Ab initio nuclear theory

from breakthroughs to applications

University of Surrey, 24-26 July 2019

Institute of Advanced Studies

Nuclear.Theory.Vision@UK

IOP Institute of Physics
Nuclear Physics Group

Location: Treetops (Wates House), Stag Hill, University of Surrey
Talks are **30'+10** mins

	Wednesday 24 July	Thursday 25 July	Friday 26 July
08:45		**COFFEE**	**COFFEE**
09:00		Chair:	Chair:
		P. Capel (U. Mainz) *Using Halo EFT to bridge the gap between ab initio nuclear-structure prediction and nuclear-reaction calculations*	P. Navrátil (TRIUMF) *The challenge of a better understanding of the three-nucleon force*
09:40		I. Vidaña (INFN Catania) *Single-particle spectral function of the Λ hyperon in finite nuclei*	A. Tichai (CEA Saclay) *Pre-processing techniques in nuclear many-body theory*
10:20	**COFFEE & REGISTRATION**	**COFFEE**	**COFFEE**
10:50		G. Colò (U. Milano) *(A few) new ideas and tests for nuclear Energy Density Functionals*	A. Bulgac (U. Washington) *From the Schrödinger many-body equation to the Density Functional Theory description of static and time-dependent phenomena*
11:30		O. Hen (MIT) *Probing the NN interaction and ab-initio many-body calculations using Short-Range Correlations and the Generalized Contact Formalism*	A. Idini (U. Lund) *Development of optical potentials from self consistent Green's functions*
12:10	**LUNCH**	**LUNCH**	**LUNCH**
13:00	Chair:	Chair:	Chair:
	C. Bertulani (TAMU Com) *Ab-initio calculation of tunneling of composite objects*	T. Otsuka (U. Tokyo) *Ab initio studies on the dripline of the Island-of-Inversion nuclei*	A. Roggero (U. Washington) *Quantum computing for nuclear physics*
13:40	M. Drissi (U. Surrey) *Towards a renormalization invariant equation of state of nuclear matter*	P. Arthuis (U. Surrey) *Automated tools for nuclear theory: diagram generation and evaluation for many-body methods*	A. Gezerlis (U. Guelph) *From alpha clustering to homogeneous matter*
14:20	A. Gnech (Gran Sasso) *Calculation of ^{6}Li ground state within the Hyperspherical Harmonic basis*	V. Somà (CEA Saclay) *Recent progress in self-consistent Green's function calculations*	C. McIlroy (U. Surrey) *Self-Consistent Green's Function studies of modern Hamiltonians in finite and infinite systems*
15:00	**COFFEE**	**COFFEE**	**COFFEE & END**
15:30	P. Danielewicz (MSU FRIB) *Nuclear slabs in terms of Green's functions: collective oscillations with short-range correlations*	N. Walet (U. Manchester) *Pionless EFT for low mass nuclei*	
16:10	C. Wellenhofer (Darmstadt) *Nuclear matter and dilute Fermi systems from effective field theory*	G. Hagen (ORNL) *A solution to the puzzle of quenched beta-decays*	
16:40	F. Pederiva (U. Trento) *First steps towards simulating quantum dynamics of nucleons on a quantum chip*	J. Keeble (U. Surrey) *Solving the many-body nuclear problem with neural networks (15'+5)*	
		F. Isaule (U. Manchester) *Cold quantum gases from functional renormalisation (15'+5)*	
17:20	**DISCUSSION**	**DISCUSSION**	
18:00	**END**	**END**	
19:30 DINNER	***Côte Brasserie*** *35 Castle St, GU1 3UQ*	***Weyside Pub*** *Millbrook, Guildford GU1 3XJ*	

ABSTRACTS

Wednesday 24 July

C. Bertulani (TAMU Com)

Ab-initio calculation of tunneling of composite objects

I will discuss relevant cases of tunneling of composite objects, such as molecules passing through thin membranes, cluster-like nuclei tunneling during a nuclear fusion process, and the emission of radiation during tunneling as, e.g., observed during alpha-decay. In atomic physics tunneling can enhance or suppress the stopping of particles at very low energies, leading to corrections for the energy loss of ions in reactions of astrophysical interest. The more difficult theoretical treatment of tunneling of composite objects through multiple barriers will be illustrated with the example of molecules diffusing in optical lattices. The role of ab-initio calculations will be emphasized.

