(INTC-P-572) Spectroscopy of ^{8}Be: Search for Rotational Bands Above 16 MeV

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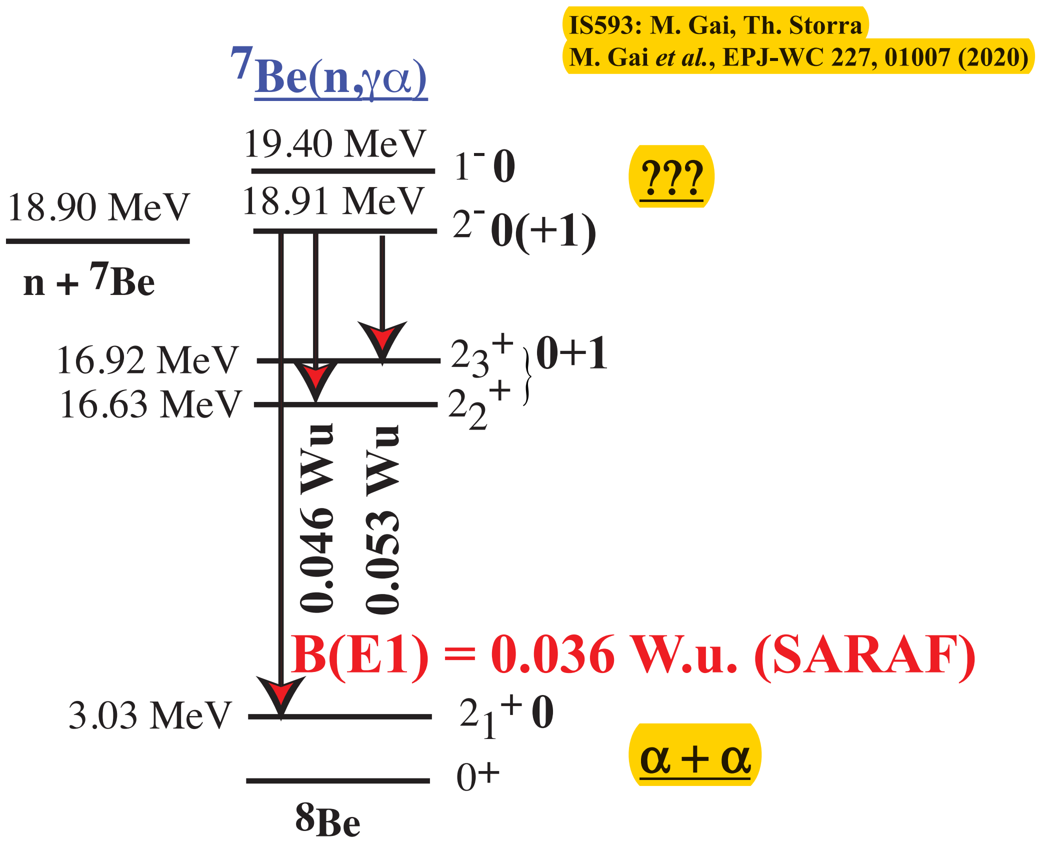
http://astro.uconn.edu

1. **Motivation:** Algebraic Cluster Model (^{12}C)
   Cluster Shell Model (^{9}Be)
2. **Particle-Hole States in ^{8}Be:** $K^\pi = 2^+$, 1^+ and 2^- Bands
3. **Goals:** 21.5 MeV $J^\pi = 3^-$ or 3^+ ? ($K^\pi = 2^-$)
   22.9 MeV $J^\pi = 3^+$??? ($K^\pi = 1^+$)

65th INTC, Geneva (Zoom), November 4, 2020



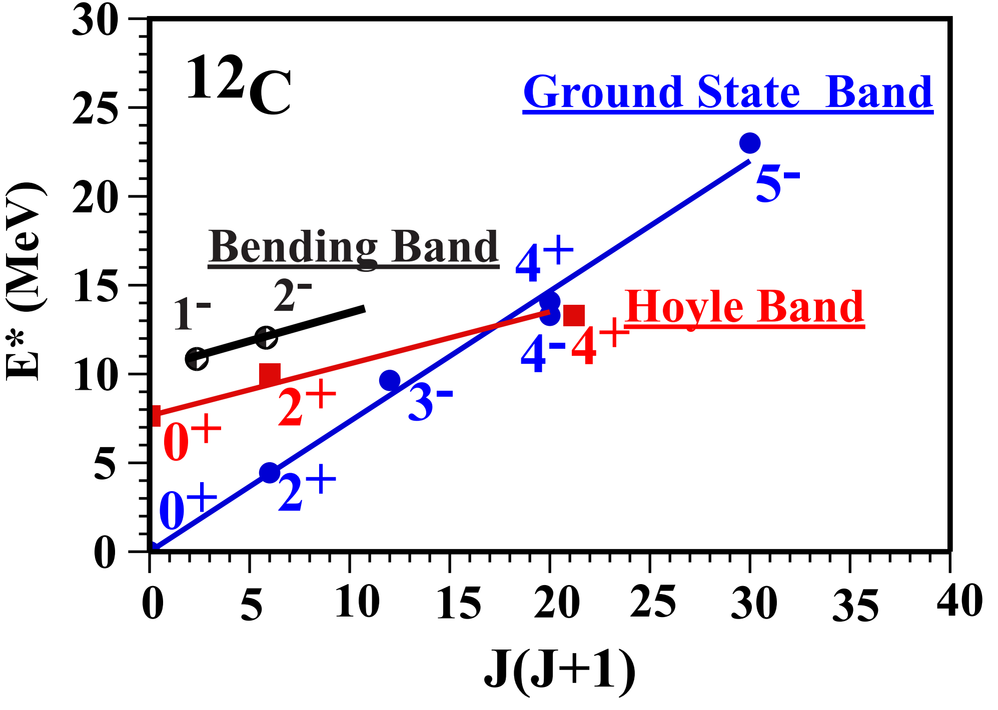
IS593: M. Gai, Th. Storra
M. Gai *et al.*, EPJ-WC 227, 01007 (2020)
^{7}Be(n,γα)
19.40 MeV
1^- 0
???
18.90 MeV
n + ^{7}Be
18.91 MeV
2^- 0(+1)
16.92 MeV
16.63 MeV
2_3^+
2_2^+
0+1
0.046 Wu
0.053 Wu
B(E1) = 0.036 W.u. (SARAF)
3.03 MeV
2_1^+ 0
α + α
0+
^{8}Be

Algebraic Cluster Model (ACM):

R. Bijker, F. Iachello, Ann. Phys. (N.Y.) 298, 334 (2002).

Evidence for Triangular $\mathcal{D}_{3h}$ Symmetry in ^{12}C:

D.J. Marin-Lambarri, R. Bijker, M. Freer, M. Gai, Tz. Kokalova, D.J. Parker, C. Wheldon, Phys. Rev. Lett. 113, 012502 (2014)



V. Della Rocca, R. Bijker, F. Iachell0, Nucl. Phys. A 966(2017)156
V. Della Rocca, F. Iachello, Nucl. Phys. A 973(2018)1

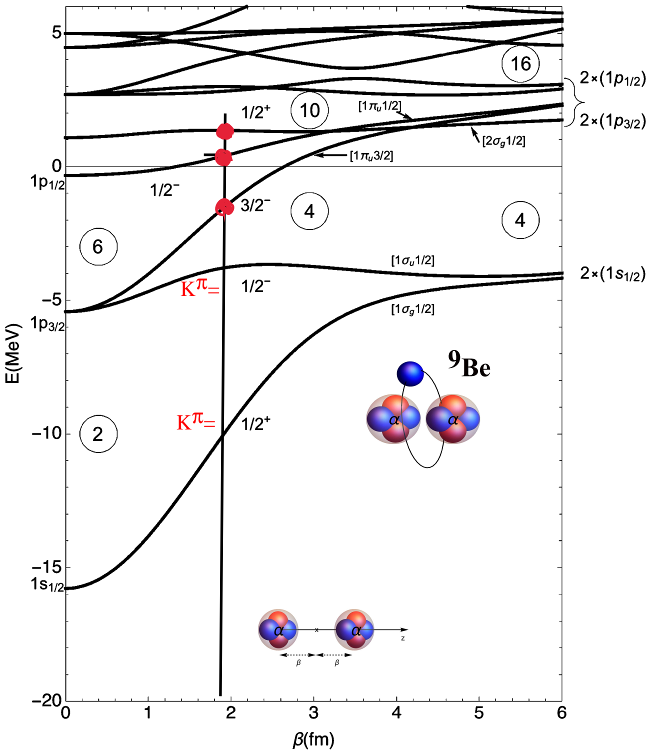


Fig. 5. Energy levels ϵ_Ω in a potential with $V_0 = 20$ MeV, $V_{so} = 22$ MeVfm^2 and $\alpha = 0.1115$ fm^{-2}, appropriate to ^{9}Be.

