Argonne Gas-filled Fragment Analyzer-AGFA

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Abstract

As the premier stable-beam user facility in the USA, ATLAS is currently being upgraded to provide high intensity (>1 pμA) stable beams. The combination of new high-efficiency detectors and intense beams will move ATLAS to the forefront as a world research center for studying exotic nuclei, such as super-heavy nuclei, nuclei at or near the proton drip line, proton-rich nuclei near ^{100}Sn and neutron-rich nuclei important for the r-process. In order to take advantage of these new opportunities, we propose to construct a gas-filled separator, based on a new, innovative Q_vD_m design, which combines the following properties: (a) high efficiency (*e.g.* 71% for evaporation residues produced in the ^{208}Pb(^{48}Ca,2n) ^{254}No reaction), (b) small image size (~ 64 x 64 mm^2), which leads to improved γ-ray detection efficiency for isomeric- or radioactive- decay of the residues, and (c) the ability to accommodate Gammasphere, with an 80-cm flight path from the target to the first magnetic element Q_v.

Introduction

With the recent loss of two facilities for the study of nuclear structure and reactions in the United States (the Holifield Radioactive Beam Facility at Oak Ridge and the XTU Tandem Van de Graaff at Yale University) the ATLAS facility at Argonne remains as the sole national user facility for low energy Nuclear Physics studies using intense stable beams. This facility is presently being upgraded to provide higher beam intensities for both stable beams and re-accelerated radioactive beams from the CARIBU injector to the experimental areas in order to meet the demand of the users. As such, it is therefore of paramount importance to continuously update the instrumentation at this facility to support a broad and leading-edge research program in this field. This proposed gas-filled separator will complement and substantially extend the research program at ATLAS by strongly expanding the capabilities for studying the rare processes and weakly populated nuclei that can be produced with the high-intensity beams at ATLAS.

Gas-filled separators remain one of the most successful and widely used tools of contemporary nuclear spectroscopy. They separate products of nuclear reactions from unreacted beam and collect them at a focal plane with unparalleled efficiency. Gas-filled separators are essential for studies of very heavy nuclei when mass separation is not required.

We propose to build a state-of-the art gas-filled separator at ATLAS, the Argonne Gas-filled Fragment Analyzer (AGFA), which will be used for a wide range of studies, *e.g.* 1) in conjunction with Gammasphere for in-beam and calorimetric studies of trans-fermium nuclei, 2) in the stand-alone mode for studies of super-heavy nuclei, isomers in heavy elements, and fast proton and alpha emitters along the proton drip-line, including heavy nuclei, 3) together with a gas cell to prepare beams of exotic radioactive ions for mass measurements and laser spectroscopy of trapped atoms, and 4) to study, via deep-inelastic reactions, heavy neutron-rich nuclei that are important in the r-process.

When the ongoing Energy and Intensity Upgrade of ATLAS is complete, Argonne will deliver the highest heavy-ion beam currents in the world. A natural course to take full advantage of this capability is to construct an efficient (>50%) separator. The combination will place Argonne in the forefront of many areas of research, in particular for heavy and super-heavy nuclei. This separator will be capable of taking full advantage of these intense beams for unique studies of nuclei produced with small cross sections. It will complement the Fragment Mass Analyzer, which has been successfully used for studies of exotic nuclei for two decades. The FMA provides M/Q identification, important in several classes of experiments, but is handicapped by low efficiency in others where mass identification is not essential. The lower efficiency is due to transport of only 2 or 3 charge states; with gas in a separator, all charge states collapse around an average, thus leading to higher efficiency.

There exist several active gas-filled separators worldwide and new separators are being commissioned. Our design represents an innovative refinement that is based on the extensive experience gathered with existing gas-filled separators, while enhancing the unique experimental capabilities which are already available at ATLAS. We have thus focused on the following important design aspects: 1) large solid angle ~22-40 msr in two different configurations, 2) efficient coupling to a 4π Ge array which requires additional distance to the first magnetic element, 3) small (~64x64 mm^2) implantation area at the focal plane, and 5) good beam suppression.

The RITU gas filled separator at the University of Jyväskylä, Finland served as a starting point for our design studies. RITU uses the QDQQ design [1]. A similar design was chosen for the new gas-filled separator at RIKEN, GARIS-II [2]. Our design represents, however, a novel approach to the problem by combining in a single magnetic element, D_m, the required bending capabilities of a dipole with the horizontal focusing and higher order magnetic field components to correct for aberrations to achieve a compact focal plane distribution of the reaction products. Vertical focusing is achieved by a single quadrupole located upstream of the main magnet. This Q_vD_m design achieves larger solid angle acceptance than most current separators, yet it has a smaller image size and path length, which leads to higher efficiency for (a) collection of evaporation residues and (b) detection of their decay γ rays.

