Bound nuclei can be populated by transfer to bound states.

Unbound nuclei can be populated by transfer to a resonance state or fragmentation of a bound projectile. Also elastic resonant method on p-target:

*Are the structure information extracted equivalent?* Do we understand the interplay with the reaction mechanism?

Do we understand the distortion involved in using “surrogate” reactions since the n-N scattering cannot be measured when N is a radioactive nucleus? Are we interested only in the “absorption” part or also “elastic”? 
~300 stable nuclei, ~7000 “exotic”

Entering the world of exotic nuclei: probing the unbound by walking at the drip line.

- What life is there beyond the dripline?
- How can we discover it without getting lost?
- Extend our understanding of the residual nuclear force.
- Check the limits of validity of structure models such as the SHELL MODEL or "ab initio" models.
- Challenges in peripheral reaction theory.
Flagships are still flagship!!!! (Uesaka san DREB2016 summary talk)

The case of $^{10}$Li

Transfer to continuum (Resonances)

$^{11}$Li+$p \rightarrow ^{10}$Li +d

Fragmentation ($^{10}$Li best example)

See also Jesus Casal talk
Unbound Nuclei “levels”

Investigation of the role of $^{10}$Li resonances in the halo structure of $^{11}$Li through the $^{11}$Li(p,d)$^{10}$Li transfer reaction

A. Sanetra$^{a, b, c, d}$, R. Ramengo$^{a, e}$, J. Tanaka$^{f, g}$, M. Alcorta$^{a}$, C. Andries$^{h}$, P. Bender$^i$, A.A. Chen$^{a, j}$, C. Christian$^{a, k}$, B. Davis$^{a}$, J. Elinson$^{a}$, J.P. Fortin$^{a}$, N. Galinski$^{a}$, A.E. Gallant$^a$, P.E. Garrett$^a$, G. Hackman$^{a}$, B. Hadria$^{a}$, S. Ishimoto$^{a}$, M. Keerle$^a$, R. Krücker$^a$, J. Ljungqvist$^a$, E. McNeice$^a$, D. Miles$^a$, J. Purcell$^a$, J.S. Randhawa$^a$, T. Rajer$^a$, A. Rijas$^a$, H. Sarazij$^a$, A. Shotts$^a$, I. Tanihata$^a$, L. Thompson$^a$, C. Unsworth$^a$, P. Voss$^a$, Z. Wang$^a$

The resonance energy spectrum (Fig. 2b) of $^{10}$Li is constructed combining the missing mass technique using the measured energy and scattering angle of the deuterons. A very prominent resonance peak is seen at $E_\gamma = 0.62 \pm 0.04$ MeV and full width $\Gamma = 0.33 \pm 0.07$ MeV is obtained from fitting the spectrum with a Voigt function with an energy dependent Breit–Wigner function width [22].

H. Simon et al., NPA791, 267 (2007)
Another intriguing nucleus: $^{10}$Be populated by 1n-transfer
Fig. 3. Inclusive energy spectrum of the reaction $^{14}C(^{16}O,^{16}O)^{14}C$ at 84 MeV. The energy threshold for the emission of one neutron, two neutrons and the α-particle are indicated: $E_{n} = 1.218$ MeV, $E_{2n} = 9.394$ MeV and $E_{4n} = 12.725$ MeV.

The red and green curves represent the one- and two-neutron elastic break-up, respectively. The blue dotted curve represents the two-neutron absorption term. The orange dashed-dotted curve is the sum of two-neutron elastic break-up and absorption. Finally, the violet full curve is the sum of all contributions folded with the experimental resolution. In the experimental spectrum, plotted with a bin size of 70 keV, the background from the $^{12}C$ impurity has been subtracted (see Fig. 1). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

