Workshop on Atomic and Nuclear Quantum Effects Near Threshold

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Book of Abstracts

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13C+a and 22+a at low energies

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The cross sections of the reactions 13C(a,n)O16 and 22Ne(a,n)Mg25 as well as 22Ne(a,g)Mg26 need to be known at energies close to the alpha threshold as inputs for stellar nucleosynthesis modelling. These cross sections are extremely difficult to measure directly, and extrapolation or determination of low-energy resonance parameters through indirect or theoretical methods is relevant. In the case of 13C+a a state only few keV off-threshold is crucial for the determination of the low-energy cross section and has been under intense study. For 22Ne+a there are a number of states between the alpha- and neutron-thresholds that could contribute to the reaction and that show pronounced signs of a cluster structure.

We describe the current state of our knowledge for these reactions and present recent and upcoming campaigns to directly measure their low-energy cross sections

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A critical review of R-matrix extrapolations to low energies

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The phenomenological R-matrix method has been used for many years to successfully describe the energy dependence of many different nuclear reaction cross sections. In the field of nuclear astrophysics, this model is often utilized not only to model the cross section of charged particle induced reactions over the energy region of experimentally measured nuclear data, but also to extrapolate to very low energies, which correspond to stellar burning temperatures, where the measurement of the cross section is too small to experimentally access. Many years of experimental study has resulted in a firm understanding of the underlying reaction mechanisms that produce the cross section over the experimentally accessible energies. This has been further confirmed by a new generation of measurements at underground facilities where cross sections have been measured to unprecedentedly low energies, which for the large part match R-matrix predictions made using higher energy data when that data is accurate. However, even with these new state-of-the-art measurements, many reactions still require extrapolation of their cross section into energy ranges that have never been experimentally accessed, and methods such as phenomenological R-matrix are largely based on theory that is more than 70 years old, it seems prudent to periodically critically re-evaluate our understanding of the underlying assumptions of this extrapolation process and its associated uncertainties.

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Atomic nucleus at the edge of stability

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Loosely bound nuclei are currently at the centre of interest in low-energy nuclear physics. The deeper understanding of their properties provided by the shell model for open quantum systems changes the comprehension of many phenomena and offers new horizons for spectroscopic studies of nuclei from the driplines to the valley of β-stability for states in the vicinity and above the first particle emission threshold [1,2]. Systematic studies in this broad region of masses and excitation energies will extend and complete our knowledge of atomic nuclei at the edge of stability.

In this talk, I will review recent progress in the open quantum system shell model description of nuclear states. In particular, I will present selected applications of the real-energy continuum shell model, the so-called Shell Model Embedded in the Continuum, and the complex-energy continuum shell model, the so-called Gamow Shell Model in the Coupled Channel basis. Salient generic features of open quantum systems will be illustrated on examples of (i) near-threshold
collectivity and clustering, (ii) modification of effective NN interactions and shell occupancies in weakly bound/unbound states, (iii) exceptional point singularities in the continuum, (iv) change of the electromagnetic transitions by the coupling to decay channels, and (v) resonances and lowenergy reactions of astrophysical interest.

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EFT for near-threshold states

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I will discuss the application of Effective Field Theory (EFT) to two problems: the interactions of 3He and 4He nuclei near threshold and two-neutron halo nuclei.

In the first part of the talk I will show how EFT provides a systematic approach to the 3He-4He elastic scattering and the capture reaction 3He(4He,γ). A crucial feature of EFT is the ability to estimate the theoretical uncertainty associated with the terms of higher order in the theory that have been omitted from the calculation. I will show how this feature aids the estimation of effective-range theory parameters for the scattering reaction.

In the second part of the talk I will discuss the application of EFT to two-neutron halos. I will show that the two-neutron momentum distribution in 11Li, 14Be, 17B, 19B, and 22C are well described by the solution of the quantum-mechanical three-body problem in the unitarity limit. I discuss how this universality of the two-neutron momentum distributions in halo nuclei could be investigated experimentally.

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Indirect methods to directly explore threshold energies

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Nuclear reactions in stars under quiescent conditions take place at energies well below few MeV so the Coulomb barrier, exponentially suppressing the cross section down to values as small as few nanobarns, makes it very difficult to provide accurate input data for astrophysics. Therefore, indirect methods have been introduced; in particular, in this presentation I will discuss about two approaches, the ANC and the THM, used to deduce the cross sections of reactions with photons and charged particles in the exit channel, respectively, with no need of extrapolation. I will present recent results of the application of the two methods: the 6Li(3He,d)7Be measurement used to deduced the ANC's of the 3He+4He->7Be and p+6Li->7Be channels and the corresponding radiative capture cross sections. Then, I will discuss about the THM measurement of the 27Al(p,a)24Mg cross section through the 2H(27Al,a24Mg)n reaction. In both cases, we were able to establish the cross section at astrophysical energies with unprecedented accuracy.

