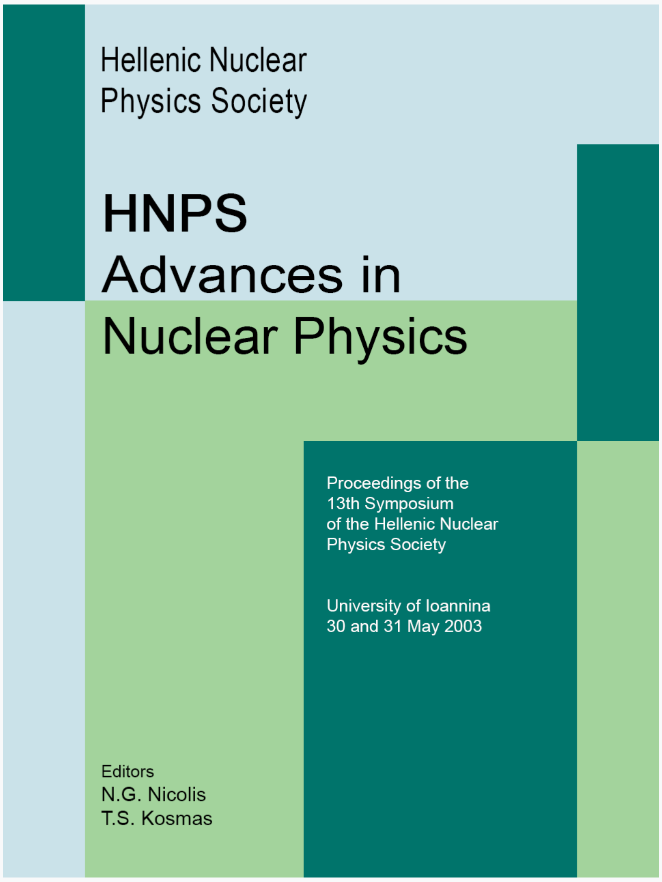

Weakly bound Nuclei

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Abstract

The development of radioactive beam facilities makes possible the study of weakly bound nuclei far from stability and close to the drip lines. A vast variety of nuclei is now available, therefore a new research ground is open for the discovery of phenomena previously unexpected. Complementary studies with stable weakly bound nuclei can assist such studies. Examples for ^{6}He and ^{6}Li are discussed.

In the past decade the development of radioactive beam facilities gave an unprecedented boost in Nuclear Physics, since the rapid increase in the number of nuclei (Fig. 1) led to the discovery of phenomena that were previously unexpected [1–3]. The vast variety of available nuclei makes possible isotope, isotone and isospin dependence studies, indicating new structures and reaction mechanisms. Moreover it opens a wholly new ground on studies of "weakly coupled systems" with non-uniform densities. Therefore it is of special interest to study such nuclei near the limit of binding (the neutron drip line and the proton drip line) as well as nuclei in resonance states outside the driplines.

Stable nuclei have well-balanced proton and neutron numbers, which are uniformly mixed composing "nuclear matter". In unstable nuclei where the number of neutrons and protons are not balanced, distributions of protons and neutrons may decouple, resulting in the formation of a region composed of only neutrons and protons. The properties of such new substances are completely unknown and thus they are very attractive. As it is well known, neutron matter does not exist naturally on earth but is regarded as existing only in neutron stars far away from the earth. Apart of the difference in proton and neutron number and their densities, such nuclei present differences in fermi energies and occupied orbitals while the binding energy of their last nucleon is sometimes as low as 1/10 of that of normal stable nuclei. Such weakly binding states may present the possibility of developing unusual cluster structures inside the nucleus as dineutron, ^{6}He and ^{8}He in addition to the well known α cluster. Further on, nuclei with a large N/Z ratio near the drip lines present abnormal material distributions as neutron halos while other topologies may

