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Principal Investigator: Ralph E. Segel

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Introduction

Most of the research on the project was conducted at the ATLAS facility at Argonne National Laboratory. The collaboration between the Principal Investigator (PI) and his students (unless otherwise noted all students were advisees of the PI at Northwestern) and Argonne goes back many years and long predates this project. On this project we collaborated with scientists from Argonne and other institutions in studies of nuclear reactions that are of particular interest in nuclear astrophysics. Towards the end of the project concentration was on the ion trapping facility at ATLAS, again in collaboration with a group that contains both Argonne and other physicists. While the Northwestern group participated in a number of trapping experiments our focus has been in two areas: 1) the measurement of nuclear masses that are of astrophysical interest and 2) beta-decay measurements of the electron-neutrino correlation as a test of the standard model. In addition to the work at Argonne the PI and one of his students worked on completing the analysis of data from an experiment that was done at Jefferson Lab that probed the effects of two-photon exchange in determinations of the electromagnetic form factors of the proton.

Astrophysically Significant Nuclear Reactions

Energy is generated in stars and nuclei are built up by nuclear reactions and in order to model the very complex processes that go on much detail must be known about the participating nuclear reactions and, particularly where lighter nuclei are involved, the properties of the levels that the various reactions go through. The primary source of energy is the CNO (carbon-nitrogen-oxygen) cycle where the net result is four protons being converted to an alpha particle + 2 positrons + 2 neutrinos with an energy release of a little under 25 MeV. One of the ways in which heavy elements are formed is through successive proton capture, known as the rp (rapid proton) process, in which proton capture competes with positron decay as increasingly proton-rich nuclei are formed. For nuclei with $A \geq 20$ the Q values of proton induced reactions are such that there will be no cycling back into the CNO cycle and therefore nuclei between ^{16}O and ^{20}Ne can be considered to be in the breakout region and our efforts were concentrated and studying reactions that could form the path between the CNO cycle and the rp process.

Three possible breakout paths that we have investigated are:

a. ^{18}F(p,γ)^{19}Ne(p,γ)^{20}Na.
b. ^{18}Ne(α,p)^{21}Na
c. ^{15}O(α,γ)^{19}Ne(p,γ)^{20}Na

The ^{18}F(p,γ) competes with the ^{18}F(p,α)^{15}O reaction and one of the first investigations in this program showed that the (p,α) is at least three orders of magnitude stronger and therefore this sequence cannot be a significant breakout route[1]. This work was completed and published before the start of the present project. At high enough temperatures α-induced reactions become competitive and ^{18}Ne can be formed via the ^{14}O(α,p)^{17}F(p,γ)^{18}Ne sequence. The 1.67 half-life of ^{18}Ne is long enough for ^{18}Ne(α,p)^{21}Na to be a possible breakout reaction. The reaction proceeds through levels in ^{22}Mg and we studied it through the time-reversed p(^{21}Na, ^{18}Ne)α reaction using a ^{21}Na beam produced by d(^{20}Ne,^{21}Na)n and found that the cross section at the lowest energy, and therefore most important, resonance was lower than had previously been reported[2]. This reaction is key to the breakout from the hot CNO cycle to the rp process and it has received considerable attention, both before and after our work, and the results have been recently summarized [3]. We have also studied both reactions in the ^{15}O(α,γ)^{19}Ne(p,γ)^{20}Na sequence. The α-capture proceeds mainly though the 4.033 MeV level in ^{19}Ne and we formed this state through both the ^{3}He(^{20}Ne,^{19}Ne)α [4] and the ^{21}Ne(p,t)^{19}Ne [5] reactions and searched for an α decay branch and ended up placing a stringent enough upper limit to conclude that this path does not occur significantly in novas although it is probably important in supernovas. The proton capture on ^{19}Ne would proceed mainly through the 2.645 Mev state in ^{20}Na. The mirror nucleus, ^{20}F, is easily investigated via the ^{19}F(d,p)^{20}F and properties of its low-lying levels are well established. The issue was which ^{20}F state corresponds to this astrophysically important ^{20}Na state and the crucial missing piece of information was the state's spin, with 1^+ and 3^+ the two possibilities. We added to the information about this state by measuring the ratio of proton to gamma width for ^{20}Na states in this energy region. The ^{3}He(^{20}Ne,t)^{20}Na reaction was used to populate the 20Na states with the tritons detected by double-sided silicon strip detectors and the coincident heavy particles by a system consisting of a gas-filled magnetic spectrometer with a parallel plate avalanche counter – ionization chamber system along its focal. Thus the recoils could be identified, most importantly the ^{20}Na from gamma decay and the ^{19}Ne from proton decay, and their energy determined. When all of the data is combined 1^+ appears to be the most likely assignment for the 2.645 MeV state and then the radiative capture rate through the state can be calculated. The studies of the breakout reactions from the CNO cycle, with emphasis on the properties of the 2.645 MeV state in ^{20}Na, formed the basis of Lou Jisonna's PhD thesis. Dr. Jisonna received his PhD in 2008 and is now an Associate Professor at Lone Star College in Houston.

