizontal and vertical positions of the detected particles in the focal plane of the spectrometer were measured in two multi-wire proportional chambers with delay-line read-out. Particle identification was achieved by means of a single-wire gas energy loss counter and a thick plastic scintillation counter placed behind the focal plane of the spectrometer. The mass resolution of this set-up was sufficient to ensure good separation of ^{6}Li from other reaction products. An example of the two-dimensional spectra was published elsewhere [8]). The beam line was set up in the high intensity

achromatic mode matched to the spectrometer dispersion 13.6 m. The spectrometer system was adjusted in order to compensate the kinematic momentum spread and to obtain good resolution for solid angles up to 1.6 msr. The overall energy resolution of 100 keV was sufficient to resolve all ^{8}Be excited states in the energy region from 16 to 19 MeV in the whole investigated angular range.

Examples of the energy spectra for both reactions measured with the counter telescopes are shown in fig. 1. Fig. 2 presents the high-resolution spectra obtained with the magnet spectrometer.

The angular distributions of the emitted ^{6}Li particles were measured in the counter experiments in the angular range from 10° to 30° (lab) in 2.5° steps for ^{12}C(d, ^{6}Li)^{8}Be (ground and first excited state) reactions, and in the range 7° to 52° (lab) in 2° or 3° steps for the ^{11}B(^{3}He, ^{6}Li)^{8}Be (ground and first excited state) reaction. In the high-resolution experiment the ^{6}Li ejectiles were observed from 8° to 40° (lab) in

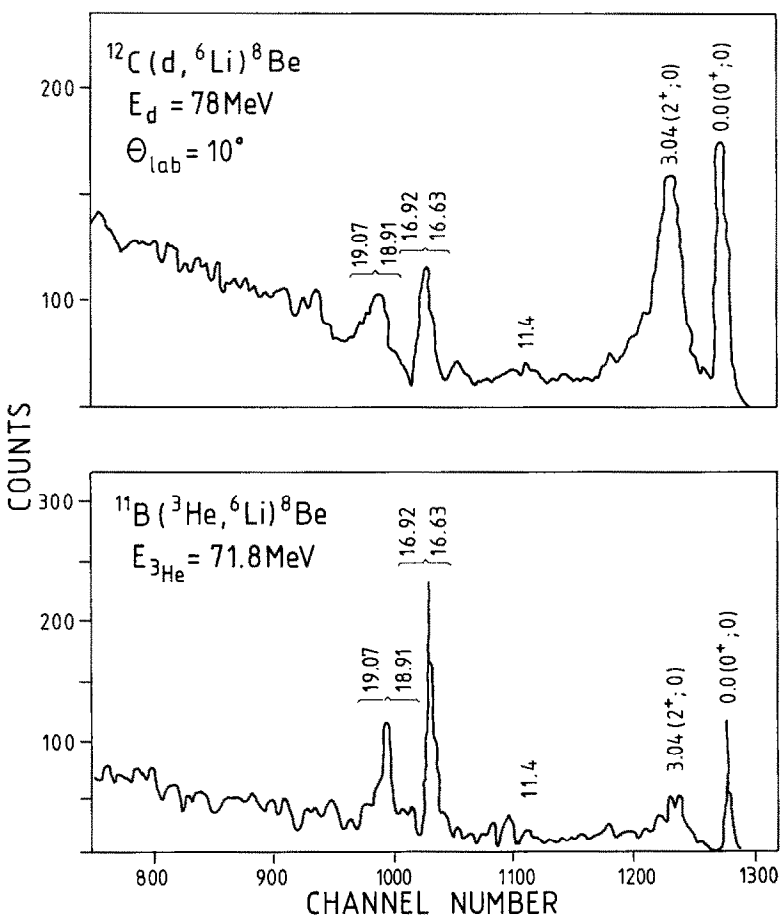

Fig. 1. The energy spectra obtained with solid state detectors for ^{12}C(d, ^{6}Li)^{8}Be and ^{11}B(^{3}He, ^{6}Li)^{8}Be reactions at $\theta_{lab} = 10°$.

