

Training in Advanced Low Energy Nuclear Theory

Antonio M. Moro



Universidad de Sevilla, Spain

Introduction

- 1 Models for inelastic scattering
 - Cluster models: bound states
 - Coupling to breakup: CDCC method
 - Example for cluster model: $^{11}\text{Be} + ^{12}\text{C}$

Remainder of Coupled-Channels method: model WF

We expand the total wave function in internal states of the target:

$$\Psi_{\text{model}}(\mathbf{R}, \xi) = \phi_0(\xi)\chi_0(\mathbf{R}) + \sum_{n>0} \phi_n(\xi)\chi_n(\mathbf{R})$$

- $\phi_0(\xi)$: target ground state wave function.
- $\chi_0(\mathbf{R})$: describes the projectile-target relative motion with the target in the initial state $\Rightarrow$ [elastic scattering](#)
- $\phi_n(\xi)$: target internal wave function in the excited state n .
- $\chi_n(\mathbf{R})$: describes the projectile-target relative motion with the target in the excited state $n \Rightarrow$ [inelastic scattering](#)

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- $\chi_n(\mathbf{R})$: describes the projectile-target relative motion with the target in the excited state $n \Rightarrow$ [inelastic scattering](#)

$$\chi_n(\mathbf{R}) \rightarrow \text{unknowns}$$

Calculation of $\chi_n^{(+)}(\mathbf{R})$: the coupled equations

- The model wavefunction must satisfy the Schrödinger equation:

$$[H - E]\Psi_{\text{model}}^{(+)}(\mathbf{R}, \xi) = 0$$

- Projecting onto the internal states one gets a system of coupled-equations for the functions $\{\chi_n(\mathbf{R})\}$:

$$[E - \varepsilon_n - T_R - V_{n,n}(\mathbf{R})]\chi_n(\mathbf{R}) = \sum_{n' \neq n} V_{n,n'}(\mathbf{R})\chi_{n'}(\mathbf{R})$$

- Coupling potentials:

$$V_{n,n'}(\mathbf{R}) = \int d\xi \phi_{n'}^*(\xi) V(\mathbf{R}, \xi) \phi_n(\xi)$$

☞ $\phi_n(\xi)$ will depend on the structure model (collective, single-particle, etc).

Expansion in J, M basis: radial coupled equations

- Expansion of total WF in channel basis:

$$\Psi_{\text{model}}^{(+)}(\mathbf{R}, \xi) = \sum_{\beta, J, M_J} C^{\beta, JM_J} \frac{\chi_{\beta}^J(R)}{R} \Phi_{\beta}^{JM_J}(\hat{R}, \xi); \quad \beta \equiv \{n, L, I\}$$

- The coupled equations:

$$\left(-\frac{\hbar^2}{2\mu} \frac{d^2}{dR^2} + \frac{\hbar^2 L(L+1)}{2\mu R^2} + \epsilon_n - E \right) \chi_{\beta}^J(R) + \sum_{\beta'} V_{\beta, \beta'}^J(R) \chi_{\beta'}^J(R) = 0$$

- Coupling potentials in the channel basis:

$$V_{\beta, \beta'}^J(R) = \int d\hat{R} d\xi \Phi_{\beta}^{JM_J}(\hat{R}, \xi)^* V(\mathbf{R}, \xi) \Phi_{\beta'}^{JM_J}(\hat{R}, \xi)$$

Solution of the coupled equations: boundary conditions

- For each $J \Rightarrow N$ coupled diff. equations (one for each β) $\Rightarrow N$ indep. solutions
- Standard choice: build solutions characterized by a given entrance channel $\beta_i = \{n_i, L_i, I_i\}$:

$$\Psi_{\beta_i, JM_T}^{(+)}(\mathbf{R}, \xi) = \sum_{\beta} \frac{\chi_{\beta, \beta_i}^J(R)}{R} \Phi_{\beta}^{JM_T}(\hat{\mathbf{R}}, \xi)$$

