Resonance scattering with exotic beams - past, present, and future

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Outline

- Historical perspective
- Experimental aspects
- Proton rich nuclei
- Clustering phenomena
- Neutron rich nuclei
Early days of RS…

- Well understood theoretically
- Perfect energy resolution (~10 keV)
- Limited accessible energy range

Special cases:
- IAS (ex. J. Fox, D. Robson in 60s at FSU)
- alpha clusters (ex. H.T. Richards, et al., U of Wis. - Mad)
Recent history...

Exotic nuclei

- Low lying states are accessible
- Level density is low

Need R/A beams and
New Experimental approach
Experimental evolution

FROM:
Thick Target Inverse Kinematics technique


TO:
Active Targets
TexAT
AT-TPC
Proton rich nuclei

stable

$\beta^-$

$\beta^+$

unbound, first observed in RS
Talk of J. Hooker on structure of $^9$C in this session
Evolution of 1p1/2 and 2s1/2 shells for neutron deficient Z=7 isotopes

Also discussed by E. Vigezzi on Tuesday for N=7 isotones
Clustering phenomena

- Clustering plays important role in nuclear structure
- Alpha clusters manifest strongly in resonance scattering

\[ \alpha \]

\[ ^{14}\text{C} \]

\[ ^{18}\text{O} \]

\[ ^{12}\text{C} \]

\[ ^{16}\text{O} \]

\[ ^{14}\text{C} \]

M. Avila, et al., PRC (2014)
E. Johnson, et al., EPJA (2009)
Negative parity $\alpha$ cluster band in $^{18}$O

W. von Oertzen, et al.
EPJ A 43 (2010)

R-matrix fit to the $^{14}$C+$\alpha$ experimental data

$\theta^2$ values:
- $\theta^2 < 0.01$
- $\theta^2 = 0.02$
- $\theta^2 = 0.04$
- $\theta^2 = 0.20$
- $\theta^2 = 0.29$
- $\theta^2 = 0.46$
- $\theta^2 = 0.48$
- $\theta^2 = 0.18$
- $\theta^2 = 0.17$
Cluster structure of $^{10}$Be

- Rotational band with high moment of inertia built on $0^+$ at 6.18 MeV
- 10.15 MeV state reported to be $4^+$ [1,2] and extremely clustered [1]. Other spin-parity assignment was reported 3$^-$ [3].
- Believed to be associated with $\alpha$-2n-$\alpha$ molecular rotational band.
- The next member of the highly deformed rotational band, 6$^+$, was predicted [4].

Cluster structure of $^{10}$Be

E. Koshchiy, et al., NIM A (2017)


$^6\text{He} + \alpha$

$\theta_{\text{cm}} = 85^\circ - 95^\circ$

$6^+??$
No evidence for $6^+$

$^6\text{He} + \alpha$

$\theta_{\text{cm}} = 85^\circ - 95^\circ$

Also talk of D. Kim on Tuesday: $^{15}\text{O} + \alpha$ and $^{15}\text{N} + \alpha$
IAS in neutron rich nuclei

\[ \text{p} + ^{8}\text{He} \rightarrow ^{9}\text{Li}(T=5/2) \rightarrow \text{p} + ^{8}\text{He} \]

ALSO:
Talks of S. Upadhyayula on \(^{47}\text{K}+\text{p}\) and C. Hunt on \(^{8}\text{Li}+\text{p}\) in this session
Structure of $^9$He

(a) Differential Cross Section [mb/sr]
(b) 135-166 Degrees
(c) 124-160 Degrees


- $^8$He beam produced by ISAC facility at TRIUMF
- No narrow states were observed
- Evidence for a very broad 1/2$^+$ state at ~2.5 MeV
Future of resonance scattering

- Active target inside a magnet
- 200 µm position resolution
- Energy resolution of few keV
- Narrow resonances (IAS, astrophysics)
Resonance scattering with exotic beams has many application and significant advantages.

Many results on structure of proton rich nuclei have been obtained.

Clustering phenomena studies with exotic beams is in its infancy - high statistics and wide angular range needs to be measured.

IAS states studies open a way to explore neutron rich nuclei - theoretical issues need to be resolved.
Positive parity inversion doublet quasi-rotation band in $^{18}$O


Cluster Nucleon Configuration Interaction Model (CNCIM)

Yu. Tchuvil’sky
A. Volya

Splitting is due to strong configuration mixing $(0p)^2(1s0d)^2$ and $(1s0d)^4$
\(Z=7\) isotopes
\(N=7\) isotones

\(^{11}\text{Be}\) \(\frac{1}{2}^+\) g.s.
\(^{11}\text{N}\) \(\frac{1}{2}^+\) g.s.

\(^{10}\text{Li}\) (2\(-\);1\(-\)) \(L=0\) g.s.?

\(^{10}\text{N}\) ?

\(^{13}\text{C}\) (1/2\(-\); g.s.)
\(^{13}\text{N}\) (1/2\(-\); g.s.)

\(^{9}\text{He}\) – all over the place
Structure of $^{10}$N and $^9$He studied using resonance elastic scattering.
Resonances in $^{10}$N were directly populated in $^9$C+p elastic scattering.
Resonances in $^9$He were studied through $T=5/2$ IAS in $^9$Li, populated in $^8$He+p elastic scattering.
Test with $^{12}$C beam - states in $^{13}$N

Red curve is an R-matrix calculation (not a fit!) based on known properties of the states in $^{13}$N.
Structure of $^{10}\text{N}$

Excitation function for $^9\text{C}+\text{p}$ elastic scattering

(b) $\theta = 139^\circ - 162^\circ$

$S_p = 0.25$ or $0.4$

$1^- (2^-)$

$S_p = 0.8$

$2^- (1^-)$


No resonances

Rutherford

$^9\text{C}$ beam at energy 8 MeV/u was produced by MARS separator at Texas A&M U.
Structure of $^{10}$N

The only previous $^{10}$N result - A. Lepine-Szily, et al., PRC 65 (2002): possible observation of a broad structure at 2.6 MeV.
$^{10}$Li structure

$^{9}$Li(d,p)

$E = 22$ keV - virtual s-state
$E = 0.38$ MeV, $\Gamma = 0.20$ MeV

H. B. Jeppesen, et al.,
PLB 642 (2006) 449

$^{11}$Li(p,d)

$E = 0.62$ MeV, $\Gamma = 0.33$ MeV

A. Sentullaev, et al.,
PLB 755 (2016) 481

$^{9}$Li(d,p)

$E = 0.45$ MeV, $\Gamma = 0.68$ MeV

M. Cavallaro, et al.,
PRL 118 (2017) 012701

$^{11}$Li frg

$\alpha = -30$ fm - virtual s-state
$E = 0.51$ MeV, $\Gamma = 0.54$ MeV

H. Simon, et al.,
Potential model extrapolation

PM parameters: $r_o = 1.25$ fm, $a=0.7$ fm, $r_c = 1.3$ fm

All values are in MeV. The experimental values for the known states are given. Potential model extrapolation are in parenthesis in red.
Previous results for $^9\text{He}$

Recent $^8\text{He}(d,p)$ measurements indicate low lying $1/2^+$ and $1/2^-$ states


This contradicts earlier $^8\text{He}(d,p)$ data

M.S. Golovkov, et al., PRC 76 (2007) 021605
Level structure of $^9\text{He}$ inferred from the $^8\text{He}+p$ measurements and the phase shifts

![Graph showing phase shifts and level structure of $^9\text{He}$]
Neutron $s$ states in loosely bound nuclei

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From $^8\text{He}+p$ phase shift analysis
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