Fig. 4. Dominant contributions to the partial wave decomposition of the theoretical energy spectrum shown in Fig. 3. The legend indicates the single particle angular momentum of each individual strength distribution. The lines starting at $E_{n} = 1.218$ MeV refer to the $^{14}C + n$ system while those starting at 9.394 MeV to the $^{12}C + n + n$ (see text).
Can Ab Initio Theory Explain the Phenomenon of Parity Inversion in 11Be?
Angelo Calci, Petr Navrátil, Robert Roth, Jérémy Dohet-Eraly, Sofia Quaglioni, and Guillaume Hupin

\( S_n = 0.5 \text{MeV} \)
\( S_{2n} = 7.3 \text{MeV} \)
$^{18}\text{O} + ^9\text{Be} \rightarrow ^{16}\text{O} + ^{11}\text{Be}$
A consistent formalism for all breakup reaction mechanisms

The core-target movement is treated in a semiclassical way, but neutron-target and/or neutron-core with a full QM method.


\[
\frac{d\sigma}{d\xi} = C^2 S \int_0^{\infty} d b_c \frac{dP_{-n}(b_c)}{d\xi} P_{ct}(b_c),
\]

\[
\xi \rightarrow \varepsilon_f, k_z, P_{//} \quad \text{also} \quad ANC = \sqrt{C^2 S C_i^2}
\]

Use of the simple parametrization

\[
P_{ct}(b_c) = |S_{ct}|^2 = e^{-\ln 2 \exp[(R_s - b_c)/a]},
\]

\[
R_s \approx r_s (A_p^{1/3} + A_t^{1/3}) \quad r_s \approx 1.4 fm
\]

'strong absorption radius'
$^{11}\text{Be} \rightarrow ^{10}\text{Be}$

$^{11}\text{Be}$

$^{10}\text{Be}$

T: $^{9}\text{Be}$, $^{12}\text{C}$, $^{208}\text{Pb}$, ... $^p$

Di Pietro A et al 2010
Phys. Rev. Lett. 105 22701
Transfer to the continuum: from resonances to knockout reactions

First order time dependent perturbation theory amplitude: 

\[ A_{fi} = \frac{1}{i\hbar} \int_{-\infty}^{\infty} dt \langle \phi_f(r)|V(r)|\phi_i(r-R(t)) \rangle = e^{-i(\omega t - mvz/\hbar)} \]  

(1)

\[ \omega = \varepsilon_i - \varepsilon_f + \frac{1}{2}mv^2 \quad R(t) = b_c + vt \]

\[ \frac{dP_{-n}(b_c)}{d\varepsilon_f} = \frac{1}{8\pi^3} \frac{m}{\hbar^2 k_f^2} \frac{1}{2l_i + 1} \sum m_i |A_{fi}|^2 \]

\[ \approx \frac{4\pi}{2k_f^2} \sum j_f (2j_f + 1) (|1 - \bar{S}_{jf}|^2 + 1 - |\bar{S}_{jf}|^2) \mathcal{F}, \]

\[ \phi_f \text{ see } (*) \]

\[ \mathcal{F} = (1 + F_{l_f, l_i, j_f, j_i}) B_{l_f, l_i} \]

\[ B_{l_f, l_i} = \frac{1}{4\pi} \left[ \frac{k_f}{mv^2} \right] |C_i|^2 \frac{e^{-2\eta b_c}}{2\eta b_c} M_{l_f, l_i} \]
Wave functions

Final continuum state:

\[ \phi_f(r) = C_f k \frac{i}{2} (h^{(+)}_f(kr) - \tilde{S}_f h^{(-)}_f(kr)) Y_{l_f,m_f}(\Omega_f), \]

\( \tilde{S}_f(\varepsilon_f) \) is an optical model (n-t (n-core in fragmentation reactions) S-matrix).

or using the potential \( V = V_{nt} + V_{eff} \) sum of the neutron-target optical and Coulomb potentials, a distorted wave of the eikonal-type

\[ \phi_f(r, k) = \exp \{ik \cdot r + i\chi_{eik}(r, t)\} \]

the eikonal phase shift is simply

\[ \chi_{eik}(r, t) = \frac{1}{\hbar} \int_t^\infty V(r, R(t'))dt'. \]