- The radial functions $\chi_{\beta, \beta_i}^J(R)$ verify:
 - $\Rightarrow$ Regular at the origin: $\chi_{\beta, \beta_i}^J(R=0) = 0$
 - $\Rightarrow$ Asymptotic behaviour:

$$\begin{aligned} \chi_{\beta, \beta_i}^J(K_{\beta}, R) &\rightarrow \frac{i}{2} \left[H_L^{(-)}(K_{\beta}R) \delta_{\beta, \beta_i} - S_{\beta, \beta_i}^J H_L^{(+)}(K_{\beta}R) \right] \\ &\rightarrow \left[F_L(K_{\beta}R) \delta_{\beta, \beta_i} + T_{\beta, \beta_i}^J H_L^{(+)}(K_{\beta}R) \right] \end{aligned}$$

$$S_{\beta, \beta_i}^J = \delta_{\beta, \beta_i} + 2iT_{\beta, \beta_i}^J$$

(Multi-channel S/T-matrix)

Some properties of the multi-channel S-matrix

- Unitarity of the S-matrix (real potentials):

$$\sum_{\beta} S_{\beta, \beta_i}^J S_{\beta, \beta_j}^{J*} = \delta(\beta_i, \beta_f) = \delta(n_i, n_j) \delta(I_i, I_j) \delta(L_i, L_j)$$

- Time reversal: $S_{nIL, n_i I_i L_i}^J = S_{n_i I_i L_i, nIL}^J$
- Parity conservation: $(-1)^L \pi(n) = (-1)^{L_i} \pi(n_i).$

Strategy

- 1 Identify the projectile-target interaction $V(\mathbf{R}, \xi)$ consistent with our structure model.
- 2 Perform a multipole expansion:

$$V(\mathbf{R}, \xi) = \sqrt{4\pi} \sum_{\lambda, \mu} V_{\lambda\mu}(R, \xi) Y_{\lambda\mu}(\hat{R})$$

- 3 Evaluate the matrix elements in the basis of internal states:

$$\langle I_f M_f | V(\mathbf{R}, \xi) | I_i M_i \rangle = \sqrt{4\pi} \sum_{\lambda, \mu} \frac{\langle I_f M_f | \lambda \mu I_i M_i \rangle}{\sqrt{2I_f + 1}} \langle I_f || V_{\lambda}(R, \xi) || I_i \rangle Y_{\lambda\mu}(\hat{R})$$

- 4 Identify the multipole transition potentials

$$V_{fi}^{\lambda}(R) \equiv \langle I_f || V_{\lambda}(R, \xi) || I_i \rangle = \mathcal{F}_{\lambda}(R) \langle I_f || \mathcal{T}_{\lambda}^{*}(\xi) || I_i \rangle$$

Inelastic scattering: cluster model

- Some nuclei permit a description in terms of two or more clusters:
 $d=p+n$, ${}^6\text{Li}=\alpha+d$, ${}^7\text{Li}=\alpha+{}^3\text{H}$.
- Projectile-target interaction:

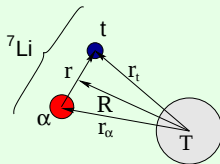
$$V(\mathbf{R}, \mathbf{r}) = U_1(\mathbf{r}_1) + U_2(\mathbf{r}_2)$$

Example: ${}^7\text{Li}=\alpha+t$

$$\mathbf{r}_\alpha = \mathbf{R} - \frac{m_t}{m_\alpha + m_t} \mathbf{r}; \quad \mathbf{r}_t = \mathbf{R} + \frac{m_\alpha}{m_\alpha + m_t} \mathbf{r}$$

Internal states:

$$[T_r + V_{\alpha-t}(\mathbf{r}) - \varepsilon_n] \phi_n(\mathbf{r}) = 0$$



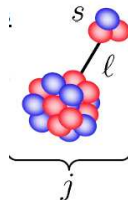
- Transition potentials:

$$V_{n,n'}(\mathbf{R}) = \int d\mathbf{r} \phi_n^*(\mathbf{r}) [U_1(\mathbf{r}_1) + U_2(\mathbf{r}_2)] \phi_{n'}(\mathbf{r})$$