M. Drissi (Surrey)

Towards a renormalization invariant equation of state of nuclear matter

The current paradigm to describe the nuclear interaction is within the frame of Chiral Effective Field Theory (χEFT) which organizes contributions to nuclear observables in a series of decreasing importance. Within this framework the leading contribution already requires to solve exactly the many-body Schrödinger equation with a particular Hamiltonian. Nevertheless, such calculations are numerically intractable for A-body observables whenever $A \gg 10$.

Consequently, following the EFT program to describe infinite nuclear matter, and in particular its Equation of State (EoS), appears to be challenging. In this talk I will focus in particular on Many-body Perturbation Theory (MBPT) and more generally on many-body approximations that can be expressed as a sum of perturbation diagrams. Such additional approximations depart from the original EFT program. The goal of this talk is thus to emphasize the impact of many-body approximation on the renormalization invariance of many-body observables. I will also present new formal developments that pave the way to a systematic approach for renormalization-invariant many-body calculations. In practice, these developments could lead, in the near future, to a reduction of systematic theoretical uncertainties of nuclear many-body observables.

A. Gnech (Gran Sasso, INFN Pisa)

Calculation of ^{6}Li ground state within the Hyperspherical Harmonic basis

The Hypespherical Harmonics (HH) method has been widely applied in studying bound states and low-energy scattering process of A=3 and A=4 systems [1]. The extension to A≥5 results to be limited by the large amount of states needed for constructing the Hamiltonian matrix element up to convergence. However, the use of the brute force parallelization combined with some new computational approach opens the door to use this method for larger system.

In this talk we will introduce the approach used for computing the potential matrix element. Then we will discuss the rst preliminary result of the calculation of the 6Li ground state using SRG-evolved two-body forces [2] with particular attention on the convergence of the HH method. Moreover, we will show also the result for other properties of 6Li like the mean square radius, the magnetic dipole moment and the electric quadrupole moment.

[1] A. Kievsky, S. Rosati, M. Viviani, L.E. Marcucci, and L. Girlanda, J. Phys. G: Nucl. Part. Phys. 35, 063101 (2008).
[2] S.K. Bogner, R.J. Furnstahl, S. Ramanan and A. Schwenk, Nucl. Phys. A 784, 79 (2007).

P. Danielewicz (MSU FRIB)

Nuclear slabs in terms of Green's functions: collective oscillations with short-range correlations

Nonequilibrium Green's functions (NGF) seem ideally suited for describing central nuclear reactions, but their use poses serious computational challenges. The attraction of NGF is in the opportunity to include on par the effects of short-range correlations, or collisions between nucleons, and the mean-field effects, in a consistent quantal framework. The computational challenge is in the double-space and double-time integrations within the approach. To progress with the application of NGF to the reactions, we start with nuclear systems modeled in one dimension and seek to develop approximations that may be carried over to two and three dimensions. We first switch on correlations adiabatically in infinite uniform systems at different densities and develop a combination of correlations and mean field that can yield systems saturated at normal density corresponding to the centers of nuclei. Upon constructing finite nuclear slabs, again through adiabatic switching, we study collective oscillations for these slabs, where neutrons move against protons, as common in highly excited nuclei. We compare the progress of oscillations between the situations with mean field only and mean field combined with short-range correlations. Finally, upon preparing two cold nuclear slabs, we slam them against each other, again without and with short-range correlations.

C. Wellenhofer (Darmstadt)

Nuclear matter and dilute Fermi systems from effective field theory

In this talk, we discuss and compare the application of EFT expansions for dilute Fermi systems and dense nuclear matter. We focus on the role of three-body interactions and the many-body reference state, and we discuss resummation methods for Fermi systems with large scattering length.

F. Pederiva (U. Trento & TIFPA-INFN)

First steps towards simulating quantum dynamics of nucleons on a quantum chip

Efficient, direct simulation of quantum dynamics is one of the long standing unsolved problems in many-body physics. In this talk a scheme is introduced, that was developed by the LLNL-UNITN collaboration that aims to implement a real-time propagation of A nucleons on a quantum chip. Our strategy makes use of the possibility of constructing tunable quantum gates that realize real a finite time propagation of an initial state in a single step for any (in principle) Hamiltonian of interest. The first case we discuss is the spin evolution in the process of scattering of two neutrons using a "realistic" Hamiltonian, i.e. a LO chiral EFT local potential, which already contains most of the ingredients that pertain to the most general problem. Device level simulations including noise parametrized on the actual device will be presented.