Initial state:

\[ \phi_i(r) = -C_i i \gamma h^{(1)}_i(i\gamma r) Y_{l_i,m_i}(\Omega_i). \]

Resonances described by

\[ \delta V(r) = 16\alpha \frac{e^{2(r-R^R)/a^R}}{(1 + e^{(r-R^R)/a^R})^4}. \]

consistent with dispersive contribution

n-\(^9\)Be scattering data + calculations
Hypothesis on the reaction mechanism for $2n$ transfer: dependence on matching conditions (D M Brink, PLB 1985)

$$E_{\text{inc}} = 84 \text{MeV} \rightarrow \sim 4 \text{AMeV}$$

$$\epsilon_f - \epsilon_i = 0.132 \text{MeV}$$

Excellent matching for $1n$ transfer to bound state in the first step, no time delay assumed.
Fig. 3. Inclusive energy spectrum of the reaction $n + ^{14}C$ and the $n + ^{13}C$ reaction at 84 MeV. The energy threshold for the emission of one neutron, two neutrons and the $\alpha$-particle are indicated: $S_n = 1.218$ MeV, $S_{2n} = 9.394$ MeV and $S_{\alpha} = 12.725$ MeV.

The red double-dashed-dotted curve represents the one- and two-neutron elastic break-up, respectively. The green dotted curve represents the two-neutron absorption term. The orange dashed-dotted curve is the sum of two-neutron elastic break-up and absorption. Finally, the violet full curve is the sum of all contributions folded with the experimental resolution. In the experimental spectrum, plotted with a bin size of 70 keV, the background from the $^{12}C$ impurity has been subtracted (see Fig. 1). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

Fig. 4. Dominant contributions to the partial wave decomposition of the theoretical energy spectrum shown in Fig. 3. The legend indicates the single particle angular momentum of each individual strength distribution. The lines starting at $E_n = 1.218$ MeV refer to the $^{14}C + n$ system while those starting at 9.394 MeV refer to the $^{13}C + n + n$ system.
Can *Ab Initio* Theory Explain the Phenomenon of Parity Inversion in $^{11}\text{Be}$?

Angelo Calci, Petr Navrátil, Robert Roth, Jérémy Dohet-Eraly, Sofia Quaglioni, and Guillaume Hupin


\[ S_n = 0.5\text{MeV} \quad S_{2n} = 7.3\text{MeV} \quad \epsilon_f - \epsilon_i = 1.25\text{MeV} \]
FIG. 2. (color online) NCSMC spectrum of $^{11}\text{Be}$ with respect to the $n^{+}\text{Be}$ threshold. Dashed black lines indicate energies of the $^{10}\text{Be}$ states. Light boxes indicate resonance width. Experimental energies taken from [1, 451].

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TABLE I. Excitation spectrum of $^{11}\text{Be}$ with respect to the $n^{+}\text{Be}$ threshold. Energies and widths in MeV. NCSMC(-Pheno) calculations are carried out at $N_{\text{max}} = 9$. 
Thanks to Angelo Calci and Jérémy Dohet-Eraly for providing the S-matrix.
Constrain the (nucleus-nucleus) S-matrix $|S|^2$ by total reaction cross section calculations vs exp. data

Status of the Art
Reaction cross sections of unstable nuclei

See for example
http://www.sinap.ac.cn/china-japan/
A. Ozawa (University of Tsukuba)
Also

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<td>6</td>
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<td>601.42 ± 1.38</td>
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Nucleon Density Distribution of the Proton Drip-Line Nucleus $^{12}$N Studied via Reaction Cross Sections