1 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154 155 156 157 158 159 160 161 162 163 164 165 166 167 168 169 170 171 172 173 174 175 176 177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232 233 234 235 236 237 238 239 240 241 242 243 244 245 246 247 248 249 250 251 252 253 254 255 256 257 258 259 260 261 262 263 264 265 266 267 268 269 270 271 272 273 274 275 276 277 278 279 280 281 282 283 284 285 286 287 288 289 290 291 292 293 294 295 296 297 298 299 300 301 302 303 304 305 306 307 308 309 310 311 312 313 314 315 316 317 318 319 320 321 322 323 324 325 326 327 328 329 330 331 332 333 334 335 336 337 338 339 340 341 342 343 344 345 346 347 348 349 350 351 352 353 354 355 356 357 358 359 360 361 362 363 364 365 366 367 368 369 370 371 372 373 374 375 376 377 378 379 380 381 382 383 384 385 386 387 388 389 390 391 392 393 394 395 396 397 398 399 400 401 402 403 404 405 406 407 408 409 410 411 412 413 414 415 416 417 418 419 420 421 422 423 424 425 426 427 428 429 430 431 432 433 434 435 436 437 438 439 440 441 442 443 444 445 446 447 448 449 450 451 452 453 454 455 456 457 458 459 460 461 462 463 464 465 466 467 468 469 470 471 472 473 474 475 476 477 478 479 480 481 482 483 484 485 486 487 488 489 490 491 492 493 494 495 496 497 498 499 500 501 502 503 504 505 506 507 508 509 510 511 512 513 514 515 516 517 518 519 520 521 522 523 524 525 526 527 528 529 530 531 532 533 534 535 536 537 538 539 540 541 542 543 544 545 546 547 548 549 550 551 552 553 554 555 556 557 558 559 560 561 562 563 564 565 566 567 568 569 570 571 572 573 574 575 576 577 578 579 580 581 582 583 584 585 586 587 588 589 590 591 592 593 594 595 596 597 598 599 600 601 602 603 604 605 606 607 608 609 610 611 612 613 614 615 616 617 618 619 620 621 622 623 624 625 626 627 628 629 630 631 632 633 634 635 636 637 638 639 640 641 642 643 644 645 646 647 648 649 650 651 652 653 654 655 656 657 658 659 660 661 662 663 664 665 666 667 668 669 670 671 672 673 674 675 676 677 678 679 680 681 682 683 684 685 686 687 688 689 690 691 692 693 694 695 696 697 698 699 700 701 702 703 704 705 706 707 708 709 710 711 712 713 714 715 716 717 718 719 720 721 722 723 724 725 726 727 728 729 730 731 732 733 734 735 736 737 738 739 740 741 742 743 744 745 746 747 748 749 750 751 752 753 754 755 756 757 758 759 760 761 762 763 764 765 766 767 768 769 770 771 772 773 774 775 776 777 778 779 780 781 782 783 784 785 786 787 788 789 790 791 792 793 794 795 796 797 798 799 800 801 802 803 804 805 806 807 808 809 810 811 812 813 814 815 816 817 818 819 820 821 822 823 824 825 826 827 828 829 830 831 832 833 834 835 836 837 838 839 840 841 842 843 844 845 846 847 848 849 850 851 852 853 854 855 856 857 858 859 860 861 862 863 864 865 866 867 868 869 870 871 872 873 874 875 876 877 878 879 880 881 882 883 884 885 886 887 888 889 890 891 892 893 894 895 896 897 898 899 900 901 902 903 904 905 906 907 908 909 910 911 912 913 914 915 916 917 918 919 920 921 922 923 924 925 926 927 928 929 930 931 932 933 934 935 936 937 938 939 940 941 942 943 944 945 946 947 948 949 950 951 952 953 954 955 956 957 958 959 960 961 962 963 964 965 966 967 968 969 970 971 972 973 974 975 976 977 978 979 980 981 982 983 984 985 986 987 988 989 990 991 992 993 994 995 996 997 998 999 1000 1001 1002 1003 1004 1005 1006 1007 1008 1009 1010 1011 1012 1013 1014 1015 1016 1017 1018 1019 1020 1021 1022 1023 1024 1025 1026 1027 1028 1029 1030 1031 1032 1033 1034 1035 1036 1037 1038 1039 1040 1041 1042 1043 1044 1045 1046 1047 1048 1049 1050 1051 1052 1053 1054 1055 1056 1057 1058 1059 1060 1061 1062 1063 1064 1065 1066 1067 1068

- Projectile states:

$$\phi_{n\ell j}^m(\mathbf{r}) = \frac{u_{n\ell j}(r)}{r} [Y_\ell(\hat{r}) \otimes \chi_s]_{jm}$$



(from J.A.Tostevin)

- So, we need to evaluate:

$$\langle (\ell_f s) j_f m_f | V(\mathbf{R}, \xi) | (\ell_i s) j_i m_i \rangle = \langle \phi_{n_f \ell_f j_f}^{m_f} | V(\mathbf{R}, \xi) | \phi_{n_i \ell_i j_i}^{m_i} \rangle$$

Coupling potentials in the angular momentum basis (cont.)