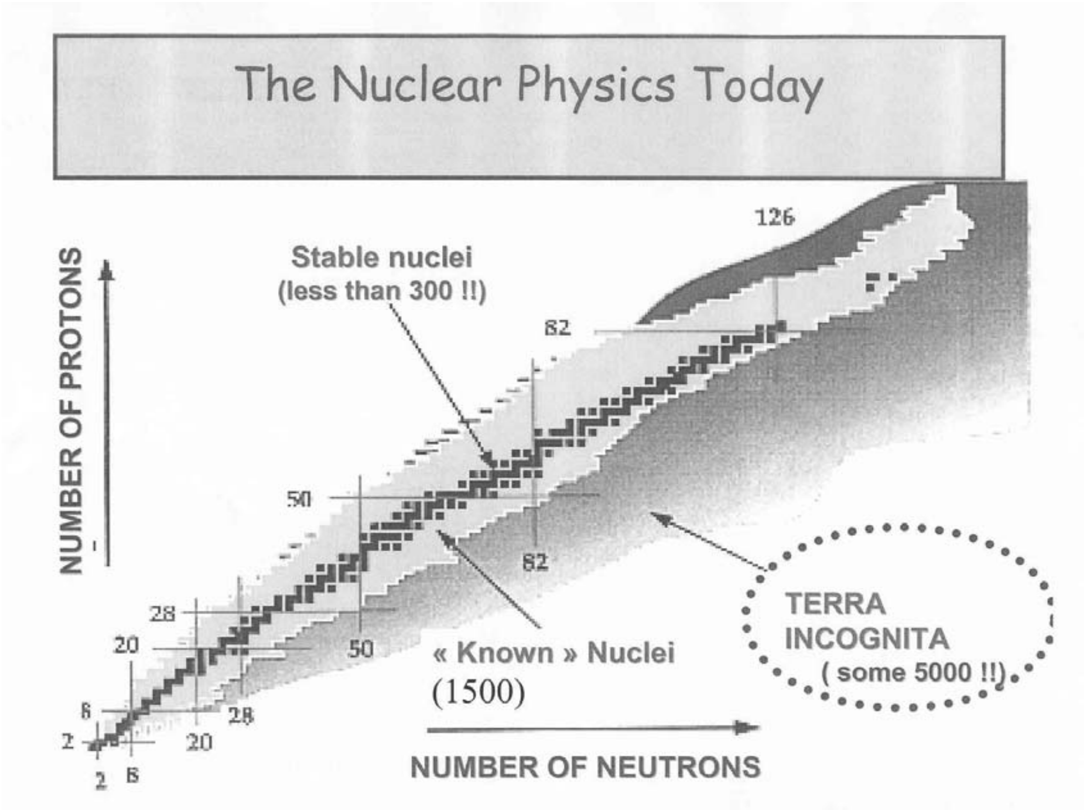

Fig. 1. Nuclear chart, which reveals the main "terra incognita" of the nuclear map, i.e. the huge grey-black region between the particle - stable nuclei on the one hand and the so called neutron drip line and fission limit on the other hand.

not be excluded (Effimov states). Another interesting feature which may be obtained in drip line nuclei is the development of exotic shapes or of superdeformation and hyperdeformation in the ground state due to the acquired high angular momenta (such as νk17/2) of the halo orbiting nucleons.

From the above it becomes obvious, that a terra incognita which extends up to the drip lines (Fig. 1) or even beyond these, waits to be explored by the young nuclear physicists and new phenomena to be revealed. Subjects that are open to research are

1. Studies of the nuclear territory-super heavy elements (a short overview was given in the symposium concerning present experiments devoted in the discovery of superheavy elements)

2. Conventional research with halo-skin nuclei on nuclear structure and reactions concerning evolution of nuclear structure with N/Z- exotic shapes-

