Brief to the Subatomic Physics Long Range Planning exercise

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Experimental Subatomic Physics and the University of Saskatchewan

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1. Programme

Our research program centers on photon induced reactions. The measurements proposed are all designed to test fundamental concepts and assumptions in subatomic physics. These include: testing current models of the nucleon-nucleon interaction through photodisintegration of light nuclei, looking for new physics through direct measurement of the Gerasimov-Drell-Hearn sum rule for the Deuteron, testing the model of the deuteron through measurement of the neutron polarization following low-energy photodisintegration of the deuteron, and testing QED predictions of the gamma ray pair-production asymmetry.

All of these experiments are approved by the Program Advisory Committee (PAC) of the High Intensity Gamma Source (HIGS) at the Duke University Free-Electron Laser Facility (DFELL) where the work will be carried out. Our group is part of a multi-university collaboration from Canada, USA, Sweden, Ukraine, and Israel. This brief discusses work expected to be completed in the next 6 year. Some details of our programme are given below.

1.1. Studies of the nucleon-nucleon interaction through photodisintegration of light nuclei

Recent advances in theoretical techniques, such as the Lorentz-Integral-Transform have allowed photo-neutron cross sections to be accurately calculated so that comparisons with data can test models of the nucleon-nucleon interaction. However present data is not of sufficient precision. For example, recently published data for the photoneutron cross section for ^{4}He [1] show significant differences with the 1983 Calarco, Berman and Donnelly evaluation for the ^{4}He(γ,n) cross section[2]. As well, there a 20% deviations of this recent data from the recent Hyperspherical Harmonic Expansion calculation that uses the LIT Method and a semi-realistic MTI-III potential [3]. A high precision measurement is needed to resolve the situation. High precision measurements on ^{4}He will also constrain its energy weighted sum rules. In particular Gazit et al.[4] have pointed out that the bremsstrahlung weighted sum rule reveals information about the internal configuration of ^{4}He. We will measure the total photoneutron cross sections and angular distributions between 20 and 40 MeV.

1.2. Gerasimov-Drell-Hearn (GDH) sum rule for the Deuteron

The GDH sum rule[5,6] is given by $\int_0^\infty \left(\sigma^P(k) - \sigma^A(k)\right)\frac{dk}{k} = 2\pi^2 \alpha S_t \left(\frac{\kappa_t}{M_t}\right)^2$ = 204 μb (proton), = 232.0 μb (neutron), = 0.6 μb (deuteron), where α is the fine structure constant, M_t is the mass of the target nucleus, ω_{th} is the threshold energy for inelastic reactions (pion production for the nucleon or photodisintegration for the deuteron), σ_P (σ_A) is the total inelastic cross section when the nucleon and photon angular momenta are parallel (anti-parallel), S_t is the target spin, and κ_t is the anomalous magnetic moment. This sum rule is based on very general principals: causality, unitarity, gauge and Lorentz invariance. Inconsistencies with the sum rule would indicate a breakdown in some generally accepted physics.

HIGS measurements will provide low energy data, which will complement high energy data measured at other facilities. It has been pointed out that measurements involving beam and target polarizations would be very useful in clarifying questions related to the details of the photodisintegration process. In particular, Arenhövel *et al.*[7] predict large contributions to $\sigma_A - \sigma_P$, due to relativistic effects, in the photon energy range 10-30 MeV. In addition, Arenhövel has shown that the integrand of the GDH sum rule is dominated by contributions from photon energies below ~5 MeV. This makes the low energy measurements crucial. Hence the significant investment we have made in preparing our neutron detector, *Blowfish*, for measuring low-energy neutrons with high precision. Small statistical and systematic uncertainties are needed since the GDH integral depends on $\sigma_A - \sigma_P$ and not just on an asymmetry. Note that the measurement requires circularly polarized γ rays and a polarized target. The polarized target has been built by our collaborators at the University of Virginia. The HIGS PAC has approved the experiment. The target is now installed in the beamline and undergoing final tests.

1.3. The photodisintegration of the Deuteron

Our group has made several measurement of deuteron photodisintegration in recent years at HIGS using the neutron detector *blowfish* [8-12]. We have noticed several discrepancies between our measured angular distribution coefficients and those predicted by the best theory [13-15]. We have not been able to find an experimental reason for these discrepancies. Further investigation and more precise measurements are needed to establish whether there is some missing physics.