Table 5
Intrinsic energies in ^{9}Be at $\beta = 1.82$ fm.

State Ω	K^P	ϵ_Ω (MeV)
$3/2^-$		-1.78
$1/2^-$		$+0.32$
$1/2^+$		$+1.35$

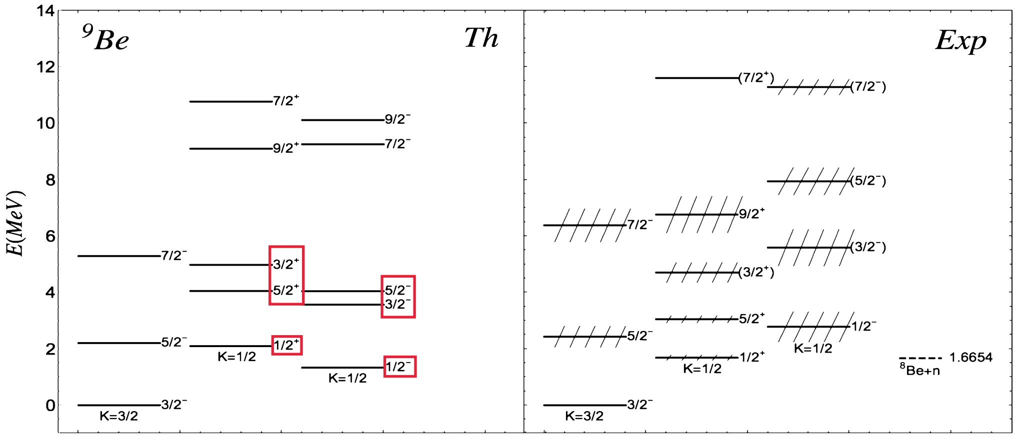


Fig. 7. Comparison between the cluster spectrum in CSM and the experimental spectrum of ^{9}Be [50]. The dashed region is given by the width of the states.

$|^9Be\rangle = |^8Be\rangle \otimes |n\rangle \qquad |^8Be\rangle = \alpha + \alpha$

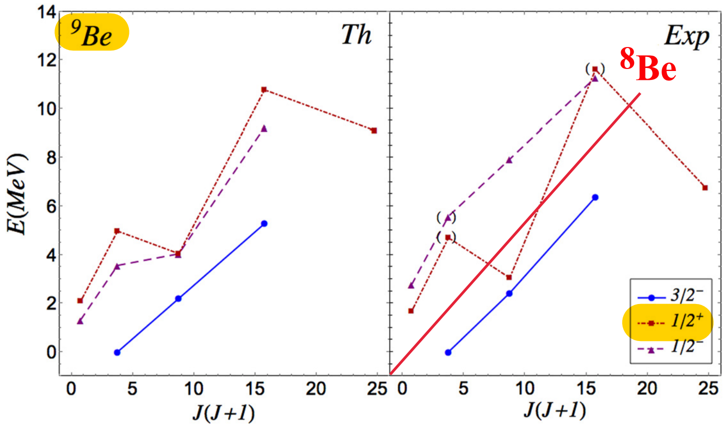
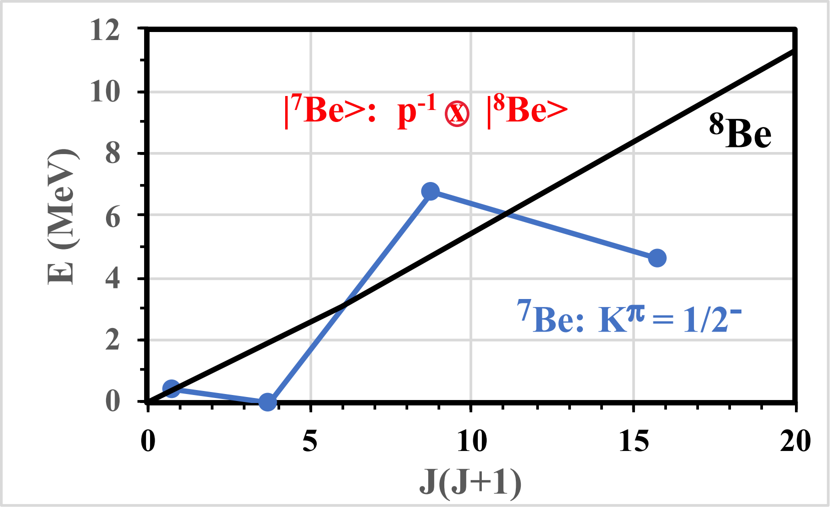
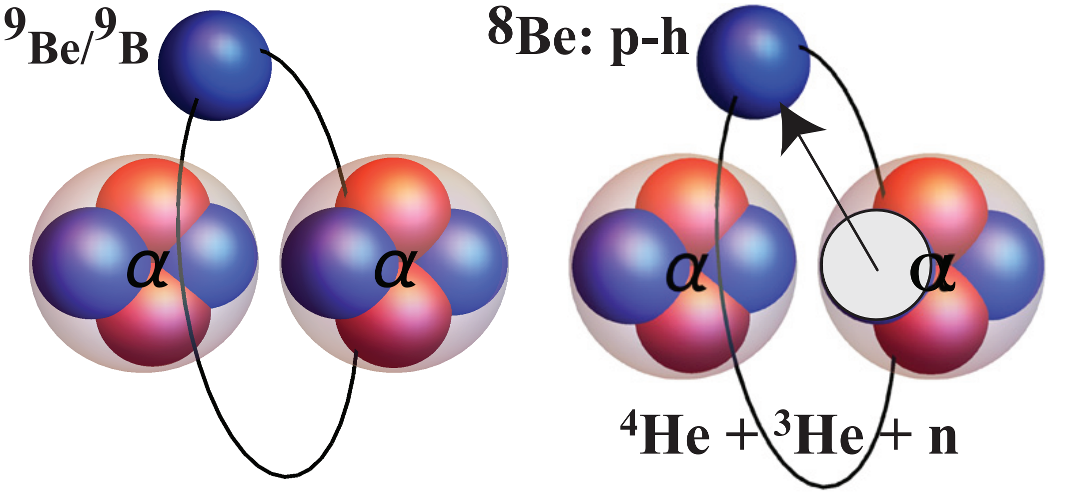


Fig. 8. Observed rotational bands in ^{9}Be.



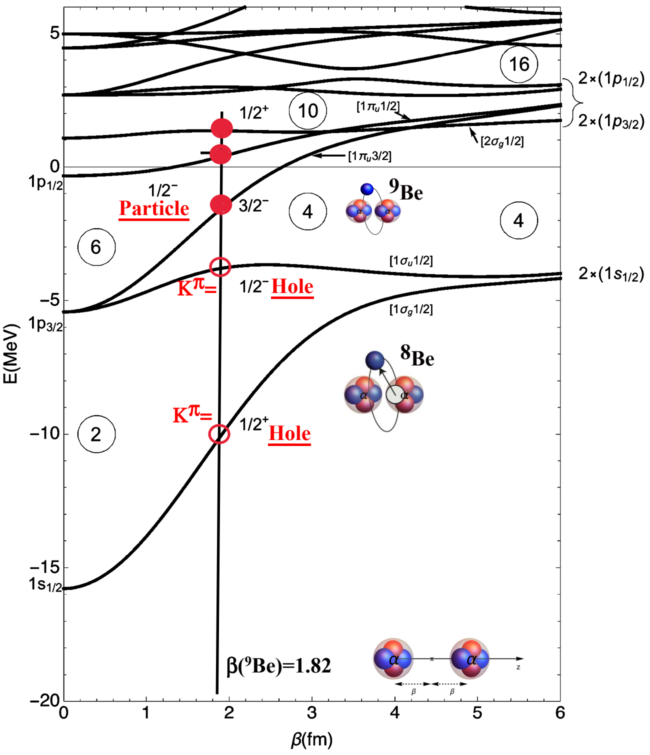
|7Be>: p-1 ⊗ |8Be>
8Be
7Be: Kπ = 1/2-
E (MeV)
J(J+1)
0
2
4
6
8
10
12
0
5
10
15
20