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Near-threshold resonances in atomic nuclei

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There are numerous examples of narrow resonances in light nuclei that can be found in the proximity of particle decay thresholds. Probably the most famous resonance of this kind is the excited 0+ Hoyle state of 12C very close to the alpha-particle separation energy. Another splendid example of a threshold resonance is the 1/2+ state in 11B that explains the beta-delayed proton decay of a neutron-rich nucleus 11Be.

According to the open quantum system shell model, the coupling to the decay channels leads to a near-threshold collectivity, which may result in a formation of a single "aligned eigenstate" of the system that carries many characteristics of a nearby decay channel. This provides a general explanation of the widespread appearance of correlated states in the vicinity of cluster emission thresholds. In this presentation, I will use the lenses of real-energy continuum shell model to discuss threshold resonances in light nuclei.

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Present Status of Direct Measurements on 12C+12C Fusion

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Carbon burning is believed to be essential for late stellar burning phases and it could also determine the ignition, burning, and nucleosynthesis pattern in cataclysmic binary systems such as type Ia supernovae and x-ray superbursts. Experimental work and developments on direct measurement of the 12C+12C fusion reaction carried out in recent years using new technologies will be reviewed. In particular, new results from 12C+12C experiments with SAND (a silicon detector array) conducted at the high-intensity St. ANA accelerator with particle-gamma coincidence and differential target techniques will be reported. The latest results of 12C+12C cross sections at low energies relevant to nuclear astrophysics will be compared with other recent measurements using different approaches. The observed resonant structures and how to merge direct data with indirect results at even lower energies will be discussed.

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Pushing direct measurement of ^{12}C + ^{12}C fusion reaction toward the Gamow window

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Stellar carbon burning proceeds primarily through the 12C(12C,α)20Ne (Q = 4.62 MeV) and the 12C(12C,p)23Na (Q = 2.24 MeV) reactions. The determination of their cross sections at the energy of the Gamow peak (1.5 MeV < E < 2 MeV) is mandatory to improve our understanding of the universe. In fact carbon burning, depending on the star's mass, can occur in quite complex scenarios, and affects several astrophysical observable. Due to the extremely small cross sections, the experimental determination of the reaction rates is quite challenging already at energies above 2 MeV. Measurements can be done detecting the γ generated by the decay of the 23Na and 20Ne excited states. In the last 4 decades the 12C(12C,α)20Ne and the 12C(12C,p)23Na reactions were directly investigated, using both charged-particle and γ-ray spectroscopy, over a wide range of energies, down to about E = 2.1 MeV. The low counting rates had to confront with severe background issues, stemming from the presence of 1H and 2H contamination in the targets. LUNA collaboration will perform γ-ray measurements, using the intense 12C beam provided by the 3.5MV accelerator available at the Ion Beam Facility, at the underground Gran Sasso Laboratory (LNGS-INFN). The reduced γ-ray background in underground will allow us to investigate the reactions directly at the relevant astrophysical energy.

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Quantal effects on thermonuclear reactions

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Stellar nuclear fusion reactions take place in a hot, dense plasma within stars. To account for the effect of these environments, the theory of open quantum systems is used to conduct pioneering studies of thermal and atomic effects on fusion probability at a broad range of temperatures and densities. Since low-lying excited states are more likely to be populated at stellar temperatures and increase nuclear plasma interaction rates, a ^{188}Os nucleus was used as a target that interacts with an inert ^{16}O projectile. Key results showed thermal effects yield an average increase in fusion probability of 15.5\% and 36.9\% for our test nuclei at temperatures of 0.1 and 0.5 MeV respectively, compared to coupled channels calculations at zero temperature.

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Quantum Many-Body Physics Near Decay Thresholds

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The interaction between the quantum many-body system and the continuum of reaction states has a significant impact on its dynamics, especially near the decay threshold. This interaction causes changes in the wave functions with respect to the decay channels, resulting in phenomena such as threshold discontinuities, collectivization of states, clusterization, symmetry breaking, and interplay between decay and internal dynamics. This talk will cover recent theoretical advancements and experimental studies on threshold physics, such as alpha clustering close to decay thresholds, isobaric mirror resonant reactions that demonstrate the importance of coupling to the continuum, and the unique case of 11Be decay. Additionally, the presentation will discuss recent research on few-body decays, both direct and sequential, as well as dynamics involving virtual excitations.

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Quantum dynamics in carbon burning

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The physics of low-energy nuclear reactions is crucial for our understanding of the creation of chemical elements in the Universe. I will report on novel quantum dynamical approaches to low-energy nuclear reactions. These approaches are the time-dependent coupled-channels wave-packet method and the coupled-channels density-matrix method. In contrast to static coupled-channels models, these approaches allow one to describe competing reaction processes at intermediate collision times, providing insights into the reaction mechanisms. Applications to fusion dynamics of 12C + 12C will be discussed. These techniques pave the way for new exciting research, such as the dynamical description of plasma-assisted nuclear fusion and the neutron capture process.

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Sub-Coulomb nuclear studies of stellar carbon burning using the Trojan Horse Method

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I discuss the basic concepts of the Trojan Horse Method in nuclear astrophysics and the opportunity it offers to determine the cross sections of various stellar burning reactions when it is difficult to perform the corresponding direct measurements. I will focus on recent results to study carbon burning in 12C+12C fusion-dominated conditions and anticipate preliminary results on the 12C+16O fusion channel.