I. Physics justification

The scientific justification for this separator spans a range of physics areas, some of which are discussed below. The combination of the proposed high-efficiency separator with intense heavy-ion beams from an upgraded ATLAS, or with Gammasphere, which is undergoing an upgrade to digital readout to substantially increase count rates, leads to a world-leading capability for research on nuclei produced with small cross sections.

- Upon completion of the Energy and Intensity Upgrade project, ATLAS will provide very high-intensity heavy-ion beams (*e.g.* > 1.5 pμA ^{48}Ca, ^{50}Ti, ^{54}Cr). Compared with our current capabilities, the spectrometer and intensity upgrade will each yield improvements by a factor of ~10, giving a total gain of ~100 compared to current capabilities. Consequently, isomer spectroscopy of nuclei as heavy as ^{265}Hs (σ ~ 70 pb) should be achievable. The use of rapidly rotating target wheels within the gas volume of the separator is a well-established technology for accommodating beam intensities of this magnitude.

- Gammasphere is currently the world's best γ-ray array, which combines high-resolution and calorimetric capability. It is necessary for in-beam γ-ray measurements for fission-barrier and high-spin measurements. In-beam measurements will not be able to take advantage of the full beam intensity available from ATLAS due to rate limitations in the Ge detectors. However, ongoing upgrades to convert Gammasphere to digital pulse-processing will enable a 4- or 5-fold increase in rate handling compared with the current analog system. Combined with the improved efficiency of AGFA the estimated gain is ~50 with respect to experiments we have performed with the FMA. This capability would extend the limit for in-beam experiments to ^{260}Sg (σ~0.6 nb).

- The structure of proton-rich nuclei near Z=N=50 is a topic of intense current interest. With the enhanced efficiency of AGFA, the intensity upgrade of ATLAS, and the improved count-rate capabilities of Gammasphere, we will be in a position to study this region of nuclei with a factor ~50 higher sensitivity relative to previous studies. Based on these improvements, a significant progress in understanding of the structure of nuclei in this region can be achieved. Over the past 20 years, the FMA has been used to discover and study a large number of proton emitters near the proton drip-line. The AGFA separator combined with the ATLAS intensity upgrade will allow us to expand the search for proton emitters with shorter half-lives and smaller production cross sections into the A=120-150 deformed region and for heavy proton emitters with Z>83.

- The possibility of studying neutron-rich nuclei near N=126 that are populated in deep inelastic collisions (DIC) between heavy nuclei has recently been recognized as the most promising avenue to reach this region of high importance to both fundamental nuclear structure and the understanding of the astrophysical r-process. Early reaction studies, as well as recent theoretical calculations, indicate that multi-nucleon transfer reactions proceed with sufficiently large cross sections to warrant further experimental study. With the large acceptance of AGFA, we will be in a position to test these predictions and possibly initiate a detailed study of nuclei in this region.

Some examples of research that can take full advantage of the above combination are detailed below. These examples illustrate the relevance of the present proposal for achieving DOE Milestones for Nuclear Structure and Nuclear Astrophysics research. In particular, the proposed studies of heavy and super-heavy nuclei aim squarely at milestone NS8, whereas the study of weakly populated channels in the ^{100}Sn region is directed at the milestone NS9. The study of weak deep-inelastic channels leading to neutron-rich nuclei near the N=126 shell gap is relevant for the Nuclear Astrophysics milestones NA6 and NA9.

I.a. Heavy and Super-heavy nuclei

This proposal will position Argonne as a leading world center for investigating the structure of heavy and super-heavy nuclei (SHN). The heaviest stable element is bismuth. Beyond that there is a big gap in the periodic table to thorium and uranium, which are unstable, but are very long-lived (~ age of universe). The heaviest element that has been reported to be synthesized is element 118 [3] – representing a large 42% extension beyond bismuth (Z=83). With the intensity upgrade of ATLAS and a completed AGFA separator, this facility would be very competitive with others around the world that engage in the research area of synthesizing and discovering new heavy elements and isotopes. At present, such a research program is not planned, but the possibility exists that this could be taken up in the future. Our primary interest is rather to perform spectroscopy of heavy nuclei in the range Z = 100-108. These have larger cross-sections (by $\times 10^2$ - 10^6) than the very heaviest elements and, hence, can be produced in sufficient (although still small) numbers to enable spectroscopy.

Our strategy is to investigate nuclei in the Z=100-108 range in more detail by studying their structure in terms of single-particle orbitals, K-isomers, fission barriers and stability against angular momentum. Such data will provide a challenging proving ground for our best nuclear models and test their ability to extrapolate beyond the region from which their model parameters were determined.