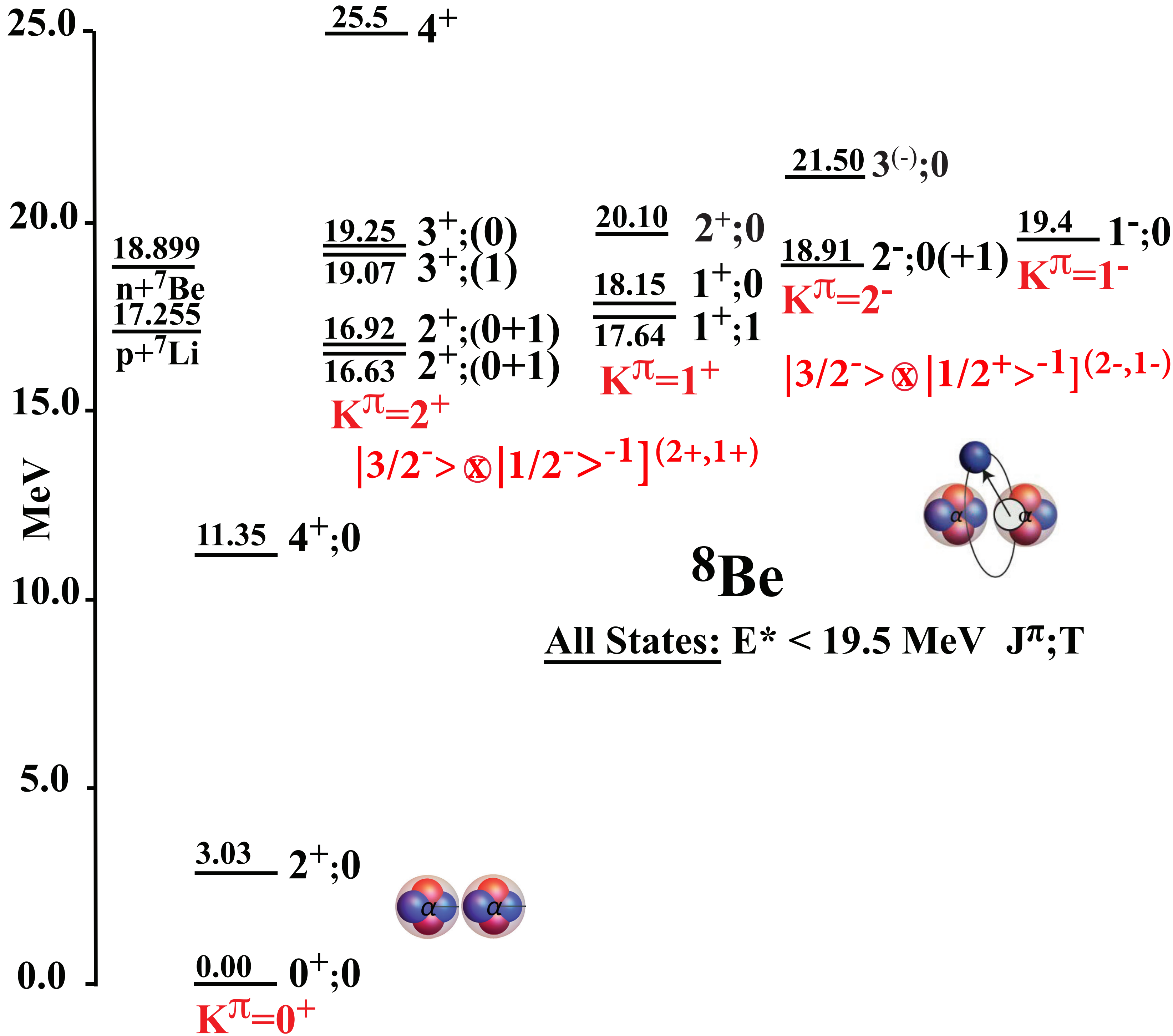


$^9Be/^9B$
α
α
^8Be: p-h
α
α
$^4He + ^3He + n$

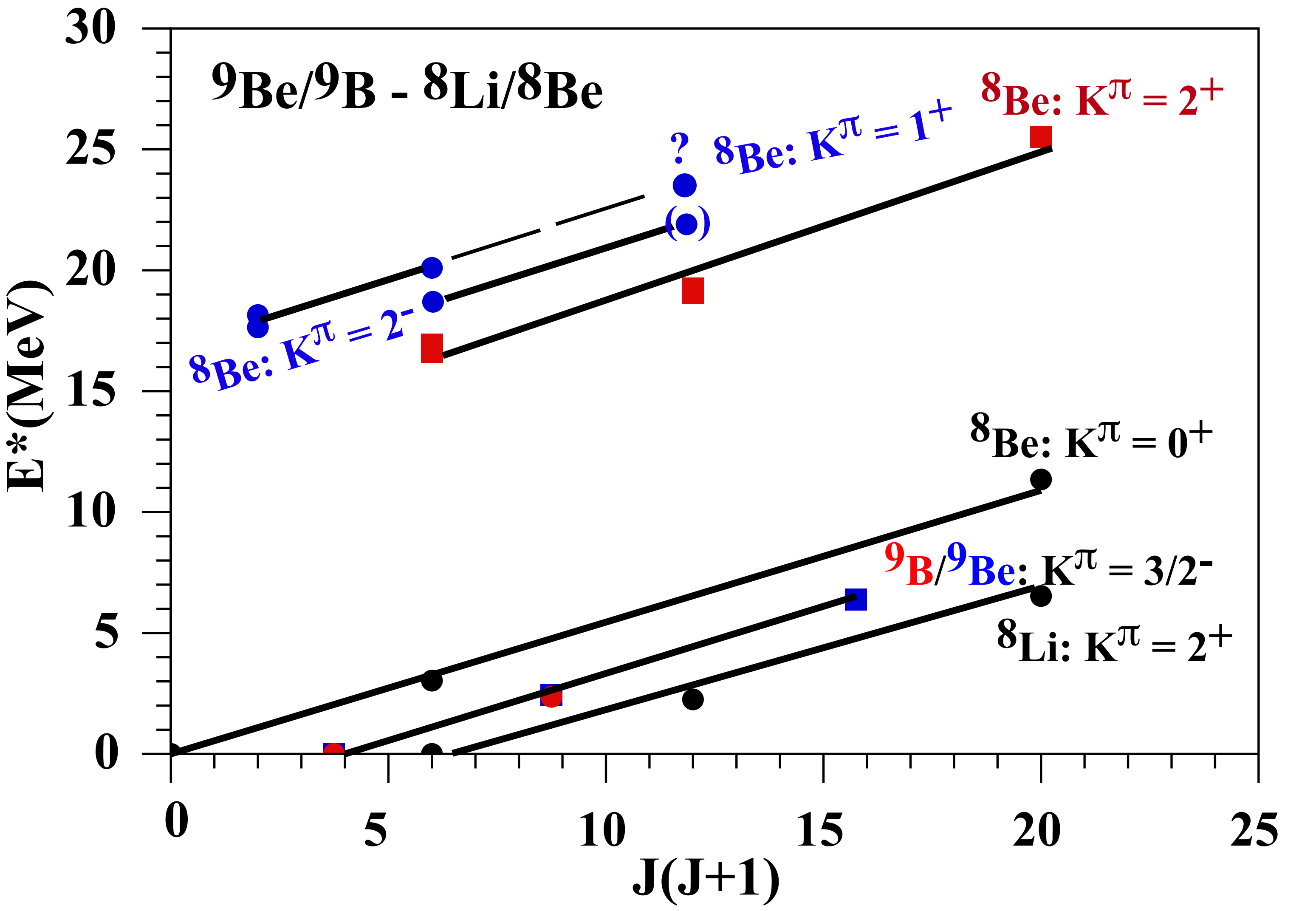
V. Della Rocca, F. Iachello / Nuclear Physics A 973 (2018) 1–32

(The Cluster Shell Model)





25.0
20.0
15.0
10.0
5.0
0.0
MeV
18.899
n+7Be
17.255
p+7Li
25.5 4+
19.25 3+;(0)
19.07 3+;(1)
16.92 2+;(0+1)
16.63 2+;(0+1)
Kπ=2+
|3/2->⊗|1/2->-1](2+,1+)
11.35 4+;0
3.03 2+;0
0.00 0+;0
Kπ=0+
α α
20.10 2+;0
18.15 1+;0
17.64 1+;1
Kπ=1+
21.50 3(-);0
18.91 2-;0(+1)
Kπ=2-
19.4 1-;0
Kπ=1-
|3/2->⊗|1/2+>-1](2-,1-)
α α
8Be
All States: E* < 19.5 MeV Jπ;T



30
25
20
15
10
5
0
E*(MeV)
0
5
10
15
20
25
J(J+1)
9Be/9B - 8Li/8Be
8Be: Kπ = 2+
?
8Be: Kπ = 1+
( )
8Be: Kπ = 2-
8Be: Kπ = 0+
9B/9Be: Kπ = 3/2-
8Li: Kπ = 2+

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Investigating the ^{10}Li continuum through ^{9}Li$(d,p)^{10}$Li reactions

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ABSTRACT

The continuum structure of the unbound system ^{10}Li, inferred from the ^{9}Li$(d,p)^{10}$Li transfer reaction, is reexamined. Experimental data for this reaction, measured at two different energies, are analyzed with the same reaction framework and structure models. It is shown that the seemingly different features observed in the measured excitation energy spectra can be understood as due to the different incident energy and angular range covered by the two experiments. The present results support the persistence of the $N=7$ parity inversion beyond the neutron dripline as well as the splitting of the well-known low-lying p-wave resonance. Furthermore, they provide indirect evidence that most of the $\ell=2$ single-particle strength, including possible $d_{5/2}$ resonances, lies at relatively high excitations energies.