Thursday 25 July

Pierre Capel (University of Mainz)

Using Halo EFT to bridge the gap between ab initio nuclear-structure prediction and nuclear-reaction calculations

Halo nuclei exhibit an exotic nuclear structure, in which one or two valence neutrons decouple from the other nucleons thanks to their low separation energy from the nucleus. They thus form like a diffuse halo around a compact core. Because of this strongly clusterised structure, these nuclei challenge usual nuclear-structure models. Recently, ^{11}Be, the best known one-neutron halo nucleus, has been computed ab initio by Calci et al. within the No-Core Shell Model with Continuum (NCSMC) [1]. Besides reproducing the well known shell inversion between the 1/2+ ground state and the 1/2- excited state of ^{11}Be, Calci et al. also predict important structure observables, like the asymptotic normalisation coefficient (ANC) of both bound states and the spectroscopic factors for the dominant single-particle configuration.

Because of their short half-lives, these nuclei are usually studied through indirect techniques, such as breakup reactions [2,3]. In these reactions, the internal core-halo structure is revealed through its dissociation on a target. To test the validity of the ab initio predictions against experimental data, one needs an accurate theoretical model of the reaction. Ideally, the model should include the full microscopic description of the nucleus provided by the NCSMC calculations. However, this is beyond current numerical capabilities, and moreover this complexity is probably not needed to confront the prediction of nuclear-structure models to data. Instead, we couple a Halo-EFT description of the nucleus [4] to accurate models of breakup reactions [5]. The low-energy constants of the projectile description are fitted to known experimental values, like the binding energy of the halo nucleons to the core and to the ab initio predictions. This offers the possibility to test these predictions on available experimental data. In addition, the systematics of the Halo-EFT expansions enables us to identify the nuclear-structure observables to which reactions are actually sensitive.

In this presentation, I will illustrate this idea on the breakup of ^{11}Be on both light and heavy target at intermediate and high energy [5,6].

[1] A. Calci, P. Navrátil, R. Roth, J. Dohet-Eraly, S. Quaglioni and G. Hupin, Phys. Rev. Lett. 117 242501 (2016)
[2] R. Palit et al., Phys. Rev. C 68, 034318 (2003)
[3] N. Fukuda et al. Phys. Rev. C 70, 054606 (2004)
[4] H.-W. Hammer, C. Ji and D. R. Phillips, J. Phys. G 44, 103002 (2017)
[5] P. Capel, D. R. Phillips and H.-W. Hammer, Phys. Rev. C 98, 034610 (2018)
[6] L. Moschini and P. Capel, Phys. Lett. B790, 367 (2019)

Isaac Vidaña (INFN Catania)

Single-particle spectral function of the Λ hyperon in finite nuclei

In this talk, we present a calculation of the spectral function of the Λ hyperon in finite nuclei which is obtained from the corresponding Λ self-energy constructed within a perturbative many-body approach using some of the hyperon-nucleon interactions of the Juelich and Nijmegen groups. Binding energies, wave functions and disoccupation numbers of different single-particle states are obtained for various

hypernuclei from ${}^{5}_{\Lambda}$He to ${}^{209}_{\Lambda}$Pb. The agreement between the calculated binding energies and experimental data is qualitatively good. The small spin-orbit splitting of the *p-*, *d-*, *f-* and *g*-wave states is confirmed. The discrete and the continuum contributions of the single-Λ spectral function are computed. Their appearance is qualitatively similar to that of the nucleons. The *Z*-factor, that measures the importance of correlations, is also calculated. Our results show that its value is relatively large, indicating that the Λ hyperon is less correlated than nucleons. This is in agreement with the results obtained by other authors for the correlations of the Λ in infinite nuclear matter. The disoccupation numbers are obtained by integrating the spectral function over the energy. Our results show that the discrete contribution to the disoccupation number decreases when increasing the momentum of the Λ. This indicates that, in the production reactions of hypernuclei, the Λ hyperon is mostly formed in a quasi-free state.

