ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Catania

INFN/BE-91/10
28 Ottobre 1991

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THE LOW-LYING ^{5}Li LEVELS

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ABSTRACT - In this work a comparison is made between the low-lying ^{5}Li level spectroscopic parameter values that are: i) deduced by the shell-model calculation, ii) adopted in literature; iii) obtained by us using only three-body reactions. Despite the seeming dependence of the above parameters on the nuclear reaction details, the agreement among the values given by i), ii) and iii) is generally satisfying.

Recently Bevelacqua performed a theoretical calculation of the ground and excited levels in ^{5}H, ^{5}He, ^{5}Li and ^{5}Be systems[1], by using an interaction model which yields reasonable structure and reaction results in A=2, 3 and 4 systems. This nuclear shell-model predicts spin, parity, isospin and excitation energy of each level of the four mentioned nuclei.

For the ^{5}Li nucleus of our concern the low-lying levels (the ones having $E_x \leq 20$ MeV) which are characterized by T=1/2 are reported in Table I. Furthermore the above theoretical model predicts a $J^\pi=1/2^+$ level at $E_x=23.55$ MeV that is a member of a T=3/2 isobaric quartet[1]. Up to now no experimental evidence for this last state has appeared. On the contrary, the levels with a T=1/2 character are well known. The theoretical predictions are for a J=3/2 and a 1/2 assigned to the ground and first excited ^{5}Li level, respectively; both with a negative-parity. The other levels with T=1/2 are predicted with a positive parity (see Table I) and spin 3/2, 1/2 and 5/2.

J^π , T	E_x (MeV)
$3/2^-$, 1/2	0.1
$1/2^-$, 1/2	6.9
$3/2^+$, 1/2	16.4
$1/2^+$, 1/2	18.4
$5/2^+$, 1/2	20.1

Table I. Energy levels of ^{5}Li deduced by shell-model calculations for the A=5 systems.

Over the past years, kinematically complete and incomplete experiments have been carried out by different reactions, beam energies and detection geometries in order to obtain the spectroscopic characteristics of the nuclear levels of light nuclei[2]. The spectrum of values deduced for both excitation energy and width as reported in literature have large discrepancies which show a seeming dependence on the nuclear reaction details[2].

At present the ^{5}Li spectroscopic characteristics adopted in literature are the ones reported by Ajzenberg-Selove in her energy level systematics[2)] (see Table II). In this Table the

Table II. Energy levels of ^{5}Li adopted in literature.

J^π , T	E_x(MeV)	Γ(MeV)	Decay
$3/2^-$, 1/2	g.s.	≈1.5	p, α
$1/2^-$, 1/2	5÷10	5±2	p, α
$3/2^+$, 1/2	16.66±0.07	~0.3[a)]	γ, p, d, ^{3}He, α
$1/2^+$, 1/2	18±1	*broad*	γ, p, d, ^{3}He, α
$(3/2, 5/2)^+$, 1/2	20±0.5	≈5	γ, p, d, ^{3}He, α

[a)] *We considered the Γ≈300 keV reported in Nucl. Phys. A413 rather than Γ=(200±60) keV reported in Nucl. Phys. A490 since Ajzenberg-Selove explained to us in a private communication that the value reported in the latter reference is incorrect.*

E_x of the $J^\pi=1/2^-$ ^{5}Li level and all the five widths are known with a large margin of uncertainty. For the excitation energy of the above first excited ^{5}Li state this is due to the $P_{1/2}$ phase-shift which changes slowly over a range of several MeV. The uncertainties on the widths are due to the large spectrum of the values present in literature. In spite of this, the theoretical predictions by shell-model calculations are in line with the excitation energies adopted in literature. Unfortunately the comparison is not complete since a theoretical estimate of the widths of those levels is beyond the present capability. We believe that the large uncertainties in the spectroscopic values are due to the interference effect, when present, and to the analysis method of the experimental data. Thus we performed measurements in a kinematically complete way and then we projected the bidimensional spectra onto the central kinematical curve (the one corresponding to the angles defined by the beam direction and detector axes) in the E_1-E_2 plane[3)]. By such a technique the effects coming from the finite geometrical and energy resolving power of detectors are taken into account. When the widths to be measured are narrow, owing to the uncertainties associated with the method of projecting the data, one is forced to carry out kinematically incomplete experiments reducing the background in some way.

We carried out several $^3He + ^6Li \rightarrow \alpha + \alpha + p$ kinematically complete and incomplete experiments to populate the above T=1/2 ^5Li states[4-7]. The E_x and Γ values obtained are summarized in Table III.

E_x (MeV)	Γ(MeV)
g.s.	1.5 ± 0.2
5.5 ± 0.6	5.5 ± 0.6
16.66 ± 0.02	0.15 ± 0.04
17.9 ± 0.4	3.5 ± 0.8

Table III. Energy levels of ^5Li we deduced using reactions leading to three bodies in the final state.

Ground ^5Li state: for this state two $^3He + ^6Li \rightarrow \alpha + \alpha + p$ kinematically complete experiments were carried out. In the former, $\alpha\alpha$ coincidence spectra were recorded at an incident energy of 2.5 MeV; in the latter, αp spectra were obtained at $E(^3He)=1.6$ MeV[4].

By the first of these experiments we show that the asymmetry of the $^5Li_{g.s.}$ energy spectrum cannot be interpreted as an intrinsic property of this state. On the contrary the experimental data are well fitted when we consider the sum of two Lorentzian forms representing the ground and the first excited ^5Li states. By the second one we can conclude that at $E_{inc}=1.6$ MeV the Γ width of the $^5Li_{g.s.}$ is, within the experimental errors, not dependent on the detection geometry.