1. Introduction

Understanding the nuclear shell evolution as a function of the proton-neutron asymmetry is one of the major goals in nowadays nuclear physics. Within this broad and ambitious program, the $N=7$ isotopic chain has received much attention both experimentally [1–21] and theoretically [22–30]. The ^{10}Li system represents a prominent member of this chain, due to its peculiar features. First, it is the first unbound $N=7$ isotone, following the weakly-bound ^{11}Be nucleus. Second, several experiments [4,11,31] suggest that its ground state consists of an $\ell=0$ virtual state, followed by a narrow p-wave resonance, whose energy sequence would point toward a persistence of the parity inversion observed in ^{11}Be. Finally, an accurate knowledge of the ^{10}Li system is crucial for a proper understanding of the ^{11}Li nucleus, the archetypal three-body Borromean nucleus.

Despite this interest, and the extensive experimental and theoretical efforts, important questions regarding the structure of ^{10}Li remain unanswered. Due to the non-zero spin of the ^{9}Li *core*, the s-wave and p-wave structures are expected to split into $(1^-,2^-)$ and $(1^+,2^+)$ doublets, respectively. However, these doublets have not yet been clearly identified experimentally. In particular, it is unclear whether the prominent peak observed in several experiments [12,14,20], and identified with the $p_{1/2}$ resonance, corresponds to the centroid of the (unresolved) doublet or just to one of its members, with the other component being pushed at higher excitation energies.

In the case of the $s_{1/2}$ virtual state, the situation is less clear. Experimentally, its presence was inferred from the narrow width of the momentum distribution in one-proton and one-neutron removal experiments of energetic ^{11}Be and ^{11}Li beams on a carbon target [31]. Another experimental evidence came from the measurement of the relative velocity distribution between the ^{9}Li and the neutron resulting from the decay of ^{10}Li produced after the collision of a ^{18}O beam on a ^{9}Be target [4]. This relative velocity was found to peak at zero, which is consistent with an $\ell=0$ configuration for the ^{10}Li ground-state. The search for this virtual state has been also pursued with transfer experiments. For example, the excitation function extracted for the reaction ^{9}Li$(d,p)^{10}$Li measured at $E=2.4$ MeV/u at REX-ISOLDE exhibited an excess of strength at zero energy which was consistent with a virtual state with a (negative) scattering length of the order of 13-24 fm [11]. However, a more recent experiment for the same transfer reaction performed at TRIUMF at a higher incident energy [20] did not show any indication of such near-threshold structure, putting into question its very existence.

The situation regarding the presence of one or more $d_{5/2}$ low-lying resonances is even more controversial. Evidence of such a resonance at $E_r \sim 1.5$ MeV has been reported in a fragmentation experiment of ^{11}Li on ^{12}C performed at GSI [12], and supported by the theoretical analysis of Blanchon et al. [26]. The excitation function extracted from the ^{9}Li$(d,p)^{10}$Li reaction [20] displayed also a small bump at $E_r = 1.5$ MeV, but the theoretical analysis

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Mario Gomez-Ramos, Septemebr 21, 2020

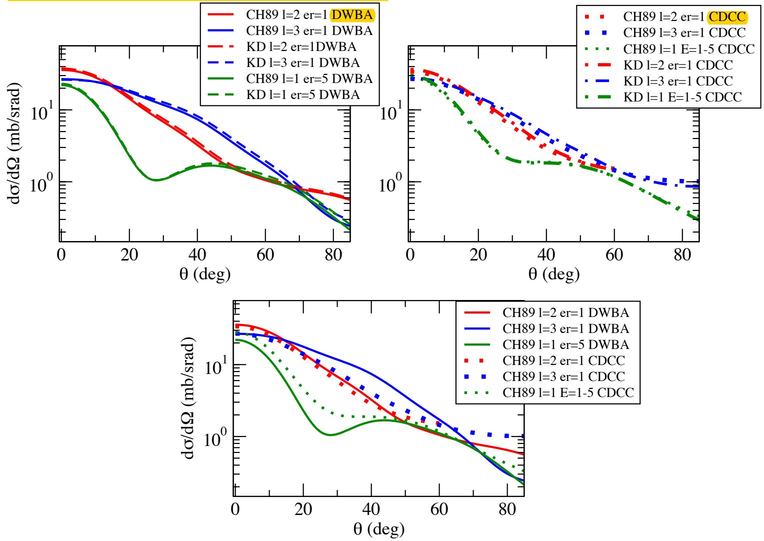


Fig. 3: DWBA (top) and CDCC (bottom) calculations for l = 1 (green), 2 (red) and 3 (grey) neutron (hole) transfer in the ^{7}Be(d,p) reaction, for a nominal state at 21.5 MeV, as discussed in the text.

^{7}Be(d,p): <^{7}Be+n|^{8}Be; p-h> <^{3}He+α+n|^{8}Be; p-h> **Jesus Casal**

^{10}B(d,α) : **Complicated interpretation, perhaps multi-step**

Liam Gaffney, September 21, 2020

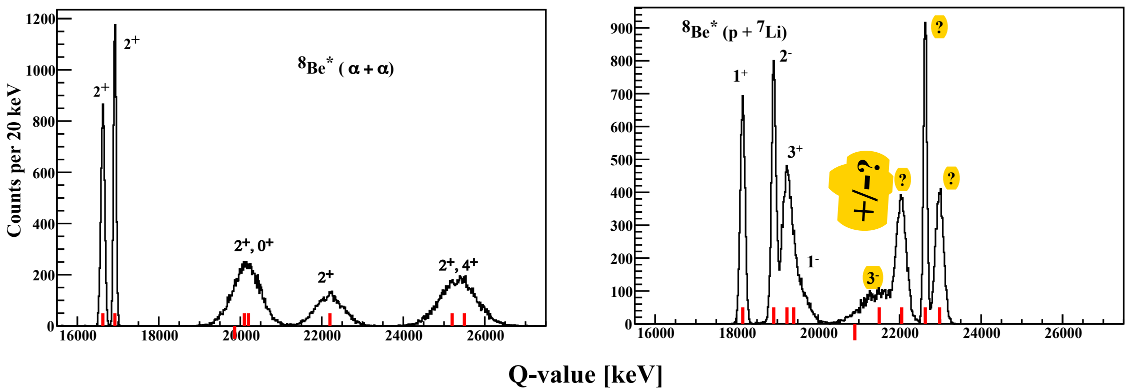
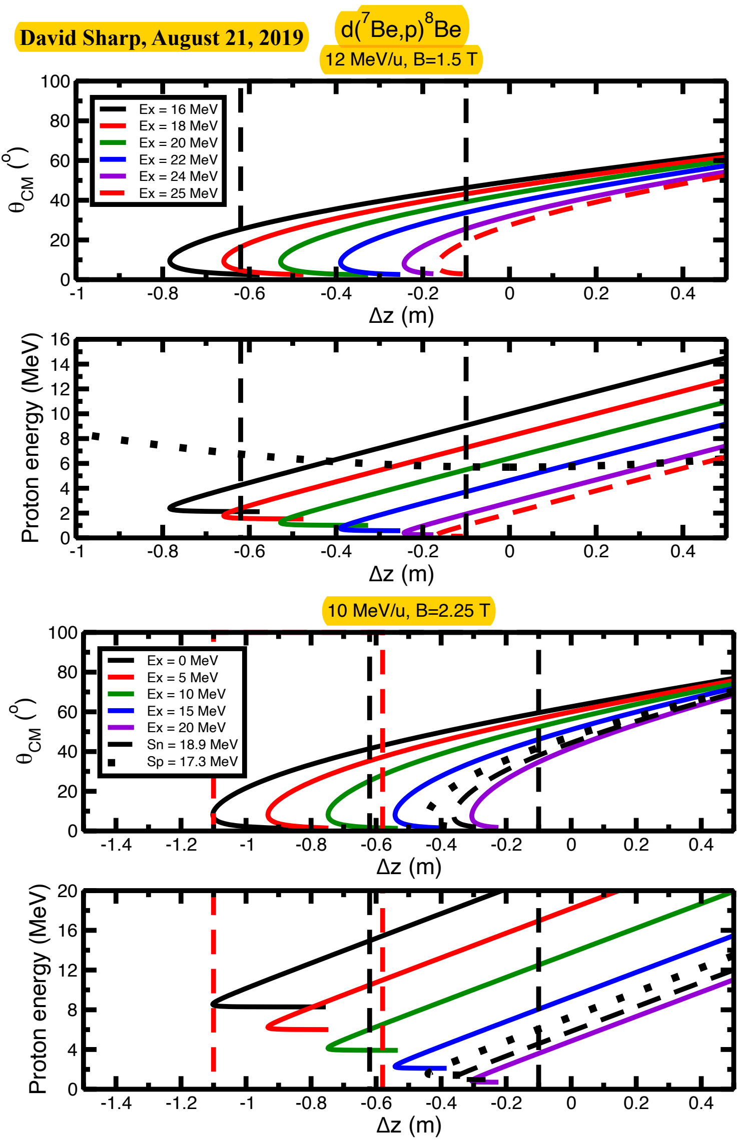


Fig. 4: Simulated proton spectra in coincidence with alpha-particle (left) and ^{7}Li (right).