G. Colò (U. Milano)

(A few) new ideas and tests for nuclear Energy Density Functionals

In this contribution, two different new subjects will be discussed, although one of them is not along the main stream of the workshop but can be rather seen as complementary to it.
Despite the steady and remarkable progress in ab initio approaches to nuclear structure, Density Functional Theory remains a tool of wider applicability. It makes sense to try to derive an Energy Density Functional (EDF) from an underlying ab initio method, but also to attempt other routes for improving EDFs. We have started to make the first steps in the so-called inverse Kohn-Sham problem, that is, in grasping information on the effective DFT potential for nuclei by starting from the knowledge of the densities, and I will report on this in the first part of the talk.
In the second part of the talk, I will move to the time-dependent problem. One of the few exact results for the description of the time-evolution of an inhomogeneous, interacting many-particle system is given by the Harmonic Potential Theorem (HPT). I will show how the theorem can be generalised in order to become relevant for the nuclear many-body problem, and discuss its usefulness to test time-dependent DFT and possibly other nuclear structure approaches (like ab initio).

O. Hen (MIT)

Probing the NN interaction and ab-initio many-body calculation using Short-Range Correlations and the Generalized Contact Formalism

I will present new results from high-energy electron scattering experiments that probe the short-ranged part of the nuclear interaction via the hard breakup of Short-Range Correlations (SRC) nucleon pairs. The data covers a missing momentum range up to 1 GeV/c and is compared to factorized theoretical cross-section calculations obtained using the Generalized Contact Formalism and various local phenomenological and Chiral-EFT based NN interactions, including both non-relativistic and relativistic formulates using light-cone dynamics for the latter.
Pursuing a more fundamental understanding of such short-distance interactions I will present new measurements of the internal quark-gluon sub-structure of nucleons and show how its modification in the nuclear medium can be related to the universal modification of SRC pairs due to short-ranged nuclear interactions.

- A. Schmidt et al., in preparation (2019).
- B. Schmookler et al., Nature 566 354 (2019).
- M. Duer et al., Phys. Rev. Lett. 122 172502 (2019).

- M. Duer et al., Nature 560 617 (2018).
- E. Cohen et al., Phys. Rev. Lett. 121 092501 (2018).
- R. Cruz Torres, D. Lonardoni, R. Weiss, N. Barnea, D.W. Higinbotham, E. Piasetzky, A. Schmidt, L.B. Weinstein, R.B. Wiringa, and O. Hen, arXiv: 1907.03658 (2019).
- R. Weiss I. Korover E. Piasetzky O. Hen and N. Barnea. Phys. Lett. B 791 242 (2019).
- R. Weiss R. Cruz-Tsorres N. Barnea E. Piasetzky and O. Hen Phys. Lett. B 780 211 (2018).

T. Otsuka (U. Tokyo)

Ab initio studies on the dripline of the Island-of-Inversion nuclei

I present recent results obtained by the EKK method for the nuclei from *Z=8* to *12*. The chiral EFT and Fujita-Miyazawa 3NF are used. The dripline will be discussed as well as the shapes of those nuclei and the *N=28* gap.

P. Arthuis (U. Surrey)

Automated tools for nuclear theory: diagram generation and evaluation for many-body methods

The past decades have witnessed the development of various new many-body formalisms as well as a tremendous increase in computing powers, allowing ab initio methods to extend their reach in terms of mass, open-shell character, observables, etc. One can expect the years to come to follow that path, with increasingly sophisticated approaches reaching always larger model spaces and more complex systems. Such a research environment calls for sets of tools supporting efforts in developing both formalisms and numerical codes. Not only can they help build robust codes, their very development can lead to new formal developments. We will illustrate this by discussing the first version of the ADG program, generating and evaluating Bogoliubov Many-Body Perturbation Theory diagrams.

V. Somà (Saclay)

Recent progress in self-consistent Green's function calculations

In the last decade, advances in many-body approaches and inter-nucleon interactions have enabled significant progress in ab initio calculations of nuclear systems. At present, several complementary methods to solve the (time-independent) many-body Schrödinger equation are available, tailored to either light systems, medium-mass nuclei or extended nuclear matter. A major step forward was achieved when wave-function expansion methods, previously applicable only to closed-shell isotopes, were generalised to singly open-shell systems. One of such techniques is the Gokov self-consistent Green's function approach that generalises standard Dyson Green's function theory. I will review the key ideas behind this method and present recent applications to mid-mass isotopic chains around Z=20. The emergence of magic numbers and nuclear pairing will be highlighted. Finally, the extension to doubly open-shell nuclei will be discussed.