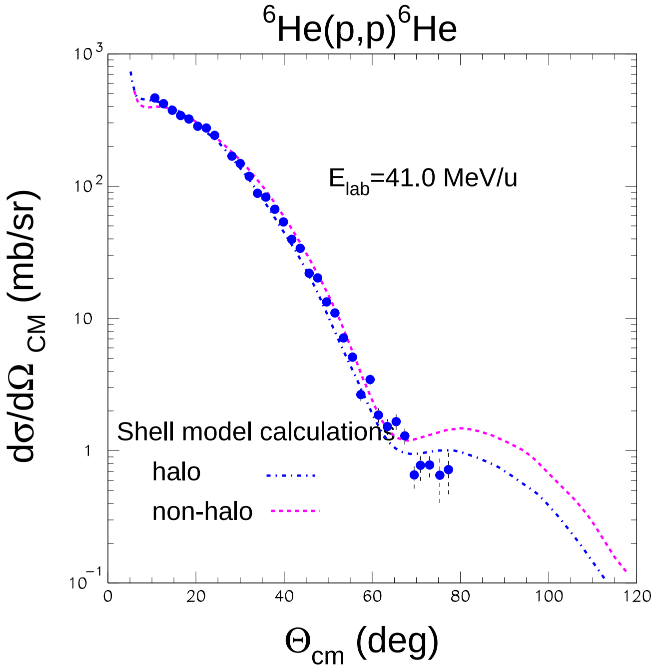

Fig. 2. Elastic scattering data of ^{6}He(p,p$'$)^{6}He in inverse kinematics. The dashed-dotted line and the dashed line corresponds to shell model calculations with halo and non-halo structure correspondingly.

weakening of the ls force with dramatic changes in nuclear structure (new magic numbers!)

Into this context, the elastic and inelastic scattering of weakly bound halo nuclei on stable targets is of major importance. In principle, with elastic scattering we probe the nuclear potential-effective interaction and density distributions while with inelastic scattering we probe multipole transition elements M_p and M_n (From Coulomb excitation measurements we get B(E2) and then M_p. From hadron (isoscalar)inelastic scattering measurement we get M_p+M_n. From hadron (isovector)inelastic scattering measurement we get M_p-M_n). For halo nuclei it is not recommended the use of macroscopic potentials [4]. Global parameterizations such as that by Becchetti and Greenlees, give in general good predictions for scattering cross sections of stable systems. However, such approaches assume similar interaction potentials for neutrons and protons. Moreover, the extracted parameters do not give direct access to the nuclear densities. In contrast by using microscopic potentials the above shortcomings may be avoided. There are two categories of microscopic potentials. In the first category, densities are used to deduce from infinite nuclear matter

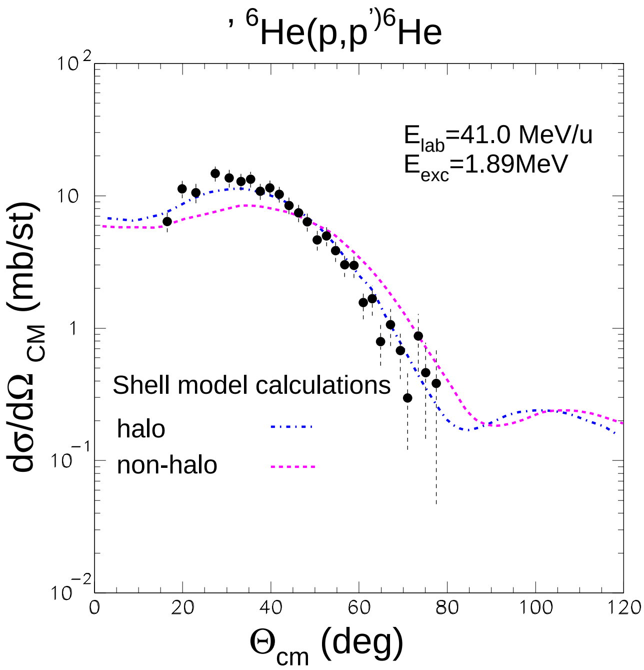

Fig. 3. Inelastic scattering ^{6}He(p,p$'$)^{6}He in inverse kinematics. The dashed-dotted line and the dashed line corresponds to shell model calculations with halo and non-halo structure correspondingly.

optical potentials-ground state and transition optical potentials. In the second category, ground state and transition densities are folded with an effective nucleon-nucleon interaction to generate ground state and transition potentials.

A good example of such studies is the elastic and inelastic scattering of protons from the dripline nucleus ^{6}He in reverse kinematics. Data of studies performed at GANIL by the Saclay group, with whom we have collaborated, are shown in Figures 2 and 3 for elastic and inelastic scattering correspondingly [5–7]. Shell model calculations by Amos and Karataglidis [5] are also shown in the same figures and help to probe the halo nature of this nucleus. In Fig. 4, JLM [8] calculations are presented against the inelastic measurements, pointing out a possible decoupling of protons and neutrons for ^{6}He [7].