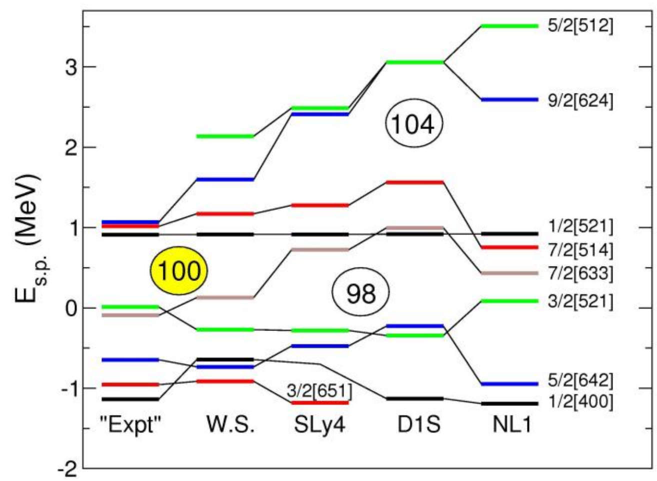

Figure 1: Comparison of single-particle energies deduced from experiment [4] and given by models: Woods-Saxon potential [5] and density functional theories with the Skyme (SLy4) [6], Gogny (D1S)[7] and NL1 [8] interaction.

I.a.1. Decay spectroscopy

A main task for us is to establish the energy spectrum of the particles filling the valence proton and neutron orbitals. The single-particle orbitals are of primary importance since gaps in their energy spectra lead to the shell-correction energy, increased binding and, consequently, a fission barrier, which would otherwise not exist for these heavy nuclei. We are especially interested in the proton single-particle energies since our work has established that the proton magic gap is likely to be Z=114 (predicted by the Woods-Saxon potential) instead of at Z=120 or 126 (predicted by models based on density functional theory). This conclusion is based on the fact that the Woods-Saxon single-particle energies are in much better agreement with those deduced from experimental data, Fig. 1. The experimental work will focus on γ and electron spectroscopy of high-K isomers [9,10,11], especially those in N=152 isotones. The choice of N=152 exploits the fact that there is a deformed shell gap here, so low-lying 2-quasiparticle states will have proton configurations. The method of choice is to search for high-K isomers, which are expected due to the high Ω values for proton (and neutron) orbitals. In addition, general α-γ and α-electron decay spectroscopy will yield rich information on the structure of SHN.

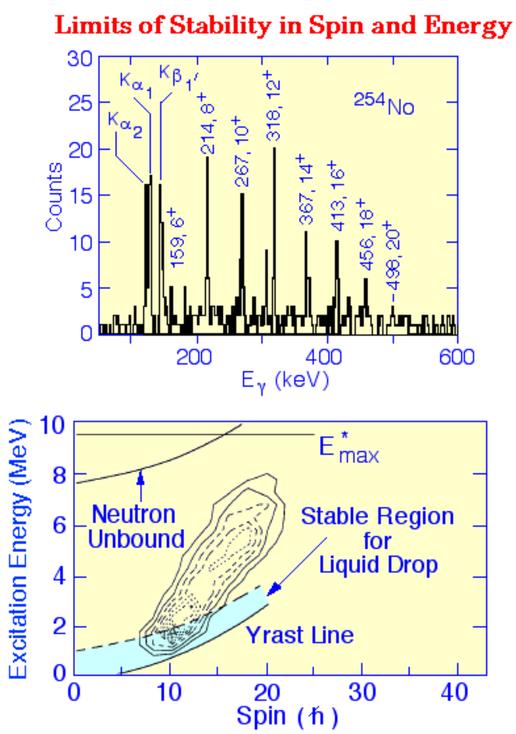

Figure 2: Gamma spectrum (top) from ground-state band and entry distribution (bottom) for ^{254}No from Reiter et al. [12]. Further experiments show that ^{254}No survives up to spin 26.

I.a.2. In-beam spectroscopy

It is the fission barrier created by the shell energy that enables super-heavy nuclei to exist. Therefore, measurements of the barrier provide critical information on the properties of these nuclei. The fission barrier can be deduced [12] from the maximum allowable excitation energy above the Yrast line. This energy (or a lower bound) can be extracted from measurements of the entry distribution leading to the formation of the nucleus as illustrated in Fig. 2. Gammasphere, with its capability for γ-ray calorimetry, endows ATLAS with a unique capability to measure entry distributions.