- Multipole expansion of the projectile-target potential

$$V_{vt}(\mathbf{r}_{vt}) + V_{ct}(\mathbf{r}_{ct}) = \sum_{\lambda} (2\lambda + 1) \mathcal{F}_{\lambda}(R, r) \sum Y_{\lambda\mu}^*(\hat{r}) Y_{\lambda\mu}(\hat{R})$$

$$\mathcal{F}_{\lambda}(R, r) = \frac{1}{2} \int_{-1}^1 [V_{vt}(r_{vt}) + V_{ct}(r_{ct})] P_{\lambda}(z) d(z); \quad z \equiv \cos(\theta) = \hat{r} \cdot \hat{R}$$

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- General multipole expansion:

$$V(\mathbf{R}, \xi) = \sqrt{4\pi} \sum_{\lambda, \mu} V_{\lambda\mu}(R, \xi) Y_{\lambda\mu}(\hat{R}) \Rightarrow V_{\lambda\mu}(R, \xi) = \frac{2\lambda + 1}{\sqrt{4\pi}} \mathcal{F}_{\lambda}(R, r) Y_{\lambda\mu}^*(\hat{r})$$

Coupling potentials in the angular momentum basis (cont.)

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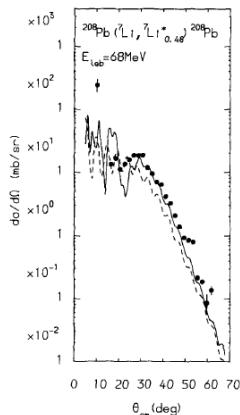
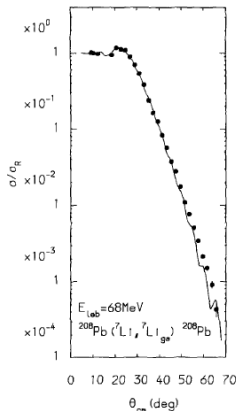
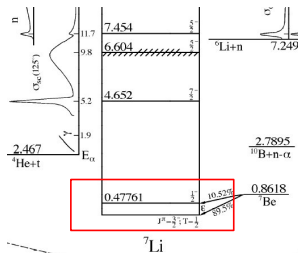
- **Multipole coupling potentials**

$$V_{fi}^{\lambda}(R) = \langle j_f || V_{\lambda}(R, \xi) || j_i \rangle = \hat{\lambda} \hat{\ell}_i \langle \ell_i 0 \lambda 0 | \ell_f 0 \rangle \int_0^{\infty} u_{n_f \ell_f j_f}(r) \mathcal{F}_{\lambda}(R, r) u_{n_i \ell_i j_i}(r) dr$$

Inelastic scattering: cluster model

Example: ${}^7\text{Li}(\alpha+t) + {}^{208}\text{Pb}$ at 68 MeV (Phys. Lett. 139B (1984) 150):

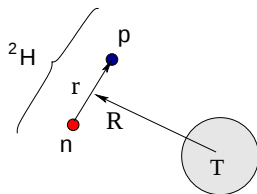
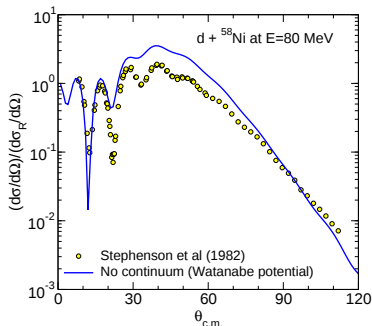
⇒ CC calculation with 2 channels ($3/2^-$, $1/2^-$)



Application of the CC method to weakly-bound systems

Example: Three-body calculation ($p+n+^{58}\text{Ni}$) with Watanabe potential:

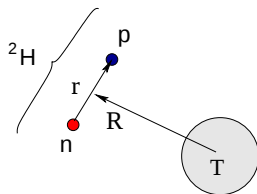
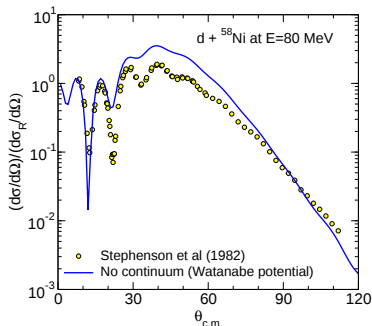
$$V_{dt}(\mathbf{R}) = \int d\mathbf{r} \phi_{gs}(\mathbf{r}) \left(V_{pt}(\mathbf{r}_{pt}) + V_{nt}(\mathbf{r}_{nt}) \right) \phi_{gs}(\mathbf{r})$$



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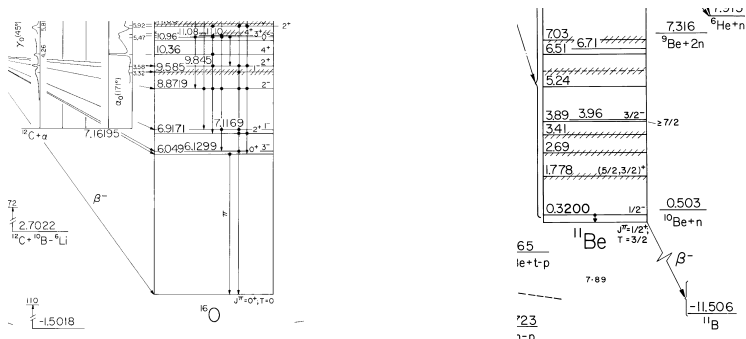
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☞ *Three-body calculations omitting breakup channels fail to describe the experimental data.*

Inelastic scattering of weakly bound nuclei

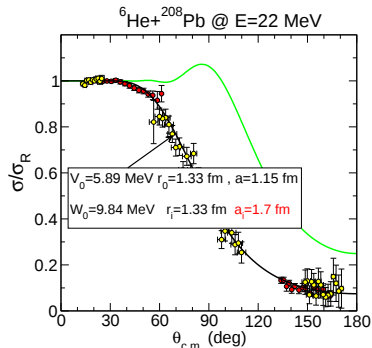
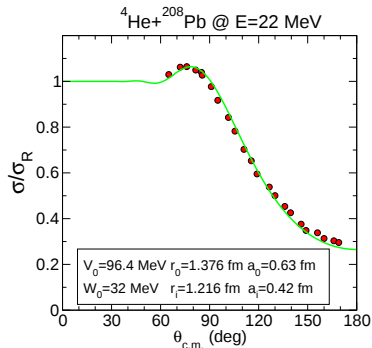
- Single-particle (or cluster) excitations become dominant.
- Excitation to continuum states important.



☞ Exotic nuclei are weakly bound $\Rightarrow$ coupling to continuum states becomes an important reaction channel

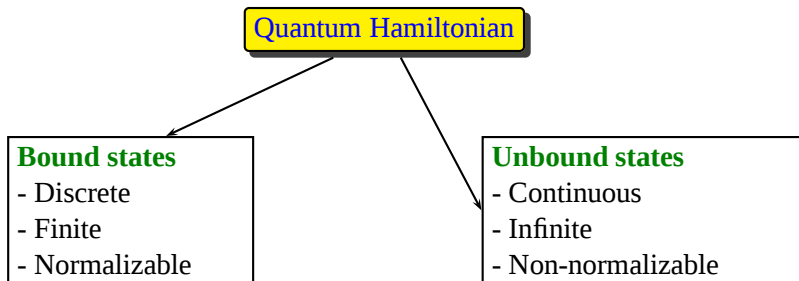
Normal versus halo nuclei

How does the halo structure affect the elastic scattering?