Nuclear Mass Measurements

About half of the elements in the universe heavier than iron are produced by successive neutron capture, known as the r-process. In this process successive neutron captures occur forming isotopes further and further away from the line of stability. However, there is also a high gamma-ray flux in the stellar environment and this can induce (γ,n) reactions. As the neutron excess increases the binding energy of the last neutron decreases until the (n,γ) and the (γ,n) are in equilibrium. These "waiting point” nuclei will eventually beta-decay forming a nucleus of higher Z and less neutron excess thus allowing the process to continue. The point at which this equilibrium occurs depends sensitively on the neutron binding energy, i.e. on the difference in mass between the nuclei ^{A}Z and $^{(A+1)}Z$. The nuclei in question are far from the line of stability and therefore have short lifetimes and can only be produced in minute amounts thus rendering conventional mass spectroscopy impractical. Reliance has to be placed on nuclear reaction and beta-decay data but these too tend to become less precise as the from stability increases.

The fact that Penning traps can be used to greatly improve the accuracy of nuclear mass measurements has been demonstrated at Argonne (6) as well as elsewhere(7). They are particularly well suited to study short-lived isotopes and need only very small samples. Nuclear fission produces neutron-rich nuclei in the A ~ 130 region many of which are in the r-process path. The Canadian Penning Trap (CPT) system at ATLAS has been used for a number of years to measure masses of nuclei produced by ATLAS. In addition, a ^{252}Cf fission source was installed and the masses of a large number of nuclei of astrophysics interest measured[8]. The CPT was recently moved to the CARIBU system where a very strong fission source emits fission fragments that can be accelerated by ATLAS but there is also a low-energy beam line where the ions can be thermalized and trapped. Because the r-process takes place far from the line of stability fission yields are low and it is the strong source at CARIBU that makes the measurements possible. Daniel Lascar played a significant role in getting the CPT moved to CARIBU and then used the facility to measure the masses of some 24 nuclei in the r-process path. These measurements, along with other mass measurements done at CARIBU, have shown that previous determinations from beta-decay data and from models are inaccurate by as much as hundreds of keV[9]. Dr. Lascar completed his PhD in 2012 and is now working in industry.

Electron-Neutrino Correlation

The Standard Model of particle physics with its V – A formulation of the weak interaction and its unification of the weak and electromagnetic interactions has been extremely successful in its agreement with a wide variety of experimental data and no contradictory evidence has ever been found. However, there are observed phenomena not predicted by the model with perhaps the most noteworthy being dark matter. This has led to extensive searches for “physics beyond the Standard Model” and one good place to look is to determine how completely V – A describes nuclear beta decay. The modern theory of beta decay is well spelled out in many text books and for our purposes it can be summarized by saying that there are five possible forms of the interaction, Axial Vector (A), Pseudoscaler (P), Scaler (S), Tensor (T) and Vector (V), that P can be neglected in nuclei, that only V and S can contribute to Fermi ($\Delta \mathbf{J} = 0$) transitions and that only A and T can contribute to Gamow – Teller ($\Delta \mathbf{J} = \mathbf{1}$) transitions, and that the form of the interaction can be determined by measuring the angular correlation between the outgoing electron and neutrino. It was established 50 years ago Fermi transitions are primarily V and Gamow-Teller primarily A but experiments limit S or T admixing amplitudes to no better than 5 – 10 % with the most sensitive experiment a 1963 determination of the (e,ν) correlation by a measurement of the ^{6}Li recoil spectrum from the decay of ^{6}He[10].

