Physics Letters B 782 (2018) 779–784

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Measurement of the full excitation spectrum of the ^{7}Li$(p,\gamma)\alpha\alpha$ reaction at 441 keV

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A R T I C L E   I N F O

Article history:
Received 28 February 2018
Received in revised form 1 May 2018
Accepted 5 June 2018
Available online 14 June 2018
Editor: D.F. Geesaman

Keywords:
Ab initio
R-matrix
^{8}Be
Radiative decay width
Light nuclei

A B S T R A C T

A current challenge for ab initio calculations is systems that contain large continuum contributions such as ^{8}Be. We report on new measurements of radiative decay widths in this nucleus that test recent Green's function Monte Carlo calculations.

Traditionally, γ ray detectors have been utilized to measure the high energy photons from the ^{7}Li$(p,\gamma)\alpha\alpha$ reaction. However, due to the complicated response function of these detectors it has not yet been possible to extract the full γ ray spectrum from this reaction. Here we present an alternative measurement using large area Silicon detectors to detect the two α particles, which provides a practically background free spectrum and retains good energy resolution.

The resulting spectrum is analyzed using a many-level multi channel R-matrix parametrization. Improved values for the radiative widths are extracted from the R-matrix fit. We find evidence for significant non-resonant continuum contributions and tentative evidence for a broad 0^+ resonance at 12 MeV.

1. Introduction

In recent years *ab initio* calculations of atomic nuclei, such as Green's function Monte Carlo (GFMC) [1] and No Core Shell Model (NCSM) [2], have advanced tremendously and now provide quite accurate predictions for light nuclei. Historically, NCSM has struggled with highly clustered states. However, the method has recently been combined with the resonating group method (RGM) to better describe clustered nuclei including continuum properties [2].

In this context ^{8}Be provides an interesting benchmark. All states in this isotope are unbound with its ground state located just 92 keV above the 2α threshold. The lowest two states are highly clustered while some of the resonances at higher energy couple relatively weakly to the 2α final state.

GFMC calculations of electromagnetic transitions in ^{8}Be have been performed by Pastore et al. [1], and experimentally γ decays of several states in ^{8}Be have been measured. The focus of the present letter is the γ decay of the 17.64 MeV 1^+ state. M1 decays of this state could populate both 0^+ and 2^+ states. There are two measurements of the transition strength to the ground- and first excited states in ^{8}Be [3,4], and two measurements of transitions to the 2^+ doublet at 16.6–16.9 MeV [5,6]. However, due to the complicated response function of previous measurements it has not been possible to extract the full γ ray spectrum – specifically none of the previous measurements were sensitive to γ decays into the unresolved energy region below the 2^+ doublet.

This region was resolved experimentally using e.g. α–α scattering and the β-decay of ^{8}B and ^{8}Li [7]. To understand these different ways of populating ^{8}Be, it is necessary to have contributions not only from the known resonances, but also a broad contribution [7] between the first excited state at 3 MeV and the isospin mixed 2^+ doublet at 16.6–16.9 MeV. It is unclear if this contribution represents a 2^+ intruder state, a non-resonant continuum contribution, or the low energy tails of high energy resonances [7,8]. From theory there is also a prediction of a 0^+ $T=0$ intruder state at around 12 MeV [9].

In this letter we will present a measurement of the γ decay of the 17.64 MeV 1^+ state using a method which is sensitive to this region of interest and essentially background free. By this method we will not only address the question of intruder states, but also derive new more reliable values for the partial decay widths of the already measured transitions.

It should be noted that electromagnetic transitions from the 1^+ states of ^{8}Be are also of high current interest due to the obser-

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https://doi.org/10.1016/j.physletb.2018.06.013

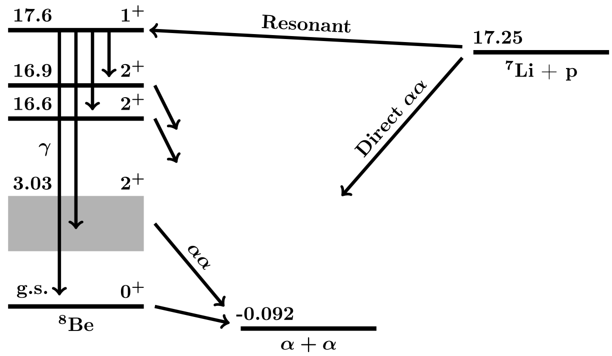

Fig. 1. Decay scheme. Only levels populated in the $p+{}^{7}$Li reaction or the γ subsequent decay is shown. Energies are in MeV relative to the ^{8}Be ground state.

vation of anomalous internal pair creation in ^{8}Be and the interpretation of that as a possible indication of a new light, neutral boson [10,11].

2. Experiment

The experiment was conducted at the 5 MV Van de Graaff accelerator at Aarhus University that provided a beam of H_3^+ with energies between 1305 keV and 1410 keV. The 17.64 MeV state was populated using the ^{7}Li(p,γ) reaction as illustrated on Fig. 1. The beam current was measured using a suppressed Faraday cup 1 m downstream of the target. Typical beam currents were between 200 pA and 1 nA and the beam spot was defined by a pair of 1×1 mm vertical and horizontal slits. The beam impinged on a natural LiF target manufactured in house by evaporation of a 160 nm ($\pm$10%) layer of natural lithium fluoride onto a thin ~ 4 μg cm^{-2} carbon backing.