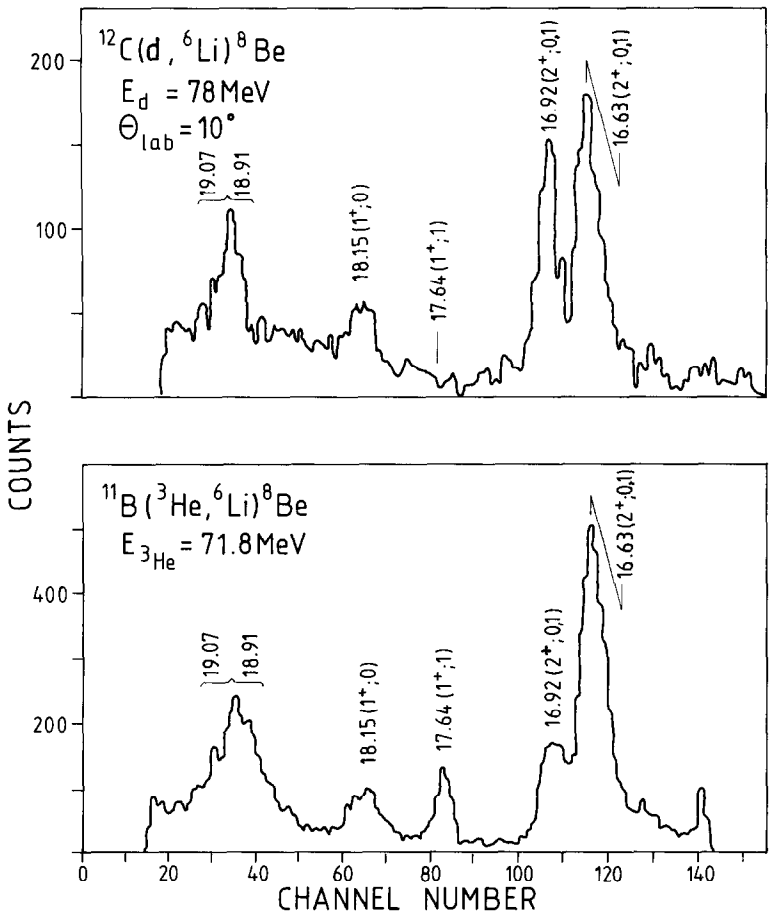

Fig. 2. Momentum spectra for the ^{12}C(d, ^{6}Li)^{8}Be and ^{11}B(^{3}He, ^{6}Li)^{8}Be reactions leading to ^{8}Be excitation energy 16–19 MeV, taken at the same angle $\theta_{lab} = 10°$.

2° steps for the reaction ^{12}C(d, ^{6}Li)^{8}Be$_{16-19\ MeV}$ and from 8° to 35° (lab) in 4° steps for the ^{11}B(^{3}He, ^{6}Li)^{8}Be$_{16-19\ MeV}$ case.

The relative values of differential cross sections at different angles were obtained by normalization of the measured numbers of counts with the corresponding beam charge measured in the Faraday cup in the BIG KARL experiment or using a monitor counter in the scattering chamber measurements. The absolute normalization of the cross sections was achieved from the target thickness, the acceptance angles and calibration of the beam charge integrator and monitor. The error bars in figs. 3 and 4 represent the statistical errors of individual points only, while the error of the absolute normalization factor is estimated to be 10%.

The experimental angular distributions are shown in fig. 3 for the ^{12}C(d, ^{6}Li)^{8}Be reaction and in fig. 4 for ^{11}B(^{3}He, ^{6}Li)^{8}Be. As can be seen from the spectrum in fig. 1