David Sharp, August 21, 2019
d(7Be,p)8Be
12 MeV/u, B=1.5 T
θCM (°)
Ex = 16 MeV
Ex = 18 MeV
Ex = 20 MeV
Ex = 22 MeV
Ex = 24 MeV
Ex = 25 MeV
Δz (m)
Proton energy (MeV)
Δz (m)
10 MeV/u, B=2.25 T
θCM (°)
Ex = 0 MeV
Ex = 5 MeV
Ex = 10 MeV
Ex = 15 MeV
Ex = 20 MeV
Sn = 18.9 MeV
Sp = 17.3 MeV
Δz (m)
Proton energy (MeV)
Δz (m)

Thank You
Continued by Robin Smith

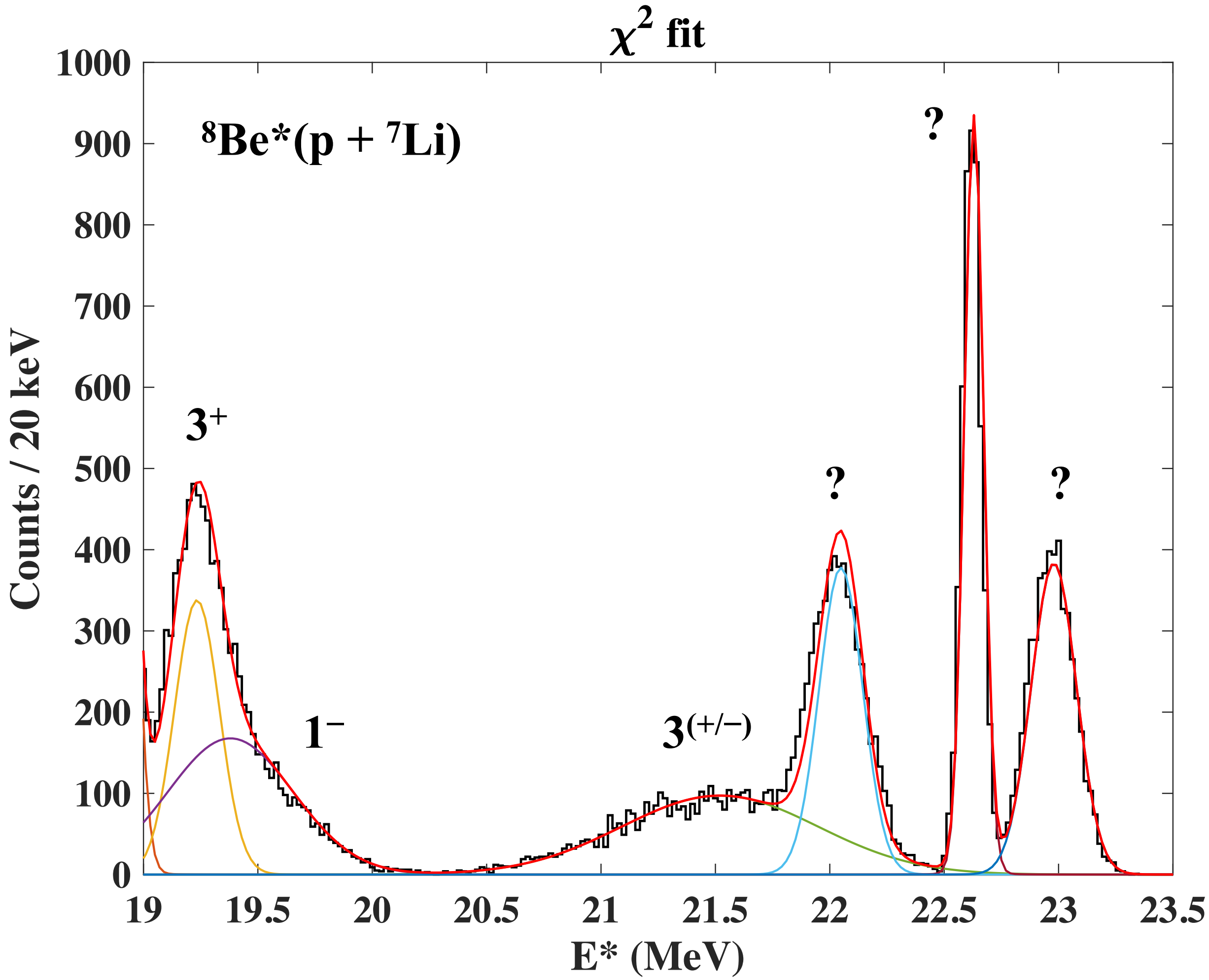
Robin Smith
Sheffield Hallam University
University of Connecticut

Experiment design

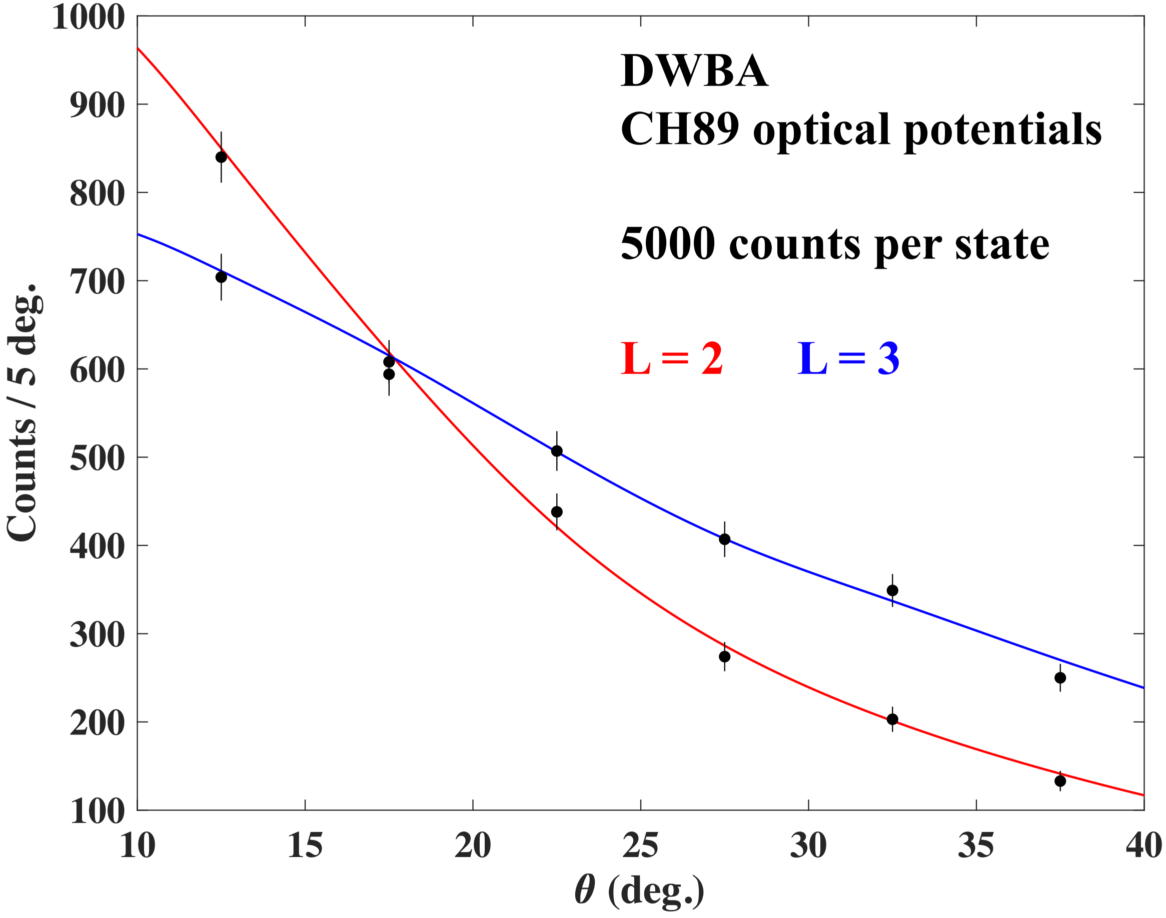
- Ensure states can be resolved in energy
- Ensure that angular distributions for different partial waves can be resolved – $3^{\pm}$
  - Evaluate counts per state required for clear comparison
- Compute efficiency to determine beam time required