The 17.64 MeV state was populated resonantly via ^{7}Li(p,γ), as depicted in Fig. 1. While gamma rays were not directly observed, the occurrence of electromagnetic de-excitation was inferred indirectly from the energies of the two α particles emitted in the subsequent breakup. Charged particles were detected with two double-sided silicon strip detectors (DSSD) of the W1 type from Micron Semiconductors [12] giving a simultaneous measurement of position and energy. Each detector had an active area of 5×5 cm divided into 16×16 orthogonal strips and was positioned 4 cm from the target at 90 deg with respect to the beam axis.

A resonance scan was performed with proton energies from 435 to 470 keV and afterwards data was acquired at 446 keV for 52 hours and at 455 keV for 63 hours.

3. Data reduction

The data was analyzed using the full kinematic approach as described in Ref. [13]. The signal of interest is two coincident α particles with missing energy corresponding to the reaction $p+{}^{7}\text{Li}\rightarrow {}^{8}\text{Be}^{*}\rightarrow\gamma+\alpha+\alpha$ as illustrated in Fig. 1.

Our coincidence requirement is a time difference of less than 13 ns. As our coincidence timing resolution is 9.3 ns FWHM this includes $>99\%$ of all true coincidences. All coincidences surviving this cut are then corrected for energy loss in the detector deadlayer and target foil assuming they were α particles. The energy of each particle in the center of mass (CM) of $p+{}^{7}$Li reaction was determined from its direction and energy. With a simultaneous detection of two α particles one can infer the corresponding ^{8}Be excitation energy from their summed 4-momentum. Fig. 2 shows the difference in CM energy versus the ^{8}Be excitation energy. In the limit of zero recoil, conservation of energy and momentum

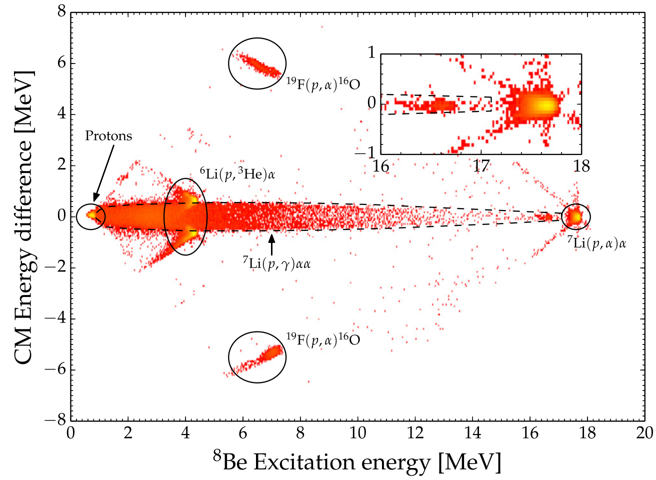

Fig. 2. Difference in CM energy vs ^{8}Be excitation energy. The circles mark various background reactions while the band within the dashed contour stretching from 1 to 17 MeV corresponds to γ delayed α particles. The insert shows the high excitation energy region. The color scale is logarithmic.

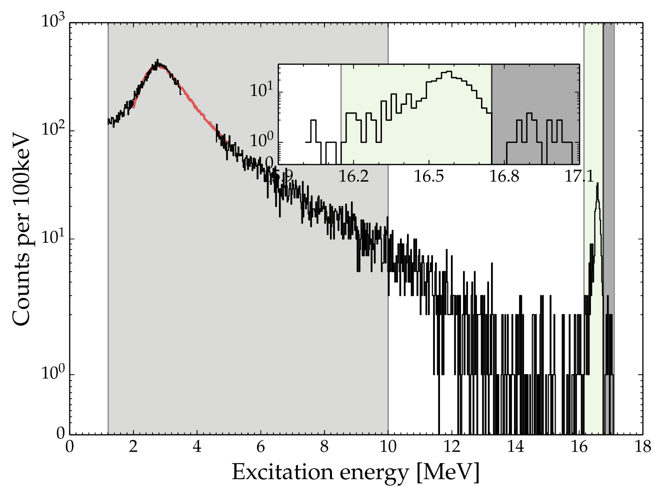

Fig. 3. Projected excitation spectrum. The superimposed curve is the best fit to the peak of first excited state with a single level R-matrix formula. See Section 4.1 for details.

dictates that the two alpha particles should have equal CM energies. When the small, but finite, recoil is taken into account, the CM energy-difference distribution remains centered very close to zero, but acquires a sizable spread. Hence the horizontal band in the figure corresponds to the ^{7}Li$(p,\gamma)\alpha\alpha$ reaction. At high excitation energy there is a distinct peak corresponding to the direct reaction ^{7}Li$(p,\alpha)\alpha$. The two weak diagonal bands extending from the peak correspond to events with insufficient energy loss correction. These do not interfere with the region of interest and their strength is negligible compared to the peak. There are two similar peaks at roughly 4 MeV, which both correspond to ^{6}Li$(p,\alpha)^{3}$He. At 7 MeV there are two bands with large deviations from equal energy. This is a background reaction on fluorine ^{19}F$(p,\alpha)^{16}$O. At low energy we see random coincidences with the beam. The identity of the various components was verified with a Monte Carlo simulation. The α-source energy calibration of the excitation spectrum was cross checked against the ^{6}Li$(p,\alpha)^{3}$He and ^{7}Li$(p,\alpha)\alpha$ peaks and was found to agree within 4 keV with the tabulated values [8]. It should be stressed that this spectrum is essentially background free in the region of interest, except for the small re-