- $^4\text{He} + ^{208}\text{Pb}$ shows typical Fresnel pattern → *strong absorption*
- $^6\text{He} + ^{208}\text{Pb}$ shows a prominent reduction in the elastic cross section due to the flux going to other channels (mainly break-up)

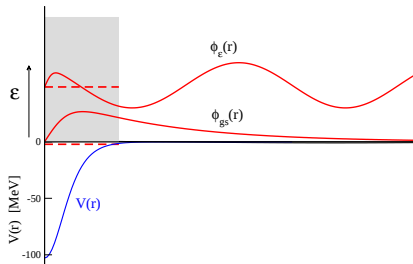
Inclusion of the continuum in CC calculations: continuum discretization



Continuum discretization: represent the continuum by a finite set of square-integrable states

True continuum	→	Discretized continuum
Non normalizable	→	Normalizable
Continuous	→	Discrete

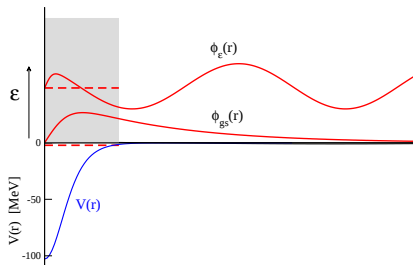
Bound versus scattering states



Continuum state:

$$\phi_{k,\ell j}^m(\mathbf{r}) = \frac{u_{k,\ell j}(r)}{r} [Y_\ell(\hat{r}) \otimes \chi_s]_{jm}$$

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Continuum state:

$$\phi_{k,\ell j}^m(\mathbf{r}) = \frac{u_{k,\ell j}(r)}{r} [Y_\ell(\hat{r}) \otimes \chi_s]_{jm}$$

Unbound states are not suitable for CC calculations:

- Continuous (infinite) distribution in energy.
- Non-normalizable: $\langle u_{k,\ell sj}(r)^* | u_{k',\ell sj}(r) \rangle \propto \delta(k - k')$

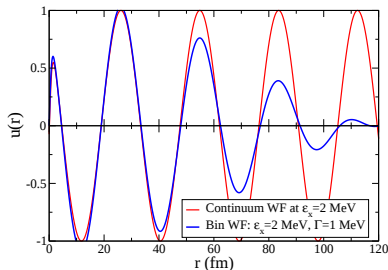
SOLUTION $\Rightarrow$ **continuum discretization**

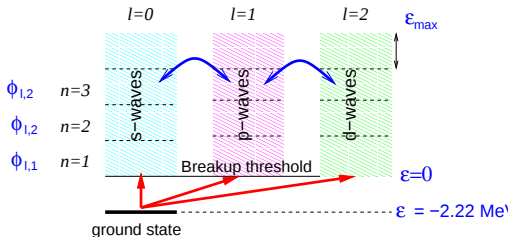
CDCC formalism: construction of the bin wavefunctions

Bin wavefunction:

$$u_{\ell sj,n}(r) = \sqrt{\frac{2}{\pi N}} \int_{k_1}^{k_2} w(k) u_{k,\ell sj}(r) dk$$

- k : linear momentum
- $u_{k,\ell sj}(r)$: scattering states (radial part)
- $w(k)$: weight function





- ⇒ Select a number of partial waves ($\ell = 0, \dots, \ell_{\max}$).
- ⇒ For each ℓ , set a maximum excitation energy $\varepsilon_{\max}$.
- ⇒ Divide the interval $\varepsilon = 0 - \varepsilon_{\max}$ in a set of sub-intervals (*bins*).
- ⇒ For each *bin*, calculate a representative wavefunction.

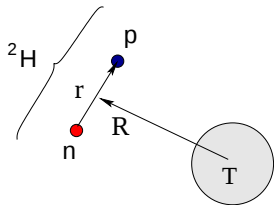
CDCC equations for deuteron scattering

- **Hamiltonian:**

$$H = T_R + h_r(\mathbf{r}) + V_{pt}(\mathbf{r}_{pt}) + V_{nt}(\mathbf{r}_{nt})$$

- **Model wavefunction:**

$$\Psi(\mathbf{R}, \mathbf{r}) = \phi_{gs}(\mathbf{r})\chi_0(\mathbf{R}) + \sum_{n>0}^N \phi_n(\mathbf{r})\chi_n(\mathbf{R})$$



- **Coupled equations:** $[H - E]\Psi(\mathbf{R}, \mathbf{r}) = 0$

$$[E - \varepsilon_n - T_R - V_{n,n}(\mathbf{R})]\chi_n(\mathbf{R}) = \sum_{n' \neq n} V_{n,n'}(\mathbf{R})\chi_{n'}(\mathbf{R})$$