1.4. Neutron polarization following low-energy photodisintegration of the Deuteron

The polarization of the emerging neutron, P_y, in the reaction $d(\gamma,\vec{n})p$, is a good example of a mystery surrounding deuteron photodisintegration. Serious discrepancies between experiment and theory for even low incident photon energies exist. In particular, the most precise measurements of this reaction at energies below $E_\gamma = 20$ MeV [8], abruptly depart from theoretical predictions at around $E_\gamma = 10$-12 MeV. In addition, the angular dependence of P_y has not been mapped well, with the available data being sparse and having large uncertainties. We propose to precisely map P_y^u, the neutron polarization produced by an unpolarized photon, and the associated beam (linear) polarization dependent quantity P_y^l with beam energies around 12 MeV over a large range of polar angles, thus filling the gaps in existing data, as well as checking some of the recent theories being used to explain the aforementioned discrepancies. The experiment will use an active target and *Blowfish* neutron cells for the neutron detection. The PAC has approved this experiment. The active neutron polarization analyzer target has been constructed and will be tested in July 2015.

1.5. Measurement of the Bethe-Heitler Pair Production Asymmetries

We propose a measurement of the energy asymmetry in wide- and medium-angle electron/positron pair production off protons and heavy targets. This asymmetry is caused by the interference between the first- and second-order Born diagrams and the Compton scattering diagram and directly probes aspects of QED, as well as providing a direct measurement of the real part of the Compton amplitude. The two-photon BH amplitude is closely related to the two-photon exchange amplitude in $ep \rightarrow ep'$ which is believed to cause the breakdown of the Rosenbluth separation in electron scattering. It may be much easier to measure two-photon exchange effects to high precision in $\gamma p \rightarrow e^+e^- p'$ than to measure the electron-positron asymmetry in $e^{\pm} p \rightarrow e^{\pm} p'$ elastic scattering. We will measure the Bethe-Heitler [17] process $\gamma Z \rightarrow e^+e^- Z$ for Uranium and lighter target nuclei, for which significant asymmetries are predicted [18]. We have constructed a pair spectrometer and built a complete geant4 simulation. The experiment has been approved by the PAC and initial running is expected in late 2015.

2. Methodology

We use the High Intensity Gamma Source (HIGS) at the Duke University Free-Electron Laser Facility [19]. This is the only facility in the world that offers the photon beam characteristics needed for the proposed experiments. This Compton back scattering gamma-ray source produce photons between 2 and 100 MeV with either circular or linear polarization with energy resolution of a few percent. The energy resolution depends on collimator size. A smaller collimator will improve energy resolution at the cost of reducing the photon flux. For example a 1 inch diameter collimator will give a 3% energy spread at a photon energy of 20 MeV, with a photon flux on target of about 2×10^7 photons/s. The photons come in sub-ns micro-bunches at a rate of 5.58 MHz, which facilitates the use of time-of-flight techniques.

Our group designed and built a photon flux monitor [20] which is capable of measuring the number of photon on target to a precision of about 3%. This monitor is now in standard use at the facility for all experiments.

The large acceptance neutron detector system known as *Blowfish* has been constructed by our group in collaboration with the University of Virginia [8]. It consists of 88 BC505 liquid scintillator cells configured in a spherical arrangement of 8 arms with 11 cells each that covers ~¼ of 4π sr solid angle. This arrangement allows measurements of angular distributions and asymmetries of emitted neutrons and may be rotated about the beam axis to remove systematic asymmetries. Pulse shape discrimination, coupled with time-of-flight from the photon micro-pulse arrival, or from a signal from an active target, allows neutron and photon signals to the separated. Since construction, several upgrades to *Blowfish* have been made to make possible many of the near-threshold and high precision measurements planned in our research program. These included: Upgrades to data acquisition electronics hardware and software (LUCID) to allow VME support resulting in a 20-fold increase in data rate. A fibre optic light pulser gain monitoring and stabilization system has be designed and installed on all 88 *Blowfish* cells. [21]. Significant effort has been put into understanding the response to neutrons of the BC505 cells [22]. A fully mature geant4 simulation of *Blowfish* is now in place.

3. Resources

The main resources needed for our participation in this research are funds for travel and graduate student stipends. Generally I and my graduate students would need to travel from Saskatoon to Durham, NC several times per year for 1 or 2 weeks per trip. Our university does not have a program providing significant funds for graduate student support. On average, in our department, about 60% of a graduate student's support must come from research grants, the rest coming from scholarships and TA work by the student. I generally have two graduate students. I often also support at least one summer student. Therefore I would spend about $30k per year on student support. In addition I have one or two undergraduate students per year doing projects as part of the undergraduate program at no cost. Therefore, adding travel costs, a minimum of about $50k per year is adequate.

Significant addition resources are not needed. We maintain a small research lab at the U of S for detector development and testing. This makes use of equipment already on hand. Access to Compute Canada/Westgrid resources is important, but our needs are modest and are available through our university's membership.

4. HQP Achievements

All graduate student from out group have found employment in fields related to nuclear physics or are pursuing further education. A recent PhD graduate student, Ward Wurtz, whose thesis was on the photo-disintegration of the Lithium isotopes [24,25] is now the Manager, Accelerator Operations & Development at the Canadian Light Source.

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