Simulated spectrum T=0

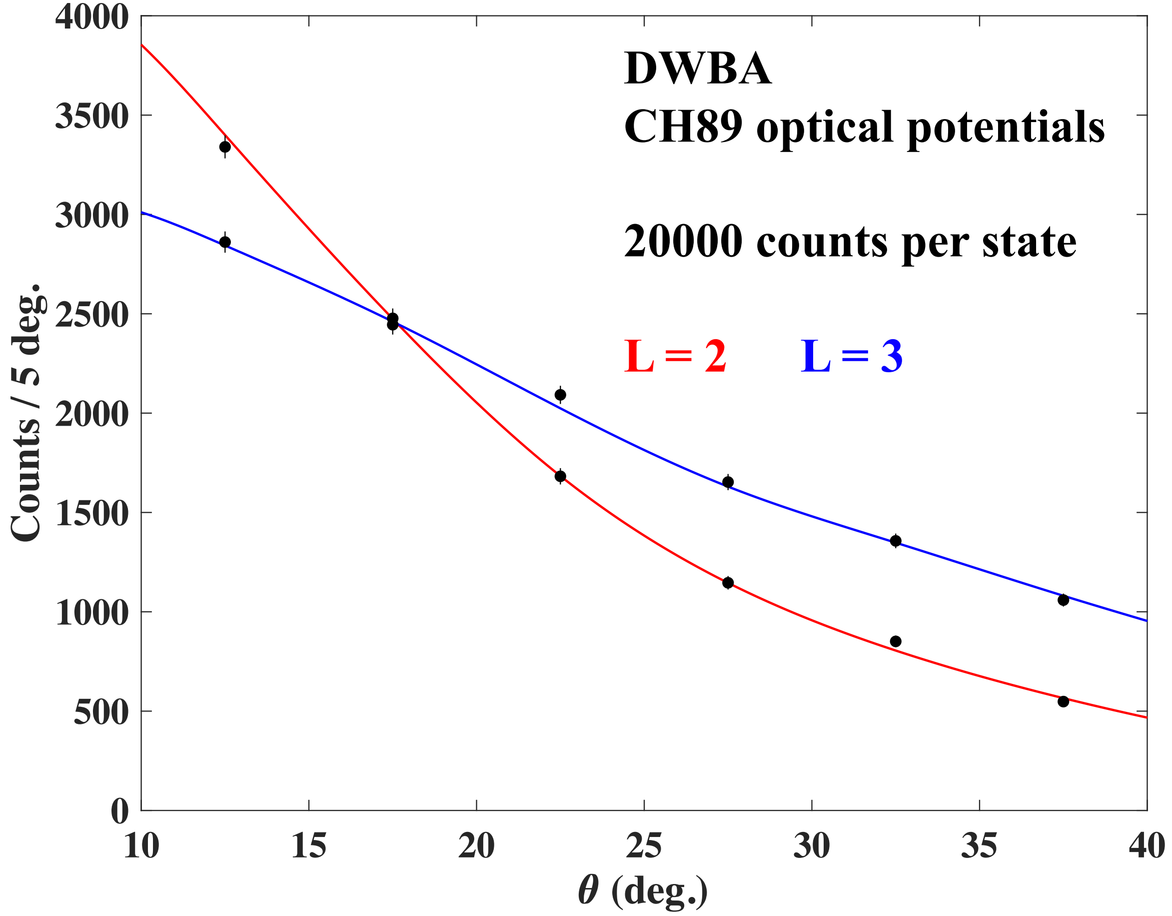
- 5000 counts per level
- Gaussian form



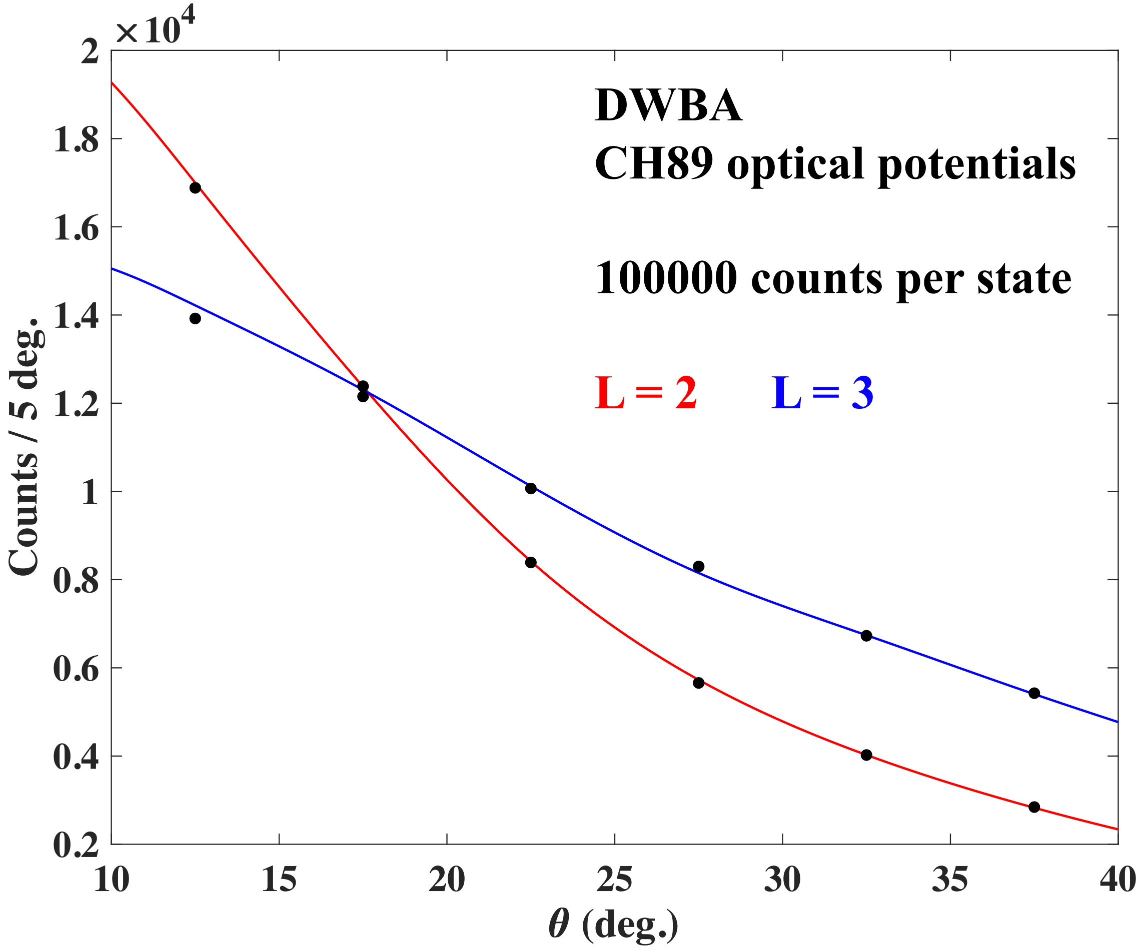
Simulated angular distributions



Simulated angular distributions

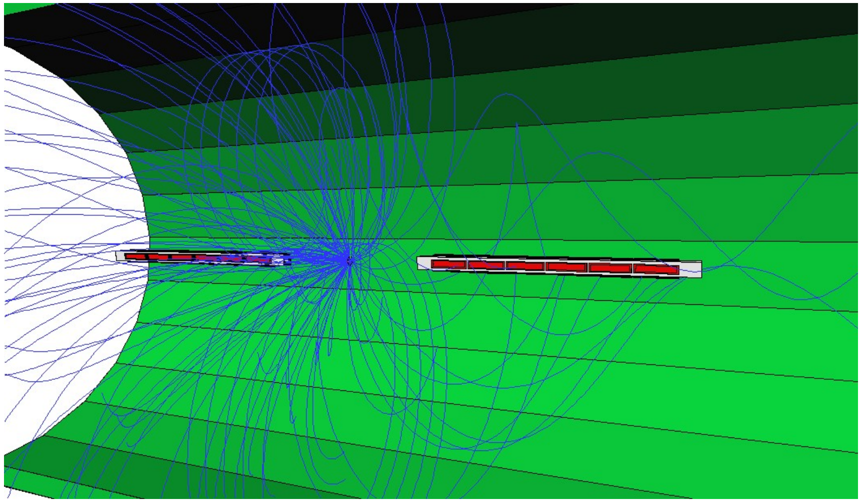


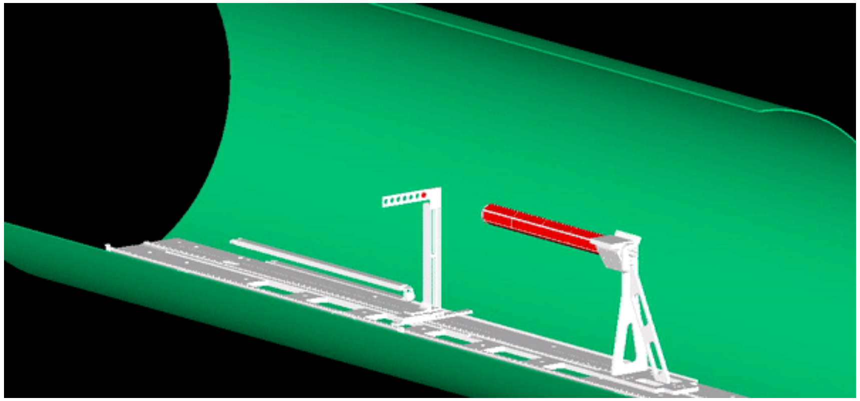
Simulated angular distributions



Detection efficiency

- ISS simulation package written using NPTool and GEANT4
- Performed by David Sharp (Manchester) and Marc Labiche (Daresbury)
- Efficiency
  - α channel – 28%
  - ^{7}Li channel – 84%