Mitsumori Fukuda$^1$, Yusuke Morita$^1$, Daito Nosema$^2$, Mayu Takemi$^3$, Kodai Iwamoto$^1$, Masayuki Wakamatsu$^2$, Yasushi Kaminoh$^2$, Junichi Ono$^1$, Masanori Tanaka$^2$, Ryosuke Kasai$^1$, Shinzo Yasumaki$^1$, Motoyuki Minamidani$^1$, Kazuaki Matsumura$^4$, Kenta Yoshimura$^2$, Itaru Zen$^2$, Junpei Kurosawa$^2$, Satoshi Yasukawa$^4$, Takayuki Yoshida$^2$, Shinji Suzuki$^2$, Masayuki Negashima$^2$, Kenjiro Ando$^2$, Kenta Tomono$^2$, Akira Hoshino$^2$, Takashi Onuki$^2$, Takagi Isomura$^2$, Shinji Suwa$^2$, Shigeru Fukuda$^5$, and Atsushi Kurosawa$^5$
A target used very often is $^9\text{Be}$ → single folding of a n-$^9\text{Be}$ phenomenological potential with a microscopic projectile density

The Glauber reaction cross section is given by

$$\sigma_R = 2\pi \int_0^\infty b \, db (1 - |S_{NN}(b)|^2)$$

(1)

where

$$|S_{NN}(b)|^2 = e^{2\chi_I(b)}$$

(2)

is the probability that the nucleus-nucleus (NN) scattering is elastic for a given impact parameter $b$.

The imaginary part of the eikonal phase shift is given by

$$\chi_I(b) = \frac{1}{\hbar v} \int dz \, W^{NN}(b, z)$$

$$= \frac{1}{\hbar v} \int dz \int d\mathbf{r_1} W^{nn}(\mathbf{r_1} - \mathbf{r}) \rho(\mathbf{r})$$

(3)

where $W^{NN}$ is negative defined as

$$W^{NN}(r) = \int db_1 W^{nn}(b_1 - b, z) \int dz_1 \rho(b_1, z_1).$$

(4)

In the double-folding method, $W^{NN}$ is obtained from the microscopic densities $\rho_{p,t}(\mathbf{r})$ for the projectile and target respectively and an energy-dependent nucleon-nucleon (nn) cross section $\sigma_{nn}$, i.e.,

$$W^{NN}(r) = -\frac{1}{2} \hbar v \sigma_{nn} \int db_1 \rho_p(b_1 - b, z) \int dz_1 \rho_t(b_1, z_1).$$

(5)

Also

$$W^{nn}(r) = -\frac{1}{2} \hbar v \sigma_{nn} \rho_t(\mathbf{r})$$

(6)

is a single-folded zero-range $n$-target imaginary potential and $v$ is the nucleon-target velocity of relative motion. The $W^{nn}$ potential of Eq.(6) has the same range as the target density because $\sigma_{nn}$ is a simple scaling factor.
Perfect example of some of the most discussed reaction mechanisms vs. structure topics of present day physics with RIBs

- Unbound nuclei
- Resonance phenomena
- Elastic scattering
- Total reaction cross sections
\[ n^+\text{Be} \]

\[ 9\text{C}^+\text{Be} \]

**SF VMC density & \( \sigma_{np} \) & \( \sigma_{pp} \)**


AB phenomenological, DOM

8Li and 8B data from Fukuda. Nishimura, private communication

In $\sigma_R$ large distances are important while breakup is localized around $R_s$
Advantages with respect to double folding models:

• The imaginary potential is correctly second order because of the phenomenological nature of the n-T potential.

• The projectile density can be better tested because one is free from the ambiguity on the target density.

• The ambiguity on the nucleon-nucleon interaction to be used is overcome.

• The energy dependence of the potential is correctly reproduced because of the underlying correctness of the n-T potential.