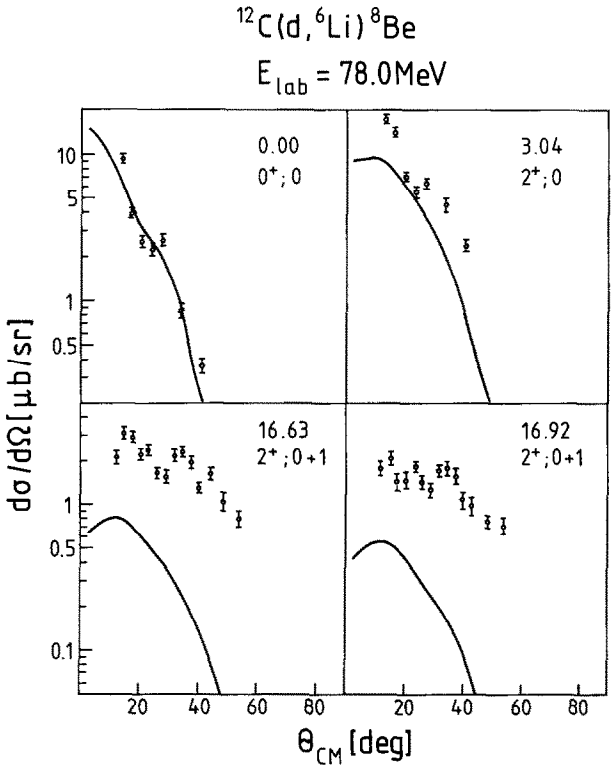

Fig. 3. Angular distributions of ^{6}Li from the reaction ^{12}C(d, ^{6}Li)^{8}Be. The curves represent the theoretical calculations of α-cluster transfer.

the 17.64 MeV (1^+, 1) state is not excited in the α-transfer reaction ^{12}C(d, ^{6}Li)^{8}Be in accordance with the isospin selection rule. As for this reaction the transition to the two 2^+ states involves only the $T=0$ components, the ratio of the cross sections gives direct information of the ratio of isospin mixing parameters in formula (1)

$$\frac{\mathrm{d}\sigma(16.63)}{\mathrm{d}\sigma(16.92)}=\frac{\alpha^2}{\beta^2}.$$

From the present measurements we obtain

$$\frac{\mathrm{d}\sigma(16.63)}{\mathrm{d}\sigma(16.92)}=1.33\pm0.10$$

in good agreement with the best value for the α^2/β^2 ratio 1.45 ± 0.01 [ref. [3]].

In the transfer reaction ^{11}B(^{3}He, ^{6}Li)^{8}Be, transitions to all investigated states are allowed by the isospin selection rule.

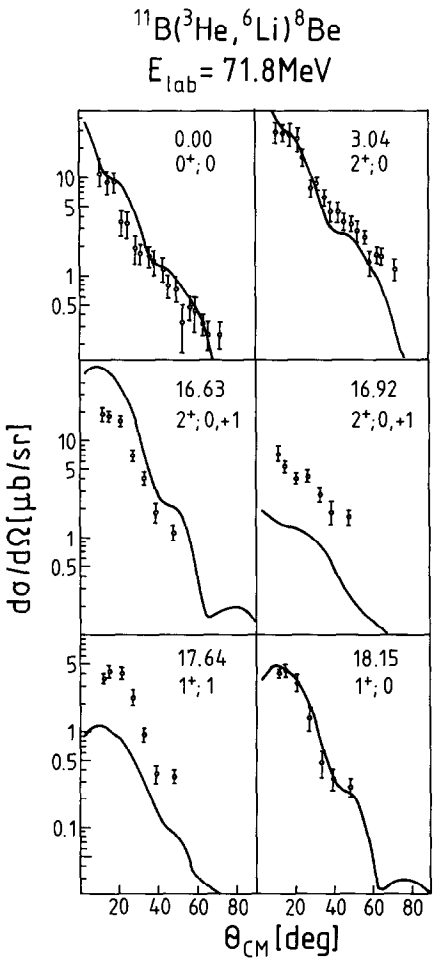

Fig. 4. Angular distributions of ^{6}Li from the reaction ^{11}B(^{3}He, ^{6}Li)^{8}Be. The curves represent the theoretical calculations of a triton-cluster transfer.