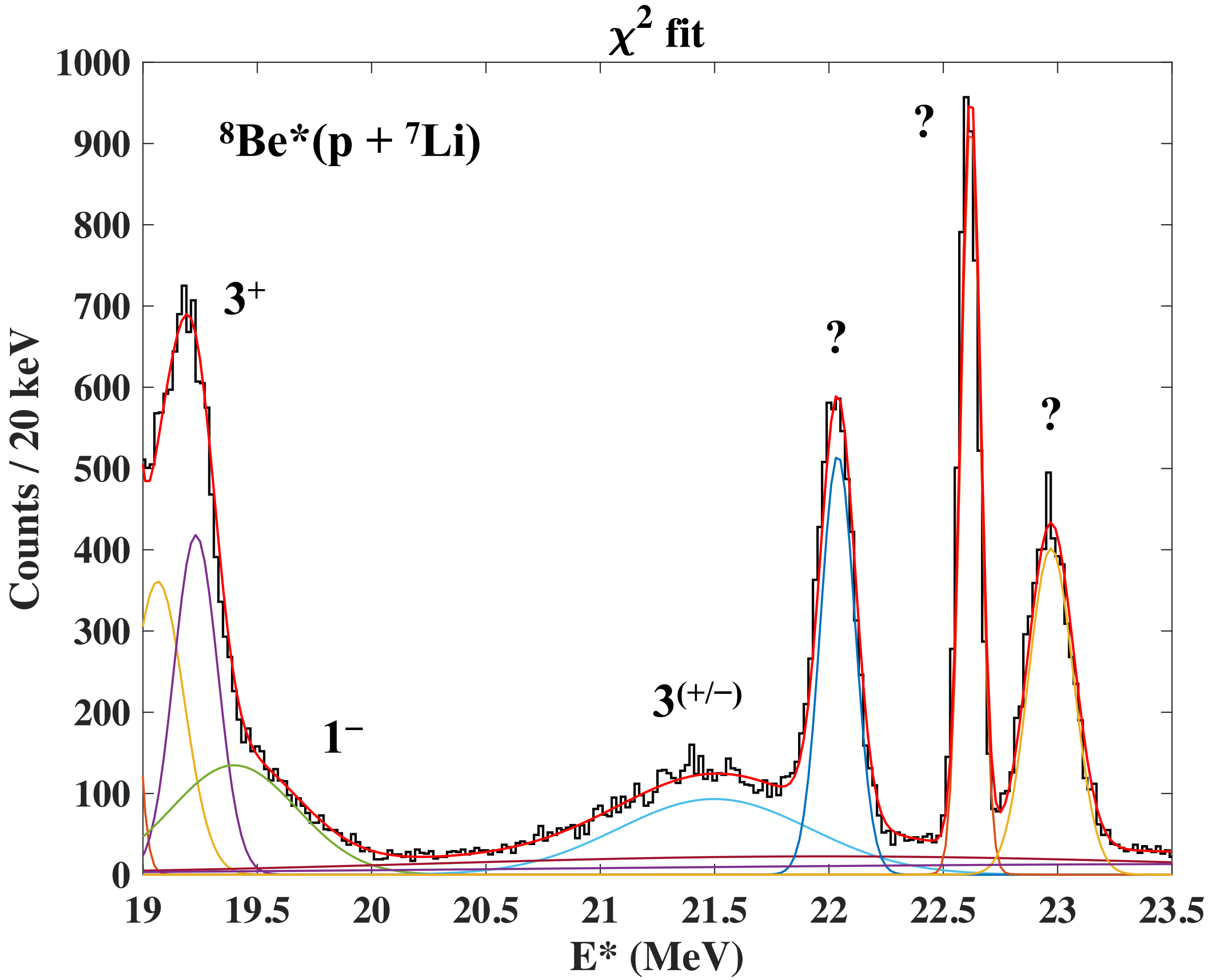


Beam time request

E_{beam} (MeV)	$\frac{d\sigma}{d\Omega}\left(\frac{mb}{Sr}\right)$	σ (mb)	Efficiency %	Target thickness $(\mu g/cm^2)$	Beam intensity (pps)	Time for 100k
12 MeV/u	~ 1	~ 4.66	84	100 – 200	5×10^6	5 days (15 shifts)

Simulated spectrum inc. T=1

- 5000 counts per level
- Broad T=1 levels appear as a small background



P. Navratil and B.R. Barrett, Phys. Rev. C **57**, (1998)

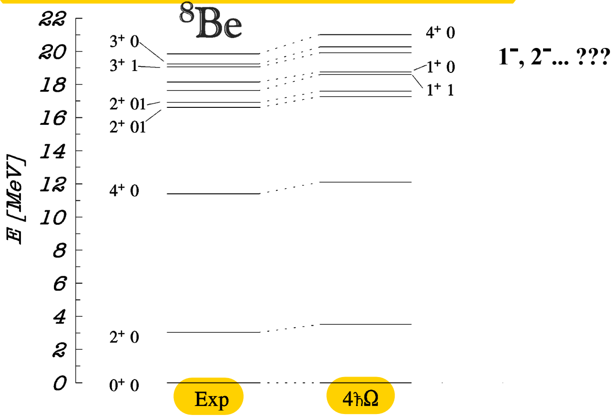


FIG. 7. The experimental and calculated excitation spectra of ^{8}Be. The results corresponding to the model-space size of $4\hbar\Omega$ relative to the unperturbed ground-state configuration are presented. A harmonic-oscillator energy of $\hbar\Omega = 17$ MeV was used.

Emergence of rotational bands in ab initio no-core configuration interaction calculations of the Be isotopes