N. Walet (Manchester)

Pionless EFT for low mass nuclei

We discuss the application and problems with applying pionless EFT to nuclei up to mass 8. We will reanalyse previous work with Vadim Lensky and Mike Birse, and will discuss the potentially problematic role of the tensor force in such an approach. It will be explained that even though we can not completely resolve all the issues, we are able to describe nuclei up to A=8 quite well. We also discuss a description of the charge density, and will discuss how well we should try and describe such a quantity in EFT -based models.

G. Hagen (ORNL)

A solution to the puzzle of quenched beta-decays.

For over 50 years, a central puzzle has been that observed β-decay rates are systematically smaller than theoretical predictions. This was attributed to an apparent quenching of the fundamental coupling constant gA in the nucleus by a factor of about 0.75 compared to the β-decay of a free neutron. The origin of this quenching is controversial and has so far eluded a first-principles theoretical understanding. This talk presents a solution to this puzzle, and shows that this quenching can be explained from two-body currents and many-body correlations. Using interactions and currents from chiral effective field theory that describe Gamow-Teller strength in light nuclei well, I will present first principles computations of Gamow-Teller strength in light, selected medium mass, and the heavy nucleus 100Sn [1]. Our results are consistent with experimental data, including the pioneering measurement for 100Sn [3,4]. These theoretical advances have been enabled by systematic effective field theories of the strong and weak interactions combined with powerful quantum many-body techniques and ever increasing computational power.

[1] P. Gysbers, G. Hagen, et al, Nature Physics, AOP, http://10.1038/s41567-019-0450-7.doi.org/ (2019).
[2] Hinke, C. B. et al., Nature 486, 341-345 (2012).
[3] Batist, L. et al., Eur. Phys. J. A 46, 45-53 (2010).

James Keeble (Surrey)

Solving the many-body nuclear problem with neural networks

Artificial Neural Networks (ANN) have recently been used to solve a variety of quantum many-body problems [1,2]. ANN efficiently encapsulate information of the many-body wavefunction and can be used to solve effectively variational problems [3]. I will discuss an implementation of these methods to solve a benchmark nuclear physics problem – the ground state of the deuteron [4]. I will describe the ANN architecture, training and energy minimization algorithm that is used in this first application to theoretical nuclear physics. I will then consider the extension to higher mass numbers, and identify challenges in the use of ANN for nuclear theory applications.

[1] G. Carleo and M. Troyer, Science 355, 602 (2017) doi:10.1126/science.aag2302
[2] H. Saito, J. Phys. Soc. Jap. 87, 074002 (2018) doi:10.7566/JPSJ.87.074002.
[3] V. Dunjko and and H. J. Briegel, Rep. Prog. Phys. 81, 074001 (2018) doi:10.1088/1361-6633/aab406
[4] V. G. J. Stoks, P. C. van Campen, W. Spit and J. J. de Swart, Phys. Rev. Lett. 60, 1932 (1988) doi:10.1103/PhysRevLett.60.1932

F. Isaule (U. Manchester)

Cold quantum gases from functional Renormalisation

The interest in cold quantum gases has greatly increased in the last two decades due to the experimental developments realising degenerate cold atom gases. Amongst these, of particular interest to nuclear physics is a two-component attractive Fermi gas near a resonance of the s-wave scattering length, where the gas at low temperatures shows a crossover from a BCS superfluid to a Bose-Einstein condensate of bosonic dimers. In this talk, I will discuss the properties of superfluid Bose and Fermi gases within the functional Renormalisation group (FRG) approach . I will show that the FRG can give a consistent and unified description of quantum gases, including low-density neutron and nuclear matter.

Friday 26 July

P. Navrátil (TRIUMF)

The challenge of a better understanding of the three-nucleon force

Great progress in nuclear *ab initio* methods in recent years uncovered deficiencies in our understanding of nuclear forces. It appears the main problems arise in the modeling of the three-nucleon (3N) interactions. For example, there is a significant dependence on the 3N interaction regulator in calculations of binding energies and densities of medium mass nuclei. Similarly, a sensitivity to the details of the 3N interaction is observed in calculations of properties of weakly bound and unbound light nuclei. I will illustrate the issues in no-core shell model with continuum studies of ^{11}Be, ^{11,12}N and in many-body perturbation theory calculations of binding energies of double-magic medium mass nuclei. I will then discuss attempts to better understand impacts of different 3N terms and highlight nuclear structure calculations in light nuclei with a novel 3N interaction that performs satisfactorily for both light and medium mass nuclei.