3. DWBA analysis

A DWBA analysis of the presented data was performed assuming single step α-particle or triton-cluster transfer. This approach implies some selection rules for the observed transition. The α-particle transfer in the ^{12}C(d, ^{6}Li)^{8}Be could not populate the unnatural parity 1^{+} states of ^{8}Be at 17.64 and 18.15 MeV. However, as can be seen from the α-transfer spectrum presented in fig. 2 the transition to the 18.15 MeV $(1^{+}, 0)$ state is observed although with rather small intensity $[\sigma(18.15)/\sigma(\text{g.s.}) = 0.06]$. This observation suggests that in the population of this state more complicated reaction mechanisms are involved. These reaction mechanisms should conserve isospin, since the other 1^{+} state at the energy 17.64 MeV with isospin $T = 1$ is not excited in agreement with the isospin conservation. In case of

the ^{11}B(^{3}He, ^{6}Li)^{8}Be reaction no such qualitative predictions of excitation strengths are valid.

The DWBA calculations were performed using the exact finite range program JUPITER-5 written by Tamura and Udagawa according to the formalism given in ref. [9]) and modified by Kamys *et al.* [10]). The potential for binding the transferred cluster to the core was assumed to be of Woods–Saxon form with the geometrical parameters taken according to ref. [11]) to be $R = 0.85\,(A_{\text{cluster}}^{1/3} + A_{\text{core}}^{1/3})$ fm, $a = 0.65$ fm, while the depths were adjusted to obtain the proper binding energy. The optical model parameters for the entrance d + ^{12}C and for the ^{3}He + ^{11}B channels were taken from ref. [5]) and ref. [6]), respectively. The optical model parameter in the exit ^{8}Be + ^{6}Li channel was determined from both the analysis of ^{7}Li + ^{9}Be elastic scattering at $E_{\text{c.m.}} = 19.12$ MeV and α-transfer reaction ^{11}B(^{3}He, ^{7}Be)^{7}Li at $E_{\text{c.m.}} = 49.3$ MeV, as explained in ref. [8]).

The cross sections were calculated from the coherent sum of DWBA amplitudes for orbitals involved in the particular transition multiplied by corresponding spectroscopic amplitudes. The values of the spectroscopic amplitudes, listed in table 1, were calculated under the assumption, that the wave functions for all states under consideration for nuclei with $A > 4$ are spanned in the space limited to the $(1s)^{4}(1p)^{A-4}$ configuration. The calculations were performed according to the method presented in ref. [12]). The three- and four-nucleon c.f.p. for partitions ^{11}B = ^{8}Be + ^{3}He and ^{12}C = ^{8}Be + ^{4}He were taken from ref. [13]) and ref. [14]), respectively. The phase consistency was assured by adjusting the signs of the c.f.p. according to the prescription given in ref. [15]). The U coefficient for the SU(4) group needed for the ^{6}Li = ^{3}He + ^{3}H partition were obtained according to ref. [16]). The spectroscopic amplitudes for the ^{6}Li = ^{2}H + ^{4}He partition were calculated according to ref. [17]) using the values for the reversed partition. Thus no normalization was introduced in the calculations. As can be seen from figs. 3 and 4 the experimental angular distributions are quite well reproduced with respect to both the shape and the magnitude for the ground state transition as well as for the transition to the first 3.04 MeV excited state in the ^{11}B(^{3}He, ^{6}Li)^{8}Be reaction. However, in the alpha-transfer reaction the strength of the 2^{+} excited state is slightly underestimated. For the higher excited states of ^{8}Be in the excitation energy region 16 to 19 MeV the calculation, performed in the simple model as described above with the shell model amplitudes of table 1, reproduces the experimental data rather moderately. The calculated cross sections for the ^{12}C(d, ^{6}Li)^{8}Be$_{16.64\text{ MeV},\,16.92\text{ MeV}}$ reaction are only by a factor of 4 lower than the experimental ones at smaller angles. However, the deviation of the shape of calculated angular distributions from the experiment indicates oversimplification of the assumed model. Such discrepancies appear to be smaller in the case of the t-transfer ^{11}B(^{3}He, ^{6}Li)^{8}Be reaction. The calculations partly overestimate and partly underestimate the magnitude of the experimental angular distributions, while the shape is rather well reproduced. The transition to the 18.15 MeV (1^{+}; 0) state is reproduced very well.