P. Maris, M.A. Caprio, and J.P. Vary, PRC 91, 014310 (2015)

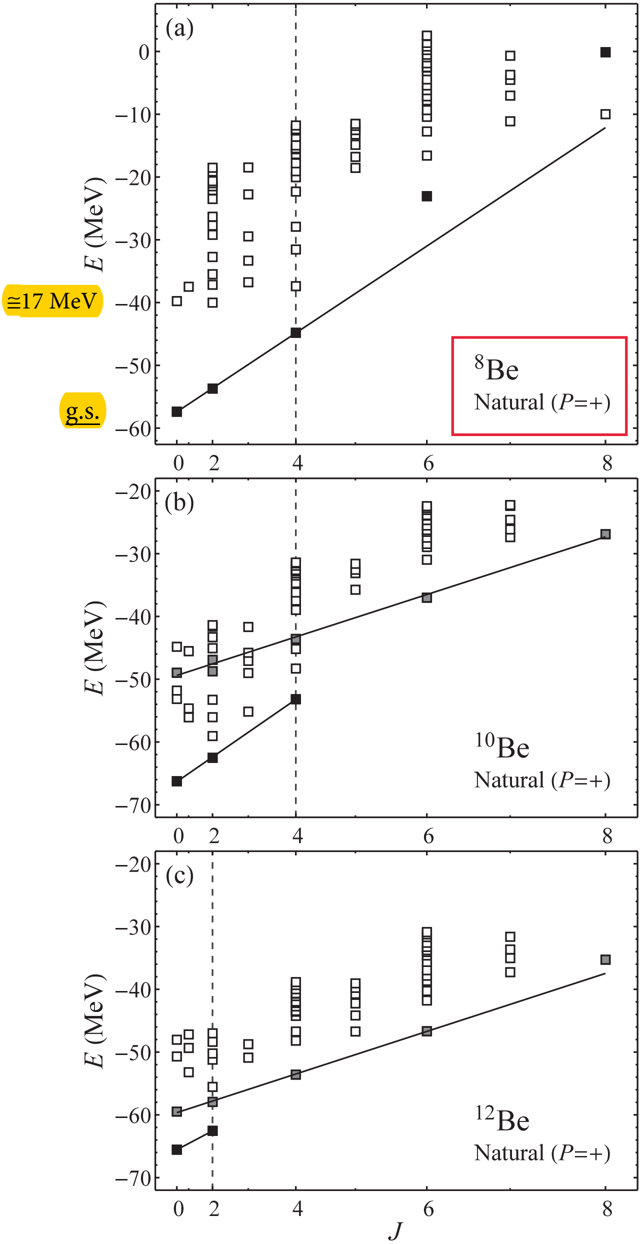
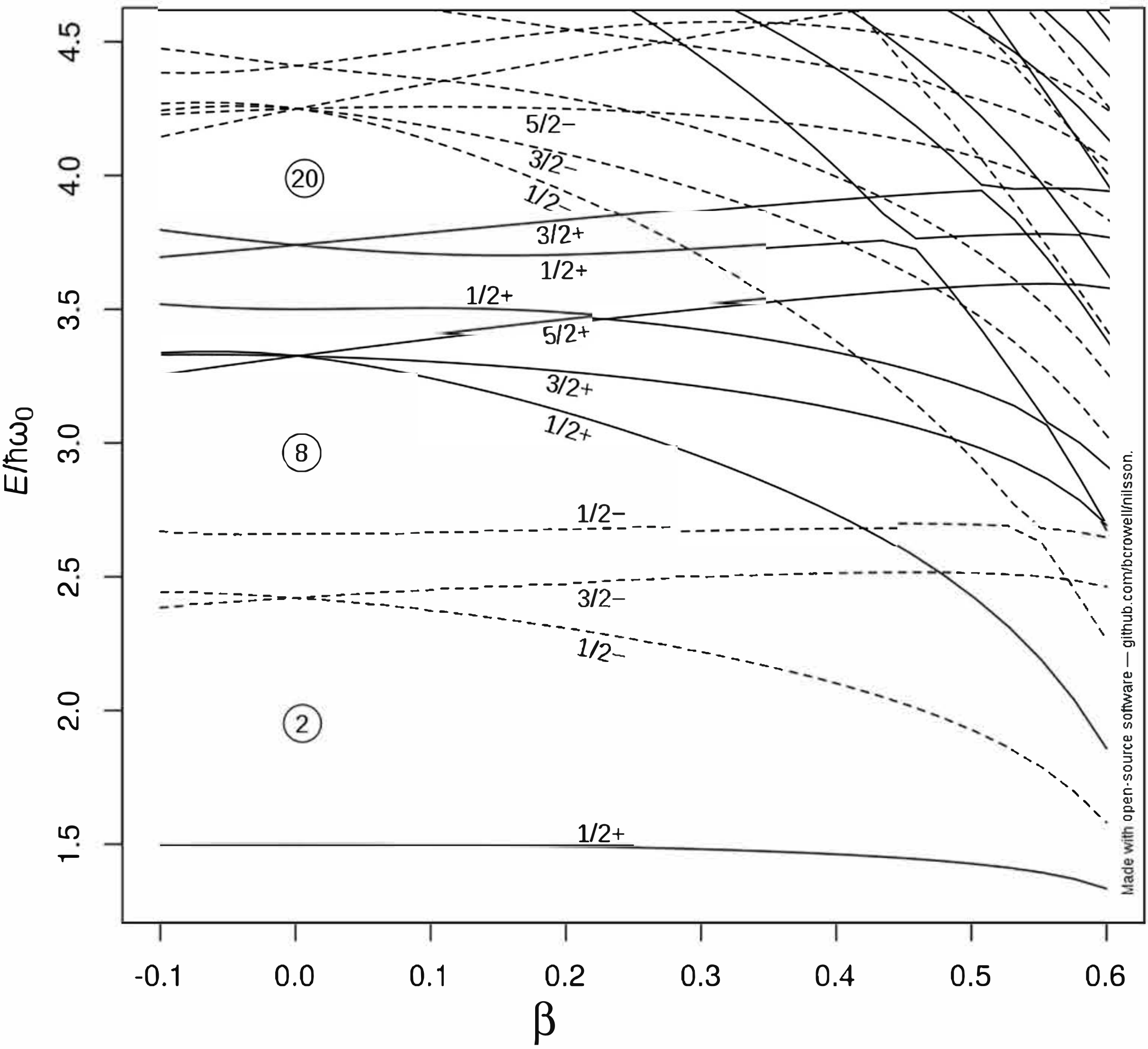
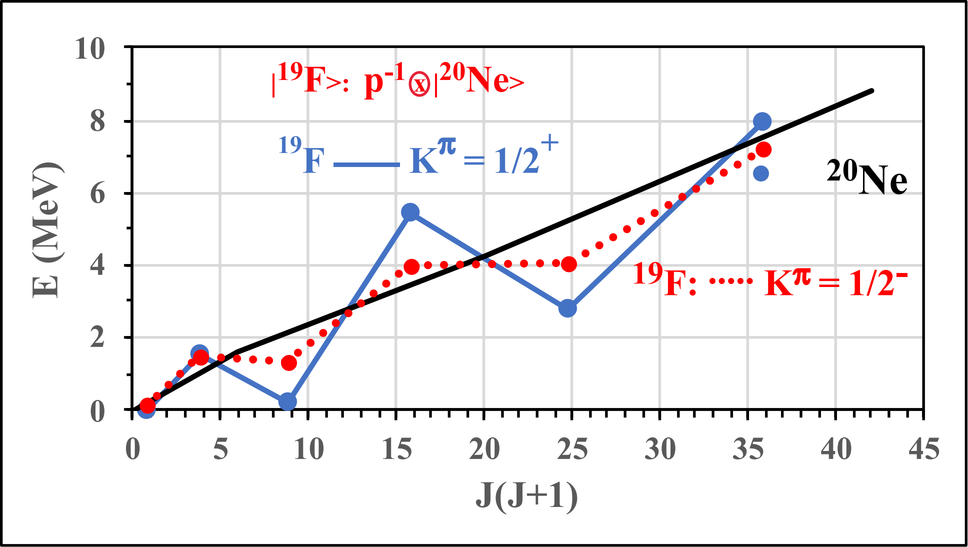


FIG. 4. Energy eigenvalues obtained for states in the *natural* parity spaces of the even-mass Be isotopes ($8 \leqslant A \leqslant 12$). See Fig. 3 caption for discussion of the plot contents and labeling.

The Nilsson Model





|19F>: p-1⊗|20Ne>
19F —— Kπ = 1/2+
20Ne
19F: ····· Kπ = 1/2-
E (MeV)
J(J+1)
0
2
4
6
8
10
0
5
10
15
20
25
30
35
40
45

TABLE I. Known States in ^{8}Be above 16 MeV, listed in TUNL A=8 (2004), amended (2005)

Energy	J^π, T	Width (keV)	Isospin ($\Delta T = 1$)	Boson Symmetry	Detected Recoil
11.35	4^+, 0	3,500	No	Yes	$\alpha + \alpha$
16.626	2^+, 0+1	108.1	No	Yes	$\alpha + \alpha$
16.6751	**(d,p) threshold**				
16.922	2^+, 0+1	74.0	No	Yes	$\alpha + \alpha$
17.2551	**proton threshold**				
17.640	$1^+, 1$	10.7	Yes	No	None
18.150	$1^+, 0$	138	No	No	p+^{7}Li
18.8997	**neutron threshold**				
18.91	$2^-, 1(+0)$	122	Yes	No	(p+^{7}Li)
19.07	$3^+, 1$	270	Yes	No	None
19.235	$3^+, 0$	227	No	No	p+^{7}Li
19.40	$1^-, 0$	~ 645	No	No	p+^{7}Li
19.86	$4^+, 0$ [a]	700	No	Yes	$\alpha + \alpha$
20.1	$2^+, 0$	880	No	Yes	$\alpha + \alpha$
20.2	$0^+, 0$	720	No	Yes	$\alpha + \alpha$
20.9	4^- [a]	1,600	No	No	p+^{7}Li
21.5	3^-[b]$, 0$	1,000	No	No	p+^{7}Li
22.0	$1^-, 1$	4,000	Yes	No	None
22.05		270			p+^{7}Li
22.2	$2^+, 0$	~ 800	No	Yes	$\alpha + \alpha$
22.2808	**deuteron threshold**				
22.63		100	No	No	p+^{7}Li
22.98		230	No	No	p+^{7}Li
24.0	$(1,2)^-, 1$	7,000	Yes	No	None
25.2	$2^+, 0$		No	Yes	$\alpha + \alpha$
25.5	$4^+, 0$	broad	No	Yes	$\alpha + \alpha$

[a] No neutron decay listed

[b] Negative parity: Philip R. Page, Phys. Rev. C **72**, 054312 (2005)

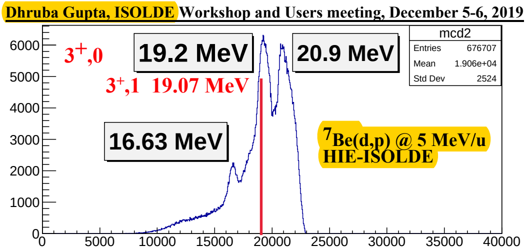


FIG. 3: Excitation energy spectrum of ^{8}Be. The x axis is energy in keV and y axis is counts/40 keV.