• Deformation and surface effects of the target are correctly taken into account and one is left with the task of modelling the same effects for the exotic projectile.
Traditional methods

- Renewed interest in highly numerical DWBA and CDCC calculations of various aspects of breakup: A. Moro & Co., B.V. Carlson et al., K.Ogata et al. So far mainly d-induced reactions.
- Resonant scattering and R-matrix: P. Descouvemont, G. Rogachev
- Semiclassical and few body (Hussein, Canto &Co), P. Capel
- Reaction cross sections OK with eikonal approach (Ogawa): improved folding models for the optical potential (Furumoto opt pot)

New methods:

- Chiral interactions used for: ab initio no-core shell model with continuum, and its applications to nucleon and deuterium scattering on light nuclei: P. Navratil, S. Quaglioni, G. Hupin, J. Dohet-Eraly
- Optical potential microscopic calculations from chiral interactions

ECT* workshop

Open questions:

- Unbound nuclei via projectile fragmentation. SEMICLASSICAL OK, but numerical (DWBA-like still in progress)
- Tetraneutron
• R=1.4-1.5 (A_p^{1/3}+A_t^{1/3}) fm …… radius

• NN Optical potentials (imag. part) describing elastic scattering and/or reaction cross sections must contain a surface term with very large diffusness 2-3 fm.

• nN optical potentials (real part) must contain a term representing particle-vibration couplings or surface oscillations/deformations, consistent with a dispersive contribution DOM

\[ \delta V(r) = \frac{16\alpha e^{2(r-R)/a}}{1 + e^{(r-R)/a}^4}. \]

• Bound&continuum
Legenda and thanks to:

M. Fukuda et al., and the R3B collaboration for allowing me to show their results

DOM Bob Charity
FC Florin Carstoiu
PD Pierre Descouvemont
Y K-E Yoshiko Kanada-Enyo
ST Stefan Typel

for providing unpublished data and calculations.

Some more historical collaborators:

David Brink, Nicole Vinh Mau, Guillaume Blanchon, Cristina Rea, the MAGNEX group at LNS-INFN, Catania.
“If you have heart you will certainly have brain…”
(paraphrased from Julian Fellowes)
FIG. 4. $^9$C densities used in the calculated cross sections shown in Fig. 2.
TABLE II. Experimental reaction cross sections, second column, from Ref. [32]. Calculated total reaction cross sections with the double-folded potential using VMC densities for both $^9$C and $^9$Be (third column); double-folded potential using HF densities for both $^9$C and $^9$Be (fourth column); using the single-folded potential with HF density for $^9$C (fifth column) and with the added surface potential (sixth column), with the "bare" JLM and with the renormalized JLM for $^9$C + $^9$Be. The renormalization factor for the JLM potential and strength of the additional surface potential for the single-folded potential are also given. For the case of $\sigma_{s,\text{fold}}^{\text{surf}}$, we then give strong-absorption radius $R_s$ from $|S_{NN}(R_s)|^2 = \frac{1}{2}$, and $R_s^{\text{fit}}$ from the fit to the calculated $|S_{NN}|^2$ according to Eq. (10). In this case also the diffuseness-like parameter is given. Last column: $r_s$ from Eq. (11) and $R_s$.

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<tr>
<td>95</td>
<td>833</td>
<td>895</td>
<td>949</td>
<td>952</td>
<td>968</td>
<td>956</td>
<td>0.97</td>
<td>0.01</td>
<td>5.40</td>
<td>5.28</td>
<td>0.79</td>
<td>1.29</td>
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<tr>
<td>97.2</td>
<td>919</td>
<td>888</td>
<td>949</td>
<td>951</td>
<td>963</td>
<td>923</td>
<td>0.90</td>
<td>0.005</td>
<td>5.35</td>
<td>5.28</td>
<td>0.80</td>
<td>1.28</td>
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</table>
Angular distributions in high-energy heavy-ion reactions are generally rather featureless and in this paper we concentrate on calculating the total cross section.
N-Z Asymmetry dependence of spectroscopic factors


Dispersive-optical-model analysis of the asymmetry dependence of correlations in Ca isotopes

R. J. Cherry, J. M. Marden, L. G. Sobota, and W. K. Dickhoff

FIG. 14. (Color online) Data points indicate spectroscopic factors deduced by Lee et al. [75] for valence neutron and particle states in Ca isotopes using ($p, d$) and ($d, p$) reactions. The spectroscopic factors are expressed as a percent of the independent-particle-model value. The DOM predictions with the asymmetry dependences $D_1$ (see Eq. (32)) and $D_2$ (Eq. (39)) are indicated by the points connected with dashed and solid lines, respectively.