The PI was, and still is, spokesperson for a program measuring the (e,ν) correlation in the beta-decay of ^{8}Li and ^{8}B. In all of these correlation measurements it is, of course, impractical to detect the neutrino and so it is the nuclear recoil that must be detected and then conservation of energy and momentum invoked to determine the neutrino direction. The large Q value (~13 MeV for ^{8}Li, 14MeV for ^{8}B) and light mass results in ^{8}Be recoils with energies up to about 12 keV, which is much higher than in other decays. The decay is to the broad 2^{+} ^{8}Be first excited state which immediately breaks up into two alpha particles. The α's are emitted in opposite directions with equal energy in the ^{8}Be center-of-mass system but because of the recoil motion the α energies can differ by as much as 400 keV and their relative direction deviate from 180^{o} by as much as 7^{o}. These effects of the recoil motion are 2 – 3 orders of magnitude greater than those in other beta decays. There is an additional enhancement due to the fact that the emission of the (e,ν) pair leaves the final nucleus oriented and for the spin sequence in the ^{8}Li and ^{8}B decays the (α,ν) correlation is, to first order, $1 - \cos(\theta_{\alpha\nu})$ if the interaction is axial vector and $1 + \cos(\theta_{\alpha\nu})$ if it is tensor when the α's are detected along the direction of the electron.

The correlation is performed in the Beta Paul Trap (BPT) [11] at ATLAS. Use of a trap assures a weightless source and the strong angle and energy correlation between the two α's assures there is virtually no background. ^{8}Li is made in inverse kinematics via the d(^{7}Li, ^{8}Li)p reaction with a ^{7}Li beam passing through a deuterium gas target and the ^{8}Li transported to the BPT. The decaying ^{8}Li are viewed by two sets of double-sided silicon strip detectors (DSSD's) that measure the energy and direction of the two α's and the direction of the electron, thus rendering each measurement kinematically complete. In a first experiment approximately $2*10^{4}$ were analyzed and an upper limit of $(C_T/C_A) \leq 0.12$ (all uncertainties 1σ) obtained which limits the tensor contribution to 1.4%[12]. This work formed the basis of the PhD thesis of Gang Li at McGill University. Dr. Li is now at Atomic Energy of Canada. The system was then upgraded by installing DSSD's with narrower strips and much less dead layer and also the efficiency of getting the 8Li into the trap was improved. In a second run $2*10^{5}$ events were collected and the limit on the tensor contribution reduced to 0.6%[13]. This work formed the basis of the PhD thesis of Mathew Sternberg at the University of Chicago. Dr. Sternberg is now a Post Doc at the University of Washington. The experiment is continuing and it is hoped that we will get to the point where a tensor admixture of as little as 0.2% could be detected. Measurements on the ^{8}B decay were started in May of 2013 and abruptly halted by a fire in the electric substation that feeds ATLAS. The experiment is expected to resume early in 2014.

Electron – Proton Scattering

There was considerable consternation when in the 1990's experiments at Jefferson Lab in which longitudinally polarized electrons were scattered by hydrogen measurements of the polarization transferred to the scattered proton showed that the ratio of the electric to the magnetic form factor, $G_E/G_{M,}$ decreased linearly with increasing momentum transfer (Q^2). This contrasted with previous work going back many years in which determinations of the proton's G_E and G_M using the Rosenbluth separation method found this ratio constant. The quoted uncertainties on the polarization transfer results were much the smaller and there was some belief that the discrepancy was due to errors in the Rosenbluth extractions. However, the PI proposed and was spokesperson for an experiment at Jefferson Lab in which Rosenbluth separations were performed that yielded form factor ratios with uncertainties comparable to that achieved by the polarization transfer method but still the ratio showed no discernible variation with Q^2 thus establishing that the discrepancy was real and not due to experimental error[14]. This work formed the basis of Issam Qattan's PhD thesis and Dr. Qattan is now on the faculty of a university in Jordan. After our work became known several calculations appeared that showed that previously neglected two-photon exchange corrections could account for the discrepancy. An electron-proton scattering experiment specifically designed to look for evidence of two-photon exchange was then performed at Jefferson Lab and form the basis for Myriam Johnson's thesis. Dr. Johnson successfully defended her thesis in July, 2013 and the implications of her results are still being assessed.

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