The values of the above Γ width deduced from both $^3He + ^6Li$ experiments do not present discrepancies and give an average value of (1.5 ± 0.2) MeV that is in line with the one of $\simeq 1.5$ MeV adopted by Ajzenberg-Selove[2].

First excited ^{5}Li state: the trend of the $P_{1/2}$ phase-shift suggests that this level is broad and, consequently, the location of the peak energy becomes very difficult. However, the discrepancies in literature for the E_x values of the mentioned excited state and the large uncertainty adopted by Ajzenberg-Selove$^{2)}$ are understandable. This should not occur for the width values and nevertheless for this quantity the uncertainty is large. We believe that it is due to interference effects, when present, and to the data analysis method used.

Bearing this in mind, we performed several kinematically complete experiments by using the ^{6}Li(^{3}He,$\alpha\alpha$p) reaction at incident energies between 1.65 and 2.2 MeV$^{5)}$. The beam energies and detection geometries were selected in a way that the spectral region of our interest were free from ^{8}Be level contributions. In this way only the ground and the first excited ^{5}Li states were present in our spectra.

By assuming that: i) in the recoil coordinate system the two above contributions can be represented by Lorentzian functions, ii) the interference effects can be neglected, we obtained a Γ value for the first excited ^{5}Li state that is in line with the one adopted in literature$^{2)}$. The excitation energy measured$^{5)}$ (see Table III), falling just at the lower limit of the wide range ($5 \div 10$ MeV) accepted by Ajzenberg-Selove$^{2)}$, is different from the 6.9 MeV deduced by the shell-model calculations for the A=5 systems$^{1)}$. The difference between the calculated value and the experimental determinations for the peak energy of the first excited ^{5}Li state can be attributed to the trend of $P_{1/2}$ phase-shift, and this makes the localization of the peak energy very difficult.

Second excited ^{5}Li state: the investigation of this long-lived level was carried out by analyzing the spectra of the $^3\text{He} + {}^6\text{Li} \longrightarrow \alpha + \alpha + p$ kinematically incomplete experiments at 8, 11, 13 and 14 MeV ^{3}He incident energies$^{6)}$. In this way we overcame all the problems and the uncertainties associated to any method of projecting the bidimensional spectra when the widths to be measured are narrow. In those experiments an appropriate choice of detector thickness allowed us to greatly reduce the background from the contribution of the protons in the spectrum region of our interest.

The obtained results do not show any difference in the values of peak energy E_x of the $(3/2^+, 1/2)$ adopted in literature[2) and the ones we measured at various beam energies and kinematical configurations. The value of (150 ± 40) keV measured for the Γ width of this state appears, on the contrary, in evident disagreement with the $\Gamma \approx 300$ keV adopted by Ajzenberg-Selove[2). We point out that the Γ value was deduced by observing coincidence spectra in order to keep the background to a minimum and to have the spectrum region involving this peak free from other contributions. Therefore the above Γ value represents a more careful determination of the 16.66 MeV ^{5}Li state width.

Third excited ^{5}Li state: the shell-model calculations assign an excitation energy of 18.4 MeV[1) to this $(1/2^+, 1/2)$ state. The last Ajzenberg-Selove compilation for the A=5 systems[2) admits the likely existence in this level region of a broad peak having $E_x=(18 \pm 1)$ MeV.

By analyzing the ^{3}He + ^{6}Li $\rightarrow \alpha + \alpha + p$ kinematically complete experiments, performed at incident energies of 11, 13 and 14 MeV, we observed the decay of this ^{5}Li state[7) in the α+p channel and by extracting the contributions of the mentioned state we measured the relevant spectroscopic parameters.

The value deduced for the excitation energy $E_x=(17.9 \pm 0.4)$ MeV is in line with both the ones calculated by the shell model[1) and the one adopted in literature[2). For the Γ width of the same state a comparison is not possible since the (3.5 ± 0.8) MeV value we measured is the first quantitative estimate of the width of the third excited ^{5}Li state[7) $(J^\pi=1/2^+, T=1/2)$.

As a result of this review on the ^{5}Li states we can affirm that the agreement among E_x values deduced by shell-model calculations[1] (Table I) and the corresponding ones adopted by Ajzenberg-Selove[2] (Table II) is quite good. Although the values of the above energies of the ^{5}Li nucleus we measured[4–7] are in good agreement with the ones adopted in literature, they are quite different from the ones deduced by the theoretical predictions[1] only for the $J^{\pi}=1/2^{-}$ first excited ^{5}Li state.

Regarding the Γ widths of the same ^{5}Li states the values we measured[4,5] for the ground and first excited ^{5}Li states are in line with the ones adopted in literature[2]. For the $J^{\pi}=3/2^{+}$ at E_x=16.66 MeV the width of (150±40) keV, obtained by analyzing the α inclusive spectra coming from the ^{3}He + ^{6}Li experiment[6] takes the place of the value≈300 keV adopted[2] up to now. Finally, for the $3/2^{+}$ state at (17.9±0.4) MeV the *broad* peak associated to the Γ value[2] of (3.5±0.8) MeV measured in our experiment[7] was assumed.

However, we can state that the E_x and Γ values (except the excitation energy of the $J^{\pi}=1/2^{-}$ state) we obtained more precisely, by analyzing three-body reactions, are in line with the ones deduced by shell-model calculations as well as with the ones adopted in literature.

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This work was supported in part by the Istituto Nazionale di Fisica Nucleare and the Comitato Regionale per le Ricerche Nucleari e di Struttura della Materia.

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