TABLE 1

Three- and four-nucleon cluster spectroscopic amplitudes

Nucleus = core + cluster	n	l	j	Amplitude
$^{6}Li = {}^{3}He + {}^{3}H$	1	0	$\frac{1}{2}$	1.333
	0	2	$\frac{3}{2}$	0.000
$^{11}B = {}^{8}Be + {}^{3}H$	1	1	$\frac{3}{2}$	0.513
$^{11}B = {}^{8}Be(3.0) + {}^{3}H$	1	1	$\frac{1}{2}$	0.012
	1	1	$\frac{3}{2}$	−0.683
	0	3	$\frac{5}{2}$	−0.249
	0	3	$\frac{7}{2}$	−0.240
$^{11}B = {}^{8}Be(16.6) + {}^{3}H$	1	1	$\frac{1}{2}$	−0.111
$^{11}B = {}^{8}Be(16.9) + {}^{3}H$	1	1	$\frac{3}{2}$	−0.446
	0	3	$\frac{5}{2}$	−0.035
	0	3	$\frac{7}{2}$	0.021
$^{11}B = {}^{8}Be(16.6) + {}^{3}H$ [a])	1	1	$\frac{1}{2}$	−0.242
$^{11}B = {}^{8}Be(16.9) + {}^{3}H$ [a])	1	1	$\frac{3}{2}$	−0.804
	0	3	$\frac{5}{2}$	−0.257
	0	3	$\frac{7}{2}$	0.359
$^{11}B = {}^{8}Be(17.4) + {}^{3}H$ [a])	1	1	$\frac{1}{2}$	−0.137
	1	1	$\frac{3}{2}$	0.141
	0	3	$\frac{5}{2}$	0.053
$^{11}B = {}^{8}Be(18.2) + {}^{3}H$	1	1	$\frac{1}{2}$	0.121
	1	1	$\frac{3}{2}$	−0.098
	0	3	$\frac{5}{2}$	−0.128
$^{6}Li = {}^{2}H + {}^{4}He$	1	0	0	1.016
	0	2	2	0.294
$^{12}C = {}^{8}Be + {}^{4}He$	2	0	0	−0.746
$^{12}C = {}^{8}Be(3.0) + {}^{4}He$	1	2	2	0.845
$^{12}C = {}^{8}Be(16.6) + {}^{4}He$	1	2	2	0.238
$^{12}C = {}^{8}Be(16.9) + {}^{4}He$				

[a]) ^{8}Be isospin $T = 1$

4. Summary

The results of the measurements of $^{12}C(d, {}^{6}Li)^{8}Be$ and $^{11}B({}^{3}He, {}^{6}Li)^{8}Be$ angular distributions are presented. Their comparison with the DWBA calculations performed under assumption of a simple α-particle or triton-cluster transfers, respectively, reveal surprisingly fair agreement with respect to shape and magnitude of cross sections. It should be stressed that the calculations were done without adjustable parameters. For some states the agreement is very good.

Discrepancies between experimental and theoretical angular distributions show that the model employed is oversimplified for some particular states. Two observations should be stressed explicitly: Firstly, the especially striking feature of the

investigated reactions is a very large probability for population of highly excited states in such processes. The cross sections for population of two 2^+ states at 16.62 MeV and 16.92 MeV are comparable with those for rather strong transitions to the ^{8}Be ground and the first excited states. This indicates rather strong overlap of the ^{12}C or ^{11}B ground state wave functions with those corresponding to the configurations "^{8}Be, 16.63, 16.92 MeV core states + α-particle or triton cluster", respectively. Secondly, the comparison of the cross sections for excitation of the states at 16.63 MeV and 16.92 MeV in the α-transfer ^{12}C(d, ^{6}Li)^{8}Be reaction reveals good agreement with the ratio of coefficients characterizing the isospin mixing determined independently from other investigations. This could be considered as an indication of the isospin invariance of the processes to be taken into account for explanation of the investigated reactions.

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