A. Tichai (CEA Saclay)

Pre-processing techniques in nuclear many-body theory

Recent developments in nuclear many-body theory are accompanied by an increase of computational complexity due to the size of the A-body Hilbert space. In particular the storage of the underlying tensor objects, e.g. Hamiltonian matrix elements or wave function parametrizations, limits the reach of ab initio simulations. In my talk, I will present two complementary methods, tensor factorization and importance truncation, that enable for efficient data compression. Both methods are tested within the recently introduced framework of Bogoliubov many-body perturbation theory giving access to ground-state energies of open-shell nuclei.

A. Bulgac (U. Washington)

From the Schrödinger many-body equation to the Density Functional Theory description of static and time-dependent phenomena

While the seminal papers of Kohn and collaborators demonstrated that there is a one-to-one correspondence between the many-body Schrödinger equations and the Density Functional Theory, a direct link between these two ways of describing quantum phenomena was not established. The accuracy and validity of the Density Functional Theory implementations should be checked against the solutions of the Schrödinger many-body equations, and not against the experiment. There is class of real physical systems for which one can solve accurately both the many-body Schrödinger equation and also derive an energy density functional and where one can confront the two approaches. Cold fermionic atomic systems at or near unitarity is one class of such physical systems, where both the static and to some extent also the time-dependent phenomena can be studied, and moreover confronted with experiment. Neutron matter is a system with properties very similar to that of the unitary Fermi gas where Quantum Monte Carlo results are available and which can be used to construct an energy density functional, which, with some reasonable phenomenological input, can be extended to mixtures of protons and neutrons and study nuclei and neutron stars.

A. Idini (Lund)

Development of optical potentials from self consistent Green's functions

This presentation will show results of nucleon scattering reactions on medium-mass nuclei making use of optical potentials derived consistently from ab-initio Self Consistent Green's Function (SCGF) with saturating interactions.

A. Roggero (U. Washington)

Quantum Computing for Nuclear Physics

The recent experimental realization of quantum devices made of tens of qubits has spurred a renewed interest in quantum information and quantum computing. In this talk I will outline some of the possible revolutionary breakthroughs that large scale quantum computation will enable us to achieve in nuclear theory. I will also try to convey the issues we will need to face to achieve that by discussing a simple quantum computation of the deuteron.

A. Gezerlis (U. Guelph)

From alpha clustering to homogeneous matter

In this talk, I will present recent Quantum Monte Carlo calculations of 8-particle systems and discuss their impact on ^{8}Be and the physics of alpha clustering. I will also discuss recent work on trying to connect ab initio theory with simpler qualitative pictures. Specifically, I will address the first ever systematic non-perturbative calculations of the single-particle excitation spectrum in strongly interacting neutron matter. In addition to impacting light and neutron-rich nuclei, this work and this talk also touch upon the physics of ultracold gases and of neutron stars.

C. McIlroy (U. Surrey)

Self-Consistent Green's Function studies of modern hamiltonians in finite and infinite systems

I will present ab initio simulation using modern nuclear Hamiltonians predicted by chiral effective field theory (ChEFT) and lattice quantum chromodynamics (LQCD), in both infinite and finite matter using self-consistent Green's function. The third order algebraic diagrammatic construction [ADC(3)] originally devised for quantum chemistry, was used to approximate the self-energy in both systems. I have implemented both two- and three-nucleon ChEFT interactions to compute the equation of state of pure neutron matter and symmetric nuclear matter, whilst also obtaining the spectral function. The calculation of finite nuclei used a potential derived from LQCD by the HAL QCD collaboration at an unphysical pion mass, M_{PS}=469 MeV/c^2. The short-range repulsion of this interaction requires one to include a resummation of ladder diagrams from the excluded model space. The effectiveness of the ladder resummation from outside the computational model space is considered by the infrared convergence of the total binding energies. The binding energy of ^{4}He was calculated to be -4.80 MeV. The heavier doubly magic nuclei, ^{16}O and ^{40}Ca, had binding energies of -17.9 MeV and -74.4 MeV respectively. This means whilst ^{40}Ca is observed to be bound with respect to α break up, ^{16}O is expected to be unstable.