- **Transition potentials:**

$$V_{n;n'}(\mathbf{R}) = \int d\mathbf{r} \phi_n(\mathbf{r})^* \left[V_{pt}(\mathbf{R} + \frac{\mathbf{r}}{2}) + V_{nt}(\mathbf{R} - \frac{\mathbf{r}}{2}) \right] \phi_{n'}(\mathbf{r})$$

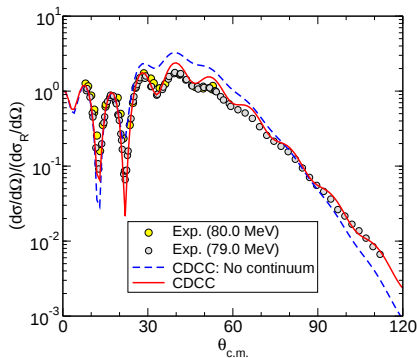
What observables can we study with CDCC

- ⇒ Elastic scattering
- ⇒ Breakup angular distribution, as a function of excitation energy:
- ⇒ Breakup energy distribution, as a function of c.m. angle:

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☞ From the S-matrices, more complicated breakup observables can be obtained, such as angular/energy distribution of one of the fragments

Application of the CDCC formalism: $d + {}^{58}\text{Ni}$ 

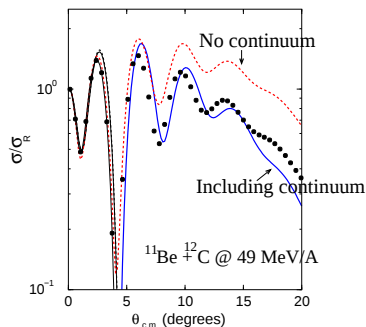
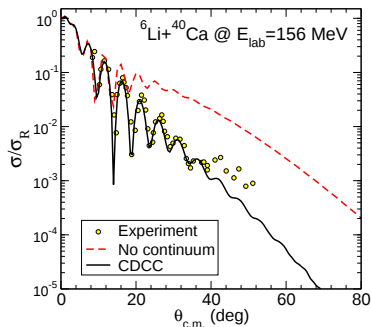
- $\ell = 0, 2$ continuum
- $p + {}^{58}\text{Ni}$ and $n + {}^{58}\text{Ni}$ from Koning-Delaroche OMP.
- $V_{pn}(r) = -72.15 \exp[-(r/1.484)^2]$

☞ *Coupling to breakup channels has a important effect on the reaction dynamics*

Application of the CDCC method: ${}^6\text{Li}$ and ${}^6\text{He}$ scattering

➡ The CDCC has been also applied to nuclei with a cluster structure:

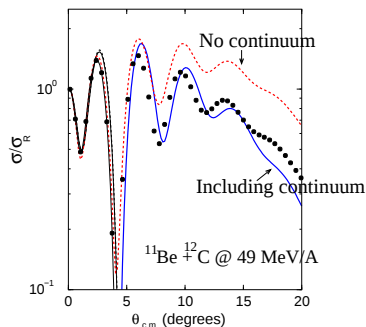
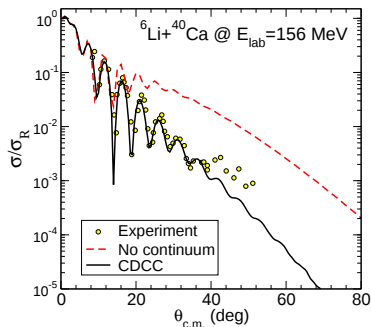
- ${}^6\text{Li} = \alpha + d$
- ${}^{11}\text{Be} = {}^{10}\text{Be} + n$



Application of the CDCC method: ${}^6\text{Li}$ and ${}^6\text{He}$ scattering

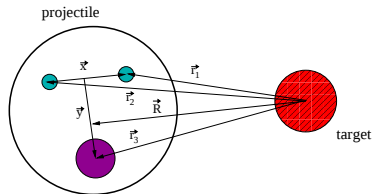
➡ The CDCC has been also applied to nuclei with a cluster structure:

- ${}^6\text{Li} = \alpha + d$
- ${}^{11}\text{Be} = {}^{10}\text{Be} + n$



➡ In Fraunhofer scattering the presence of the continuum produces a reduction of the elastic cross section

Eg: ${}^6\text{He} = \alpha + n + n$



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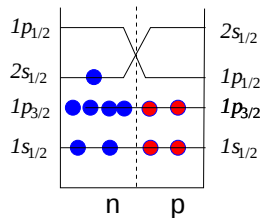
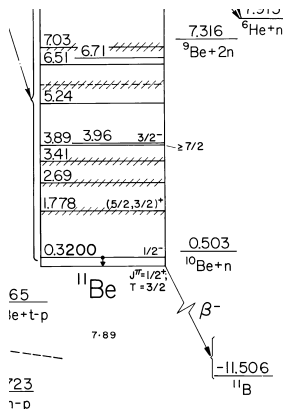
Input example for inelastic scattering within cluster model



Cluster model example: $^{11}\text{Be} + ^{12}\text{C}$

Example: $^{11}\text{Be} + ^{12}\text{C} \rightarrow ^{11}\text{Be}(1/2^+, 1/2^-) + ^{12}\text{C}$ at 49.3 MeV/A

Phys. Rev. C 67, 037601 (2003)



Cluster model example: $^{11}\text{Be} + ^{12}\text{C}$

General variables:

```
&FRESKO hcm=0.05 rmatch=60.
      jtmin=0.0 jtmax=150.0      < ---- total angular momentum
      thmin=0.0 thmax=45. thinc=0.5
      iblock=2 smats=2 xstabl=1
      elab=542.3 /
```

- **iblock=2**: number of channels coupled to *all orders*.

Cluster model example: $^{11}\text{Be} + ^{12}\text{C}$

Partitions & states:

```
&PARTITION namep='11Be' massp=11. zp=4
           namet='12C' masst=12. zt=6 nex=2 /
&STATES jp=0.5 bandp=1 cpot=1 jt=0.0 bandt=1 /
&STATES jp=0.5 bandp=-1 ep=0.3200 cpot=1 jt=0.0 copyt=1 /
```

- **nex=2**: This partition will contain two pairs of states.
- **copyt=1**: The target of the second pair of states is just the same (a copy) of the first target stat.

```
&PARTITION namep='10Be' massp=10.0 zp=4
           namet='12C+n' masst=13.0 zt=6 nex=1 /
&STATES jp=0.0 bandp=1 cpot=2 jt=0.0 bandt=1 /
```

Cluster model example: $^{11}\text{Be} + ^{12}\text{C}$

Projectile-target Coulomb potential (monopole):

```
&POT kp=1 ap=11.0 at=12.0 rc=1.111 /
```

Neutron-target & core-target potentials:

```
&POT kp=3 ap=0.0 at=12.0 rc=1.111 /
&POT kp=3 type=1 p1=37.4 p2=1.2 p3=0.75
                p4=10.0 p5=1.3 p6=0.6 /
```

```
&POT kp=2 ap=10.0 at=12.000 rc=1.111 /
&POT kp=2 type=1 p1=123.0 p2=0.75 p3=0.8
                p4=65.0 p5=0.78 p6=0.8 /
```

Neutron binding potential:

```
&POT kp=4 ap=0 at=10.0 rc=1.0 /
&POT kp=4 type=1 p1=87.0 p2=1.0 p3=0.53 /
```


$^{11}\text{Be} + ^{12}\text{C}$ inelastic scattering

Couplings:

```
&COUPLING icto=1 icfrom=2 kind=3 ip1=4 ip2=1 p1=3.0 p2=2.0 /
```

- **kind=3**: Single-particle excitations of projectile
- **icto=1**: Partition containing nucleus being excited (^{11}Be)
- **icfrom=2**: Partition containing core (^{10}Be)
- **ip1=4**: Maximum multipole for coupling potentials
- **p1/p2**: KP index for fragment-target / core-target potentials

Spectroscopic amplitudes:

```
&CFP in=1 ib=1 ia=1 kn=1 a=1.000 /  
&CFP in=1 ib=2 ia=1 kn=2 a=1.000 /
```

- **in=1/2**: Projectile/target
- **ib/ia**: Index for composite/core state
- **a**: Spectroscopic amplitude