^{6}He is one of the most popular weakly bound nuclei, which was explored extensively worldwide. Several problems however remain opened. Between them the interpretation of fusion results on heavy targets[9,10] at barrier and sub-barrier energies. As it was pointed out in [10] to interpret fusion data of weakly bound nuclei either discretized coupled channel calculations have to

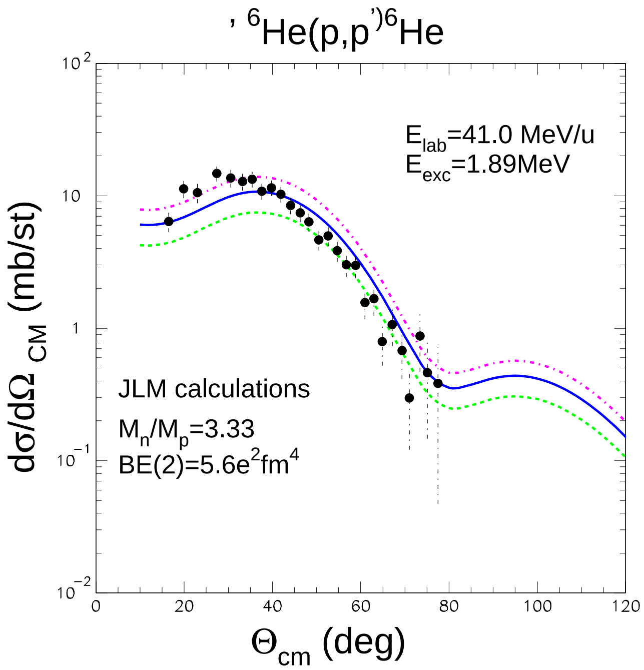

Fig. 4. Inelastic scattering data of ^{6}He(p,p$'$)^{6}He in inverse kinematics. JLM calculations gave a best fit-solid line, assuming a ratio of multipole elements of neutrons over protons equal to M_n/M_p=3.33. This value is much greater than the hydrodynamical one, implying the decoupling of protons and neutrons.

be performed, in order breakup to be considered explicitly or an appropriate potential has to be invoked. It is well known, however the phenomenon of "threshold anomaly" in the optical potential which appears around the barrier for stable encounters [11]. This is visualized as a rapid energy variation of both the real and imaginary parts in the barrier where a localized peak is developed in the real part associated through dispersion relations with the decrease of the imaginary part as the energy is decreasing [12]. The physical origin of the effect is due to strong couplings to low-laying states in both the projectile and target, in inelasting scattering and transfer reactions. It was suggested [12] that the same effect may not appear for weakly bound systems where due to breakup a Dynamic Polarization Potential develops which as it is repulsive in nature may smooth out the attractive polarization term due to the anomaly. Such issues have to be resolved and this can be done equally well by using stable weakly bound nuclei. In that respect the heavy schedule of the radioactive accelerators can be decongested while such studies can give the initiative to studies with halo nuclei. For example ^{6}He and ^{6}Li can be considered as "associate" weakly bound nuclei, one of them radioactive the other stable. Properties of the two nuclei are summarized in Table 1. In particular we stress out the similarity in the r.m.s radii and distance of closest approach.