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The electron screening of nuclear reactions in the laboratory and within stars

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I will discuss the longstanding puzzle of electron screening of nuclear reactions in the laboratory and within stars. A comparison between existing experimental data and multiple theories will be highlighted. I will focus on the modeling of nuclear/atomic reactions including (a) excitation, (b) ionization, (c) atomic transfer of electrons, (d) the role of stopping power at low energies and (e) applications of mean-field theories to electron screening in the stellar environments.

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The nature of the 0+ strength in 12C above threshold

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The structure of nuclei is a dynamic interplay between microscopic and macroscopic properties guided by the nature of the strong interaction. Though fundamentally a system whose properties are governed by the nature of these inter-nucleon forces, with the influence of many-body components, the nuclear structure is guided by emergent symmetries. A recent study using quantum many-body simulations formulated from first principles [1] has explored the emergence of α-particles which reproduce the densities of the nuclei 8,10Be and 12C. Lattice based Chiral Effective Field Theory calculations, where nucleons are free to move between the lattice sites under the influence of the strong interaction also demonstrates the emergence of α-clustering [2]. These correlated 4 nucleon systems are evident in experimental observations across the nuclear chart, but an interesting question is how these correlations then imprint onto the mean-field/shell-model interpretation of nuclei. In 12C, the cluster correlations appear above and below the cluster decay threshold and appear to have a very different character. This talk will explore how the nature of the cluster structure evolves from the mean-field picture to separate, distinct, clusters and the role the continuum might be playing.

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Threshold effects on proton-induced reactions in light nuclei

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An enhanced probability for single-particle or cluster states to be located near the particle or cluster threshold in nuclei is observed experimentally. A partial explanation for this observation is provided

by phenomenological R-matrix theory. The R-matrix approach can also used to model the mixing between levels induced by the long-ranged Coulomb interaction. These effects are found to be important when utilizing mirror symmetry to estimate (p,γ) reaction rates utilizing nuclear structure information from the mirror nucleus. Results will be presented for the specific cases of 18O <-> 18Ne and 27Al <-> 27Si, that are important for estimating the 17F(p, γ)18Ne and 27Al(p,γ)27Si reaction rates, respectively. On the experimental side, a study for the nucleus 11B will be presented, where there are four thresholds between 8 and 12 MeV excitation energy. We have measured the 10Be(d,n)11B proton transfer reaction. Other recent experiments have found evidence for a 1/2+just above the proton threshold in 11B, with a large proton spectroscopic factor. The (d,n) proton transfer data are particularly sensitive to any levels with a large proton spectroscopic factor.

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Using high energy density plasmas for nuclear experiments relevant to nuclear astrophysics

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Thermonuclear reaction rates and nuclear processes have traditionally been explored by means of accelerator experiments, which are difficult to execute at conditions relevant to stellar or big bang nucleosynthesis. High energy density (HED) plasmas generated using lasers, e.g., such as the inertial confinement fusion platform, more closely mimic astrophysical environments in several ways, including with thermal distributions of reacting ions as opposed to mono-energetic ions impinging on a cold target; stellar-relevant plasma temperatures and densities; and neutron flux densities not found anywhere else on earth. The most extreme conditions in terms of plasma densities and neutron flux can currently be achieved at the National Ignition Facility (NIF) laser in the US, where densities of 10^3 g/cm3 and neutron fluxes up to $5x10^{27}$ neutrons/cm/s have been demonstrated over a time period of a few tens of picoseconds [1]. Other HED facilities, including the OMEGA laser facility [2] and short-pulse laser facilities, also offer capabilities to execute nuclear experiments in a plasma environment (see e.g., [3]), and the HED platform is now emerging as an interesting complement to accelerator experiments [4].

This talk will discuss the potential of this new platform for helping address questions including nuclear rates in plasmas, plasma effects on nuclear reactions, electron screening, and neutron reactions on excited states. Achievable plasma conditions will be described, and enabling nuclear diagnostics available at, in particular, the NIF will be presented [5]. Initial nuclear astrophysics-relevant results including S-factor measurements using this platform illustrate the possibilities [6-12]. Ongoing efforts will also be highlighted, including development towards experiments to study screening effects [13] and charged-particle-induced reactions involving mid-Z reactants [14].

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Welcome and Uncertainties at Threshold Energies

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There is mounting evidence from increasingly accurate observation on discrepancies between observed and predicted isotopic abundances. On the one hand side, this could be assigned to convective and mixing processes in the stellar environment not being properly taken into account, on the other side it may point to very low energy phenomena that modify the reaction rates from the presently predictions collected in the reaction rate tabulations from NACRE to STARLIB and REACLIB. These effects may point to inconsistencies in the modeling of electron screening, but it may also be due to yet unknown quantum effects, which lead to clustering phenomena at very low energies. This talk will provide a short overview of some of the observed discrepancies as well as possible explanations as an introduction to the conference goals.