122503 (2013) PHYSICAL REVIEW LETTERS 22 MARCH 2013

Limited Asymmetry Dependence of Correlations from Single Nucleon Transfer

γ,1,2, A. Gillibert, L. Najafi, A. Obertelli, N. Keeley, C. Barbieri, D. Beaumel, S. Boissinot, G. Burgunder, lone,1,2, A. Corsi, J. Ghibaudo, S. Giroux, J. Gallais, F. Hamacher, V. Lapatov, A. Matar, E. C. Pollacco, R. Paulet,1,2 M. Rejimbold, N. Al Serkkeli,1,2 A. Shirokov,1,2, A. Vossen,1,2, and Y. Usmani

FIG. 27. (Color online) Spectroscopic factors (relative to the independent-particle-model value) for valence-hole levels determined from the fitted potentials. Results are shown for the $Z = 20, 25$ and $N = 28$ and the square and circular points represent neutrons and protons, respectively. In (a), these are plotted versus the separation energy of the level, while in (b), they are plotted versus the difference in proton and neutron separation energies.

Reduction Factors from ($p, 2p$) Cross Sections for $^{14-22}$O Projectiles

- A weak or no dependence of single-particle strength on the isospin asymmetry
- In contrast to the observed trend from knockout reactions at intermediate energies using composite targets
- Comparable with the ab-initio Green's function and coupled cluster calculations as well as ($e, ep$) data

L. Atar, Panin, Paschalis, Aumann, Bertulani et al. for the R3B collaboration

Reduction factor $R = \frac{\sigma_{\text{exp}}}{\sigma_{\text{calc}}}$
Experimental data vs. **Reaction theory** vs. Structure theory

- Direct reactions involve few nucleons and few degrees of freedom but to “model” them requires understanding the whole nucleus and all other possible reactions. Ex: **elastic scattering and the optical potential**.

- It requires also the understanding of **experimental setups** and the handling of data to extract meaningful observables.

- It has to be **simple and transparent** in its interpretation to help disentangling the physical processes and allow experimentalists to describe their data.

- Reaction theorists must understand **structure**, experiments and they must describe data reliably but in a simple way.
FIGURE 2. (a) Experimental $^6$Be invariant-mass spectrum and (b,c) the parallel-momentum distributions [3] of the reactions: $^9$Be($^7$Be,$^6$Be)X, $^9$Be($^7$Be,$^6$Li)X at mid-target energy of 65.2 MeV. Here and the following figures the dashed line on the $P_\|$ spectra indicates the momentum of the unreacted beam. The dashed lines in (a) show the gate on the $^6$Be ground state.

FIGURE 3. (a) The experimental $^8$C invariant-mass spectrum and (b) the parallel-momentum distributions [3] of the reactions: $^9$Be($^7$C,$^8$C)X at mid-target energy of 63.8 MeV. The gate on the ground state of $^8$C is indicated by the dashed lines in (a).
Some of these nuclei are important in the pp-chain, we try to understand their structure from high energy data

RJ Charity et al., private comm.

| $\langle 7\text{Be} \mid 6\text{Be}_{g.s} \rangle$ | $65.2$ | $10$ |
| $\langle 7\text{Be} \mid 6\text{Li}_{g.s} \rangle$ | $65.2$ | $50$ |
| $\langle 9\text{C} \mid 8\text{C}_{g.s} \rangle$ | $63.8$ | $3.82$ |
| $\langle 9\text{C} \mid 8\text{B}_{g.s} \rangle$ | $64.4$ | $54.5$ |
| $\langle 9\text{C} \mid 8\text{B}_{1+} \rangle$ | $64.4$ | $12.2$ |
| $\langle 9\text{C} \mid 8\text{B}_{3+} \rangle$ | $64.4$ | $42.6$ |