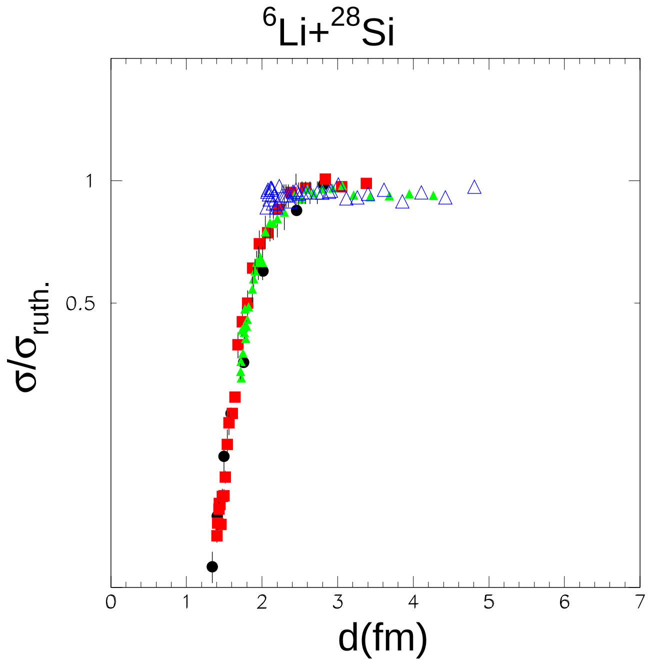

Fig. 5. Elastic scattering data of ^{6}Li+^{28}Si at 13,11,9 and 7.5 MeV[13] designated with the solid circles, solid boxes,solid triangles and open triangles correspondingly, as a function of reduced distance of closest approach.

Property	^{6}He	^{6}Li
S_{2n}-S_α (MeV)	0.975	1.475
r.m.s (fm)	2.30 - 2.48	2.32 - 2.45
d (fm)	2.2	2.2

Table 1

Properties of ^{6}He and ^{6}Li which point out the similarities of the two nuclei (S:separation energy, d: reduced distance of closest approach

According to Kim et al. [15] the reduced distance of closest approach of stable nuclei is 1.67 fm while for halo nuclei as ^{6}He is 2.2 fm. We report herewith the reduced distance of closest approach for ^{6}Li as 2.2 fm (fig. 5).

Into that context we have started studies concerning the behavior of the potential for ^{6}Li at barrier energies. As we have established in [13], where we report angular distribution measurements for the elastic scattering of ^{6}Li+^{28}Si and their theoretical analysis as well as the theoretical analysis under the same footing of previous data on heavier targets, the imaginary potential increases as the energy is decreasing approaching the barrier while the real potential remains constant (fig. 6). This fully contrasts the behavior of stable nuclei and

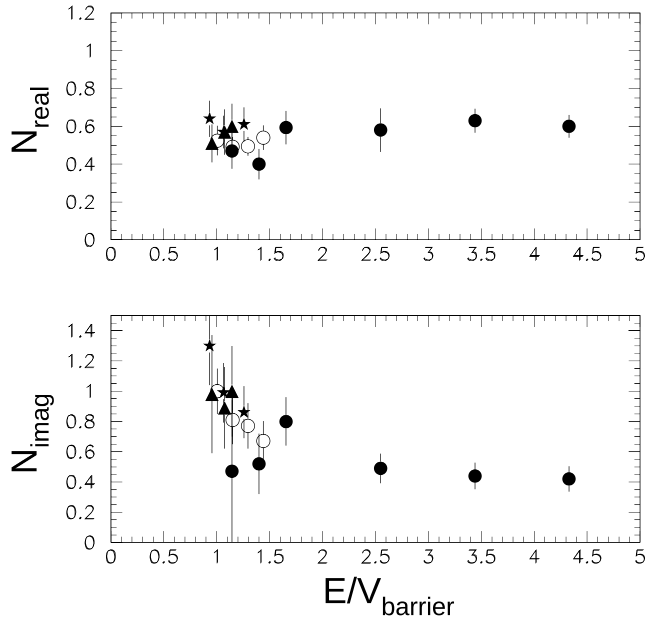

Fig. 6. Normalization factors of the real and imaginary potential as a function of the ratio of lithium bombarding energy over the barrier. Solid circles correspond to data for the ^{6}Li+^{28}Si system, open circles to the ^{6}Li+^{58}Ni, triangles to the ^{6}Li+^{118}Sn system and stars to the ^{6}Li+^{208}Pb system. The adopted barriers in the laboratory, were the BDM3Y1 potential barriers obtained in the present calculations equal to 7.83, 13.9, 20.95 and 31 MeV for the above systems respectively.

as it is suggested in [14] it is the result of the α -production due to breakup of the ^{6}Li projectile and transfer reactions. It is also shown in [14] that the α-production over the total reaction cross section shows also an increasing trend and this same trend is exhibited by ^{6}He too.

In summary, the development of radioactive beam facilities makes possible the study of weakly bound nuclei far from stability and close to the drip lines. A vast variety of available nuclei broadens our research ground and give the possibility for the discovery of phenomena previously unexpected. Complementary studies with stable weakly bound nuclei can assist this endeavor.

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