ARTICLE IN PRESS

Progress in Particle and Nuclear Physics ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

Direct reaction theories for exotic nuclei: An introduction via semi-classical methods

Angela Bonaccorso

INFN, Sezione di Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy

ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Direct reactions
Exotic nuclei
Semi-classical theories

ABSTRACT

The structure of exotic nuclei has only been studied from around 1985, because they are very short lived and because before that, it was not possible to produce and deliver them as beams on a target. They have large N/Z or Z/N ratios, are weakly bound and quite extended most of the time. Thus breakup, transfer and/or inelastic excitations of the surface are some of their most common reaction mechanisms. Direct reactions, for their simplicity, have played a fundamental role in the last thirty years in the process of understanding such "new" type of structures. On the other hand, direct reactions have been studied and understood for a much longer time, starting with the pioneering experiments in the early '50 on deuteron-induced reactions and the reaction models developed by S.T. Butler and collaborators. Both subjects are extremely vast and there is a large literature available of books, review articles and original papers. I will discuss here only a few selected examples of the many interesting problems that have been encountered and solved in all those years. I consider them breakthroughs in the field and as such I hope they can inspire young generations of researchers.

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E-mail address: angela.bonaccorso@df.unipi.it.

https://doi.org/10.1016/j.ppnp.2018.01.005
0146-6410/

Please cite this article in press as: A. Bonaccorso, Direct reaction theories for exotic nuclei: An introduction via semi-classical methods, Progress in Particle and Nuclear Physics (2018), https://doi.org/10.1016/j.ppnp.2018.01.005.

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1. Introduction

For the last thirty years, Nuclear Physics has known a big revival thanks to the advent of Radioactive Ion Beams (RIBs). These nuclei are often called "exotic" because they have unusual properties, like large neutron over proton ratios, N/Z; small separation energies for the valence particles; large root mean square radii, r.m.s., and of course being radioactive they have, first of all, very short life times (for example ^{11}Be has a $T_{1/2}$=13.8 s while ^{11}Li has a $T_{1/2}$=8.6 ms).

The most exotic nuclei are those just beyond the dripline. They are unbound but their ground state is often a resonance that lives long enough for its properties to be measured. The same might happen for the lowest excited states and thus these exotic systems are called "nuclei" and their properties studied in the same way as the more "normal" species that lie more or less closer to the stability line. Because exotic nuclei are very weakly bound in most of the cases, their surface is quite extended. Thus several of their new properties have been discovered thanks to experiments employing peripheral, direct reactions. This field is so rich and active that since 1999 there is a biennial conference called DREB (Direct Reactions with Exotic Beams) in which a large number of physicists gather to discuss the latest developments.

The physics of exotic nuclei has shed a completely new light on the concept of the nuclear interaction and the way it acts to bind matter. The basic concepts in Nuclear Physics, such as nuclear radii, binding energies, decay schemes etc. have been rediscussed. So much so that it has been deemed necessary to organize schools for undergraduates in which these new concepts not contained in standard Nuclear Physics textbooks have been presented. One such a School, which has been held twice so far in Pisa, Italy, is indeed called "Re-writing Nuclear Physics Textbooks..." [1].

In the following we will review the main steps in the history of direct reactions to set the framework in which reactions with exotic nuclei have been used. There is a twenty to thirty year recurrent time span between fundamental turning points in such a history. I will mainly concentrate on such turning points.

The first twenty five years or so were dominated by deuteron and light nuclei induced reactions (1950–1970). Deuteron induced reactions, including the latest developments, are the subject of another review paper by Ron Jonhson on this journal and because of that I will just touch upon them. On the other hand, in the 70s heavy-ions started to be used as projectiles following the advent of new, more powerful accelerators, finally from 1985 up-to-date exotic nuclei have dominated the field of Nuclear Physics with hadronic probes.

2. The dawn of direct reaction theory

The book of Norman K. Glendenning, "Direct Nuclear Reactions" [2] describes the beginning of nuclear reaction theory when it was thought that all reactions proceeded via compound nucleus [3] and resonance phenomena. They were first studied by Feshbach and Weisskopf [4], Breit and Wigner [5] and Kapur and Peierls [6]. Resonances are nowadays very important again to understand and describe unbound nuclei and an updated review can be found in R. J. Charity contribution to the Pisa Summer School [7].

In the book of Glendenning there is also a nice figure from P. Hodgson book [8], that we report here as Fig. 1, in which every reaction seems to go through "compound nucleus" apart from direct reactions which are indicated to go to "...etc". In 1950 the first experiments [9] and theoretical papers [10] clarified what that "...etc" meant. From the point of view of the experimental observations, direct reactions were characterized by forward-peaked angular distributions and oscillations see Fig. 2 from Refs. [9,10]. Compound-nucleus reactions had instead isotropic angular distributions. Bethe and Butler [11] first understood the mechanism of direct reactions as due mainly to a surface diffractive effect and showed the way to use them

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