To investigate the shell energy of SHN as a function of spin requires in-beam spectroscopy of the yrast line with the high-resolution Ge detectors of Gammasphere, see Fig. 3. The yrast energy at high spin also provides information on single-particle energies, notably of the high-j configurations, whose alignment under rotation is expected to lead to "backbending''. We propose to search for backbends attributed to neutrons originating from the $h_{11/2}$ or $k_{17/2}$ spherical shells, which lie above the predicted N=184 gap. This method provides the best chance to deduce the magnitude of that gap, by exploiting the fact that both deformation and rotation drive the orbitals of interest down in energy to the Fermi level in systems, which are accessible for study, with ~152 neutrons.

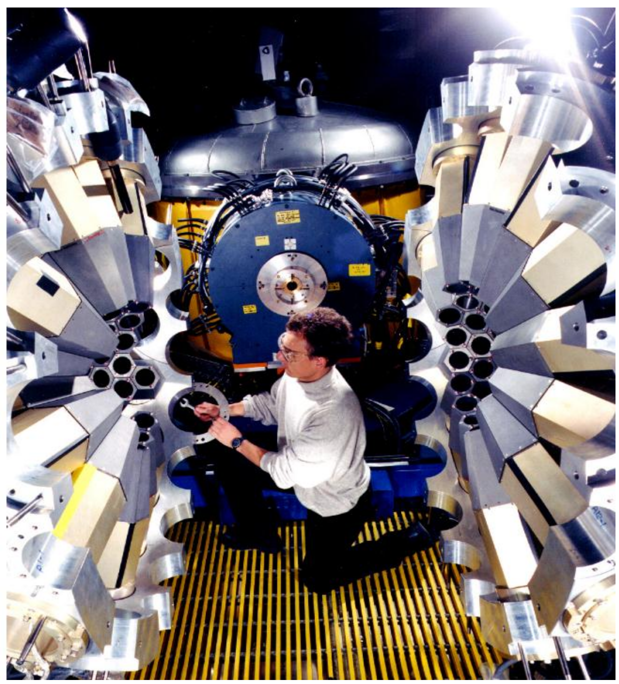

Figure 3: Gammasphere, a 4-π, high-resolution, γ-ray detector in front of the Fragment Mass Analyser at ATLAS.

I.a.3. Synthesis of SHN, mass and laser spectroscopy measurements

The synthesis of SHN normally requires months of beam time. This would be difficult at ATLAS, which has a multi-faceted program, including research with new beams from CARIBU. However, limited campaigns in selected cases with are envisioned. Our developments of γ-ray detection at the decay station offer a chance for element identification via X-rays coincident with decay α's. Also, because of the predicted high X-ray multiplicity (~ 3-5) in the gamma-decay cascade of the SHE evaporation residue, element determination will be pursued through in-beam X-ray spectroscopy around the fusion target.

We also have plans to stop heavy recoils in a gas cell at the focal plane of the separator, thus exploiting Argonne's world-leading expertise in stopping radioactive ions in gas cells. The ions will be directed to Penning and Paul traps for mass measurements and laser spectroscopy, respectively. Masses generally provide a direct measure of the extra binding from the shell energy and are necessary to confirm the parentage of the SHN reported by Dubna [3], which pressingly require a definite mass assignment. Laser spectroscopy permits measurements of quadrupole and magnetic moments, spins, and radii.

I.b. Studies of exotic proton-rich nuclei

Studies of nuclei with a large excess of protons require high sensitivity and selectivity. In recent years, Gammasphere and the FMA have provided data for many exotic nuclei. More than half of the known proton emitters were discovered at ATLAS, including the first highly deformed proton emitters ^{131}Eu and ^{141}Ho [13] and the first case of the proton decay fine structure in ^{131}Eu [14]. The Recoil-Decay Tagging (RDT) [15] method was used to assign prompt γ rays to weak reaction channels in the presence of ubiquitous background by tagging with characteristic decays observed at the FMA focal plane. Among others, it resulted in the first observation of a γ-ray transition between single-neutron states in ^{101}Sn which was correlated with the ^{101}Sn β-delayed protons [16]. Another example is the study of excited states in proton emitters such as ^{141}Ho [17] and ^{145}Tm [18], which highlighted the role of triaxiality in these nuclei.

A gas-filled separator, which has about a factor 5-10 times larger efficiency than the FMA depending on the reaction, will allow studies of even weaker and more exotic reaction channels. The lack of mass separation will be offset by higher pixilation of a Double-Sided Si Strip Detector (DSSD) to reduce random correlations, which are the main source of background. Also, because of the increasing decay Q-values for the more exotic nuclei, the half-lives are expected to be shorter and correlation between implantation and decay events easier to recognize. The recently implemented digital readout of the DSSD enables the measurements of very short-lived decays. This is shown in Fig. 4 for a conversion electron decay occurring 2.6μs after implantation of a ^{254}Rf recoil ion in the same DSSD quasi-pixel at the focal plane of the FMA.

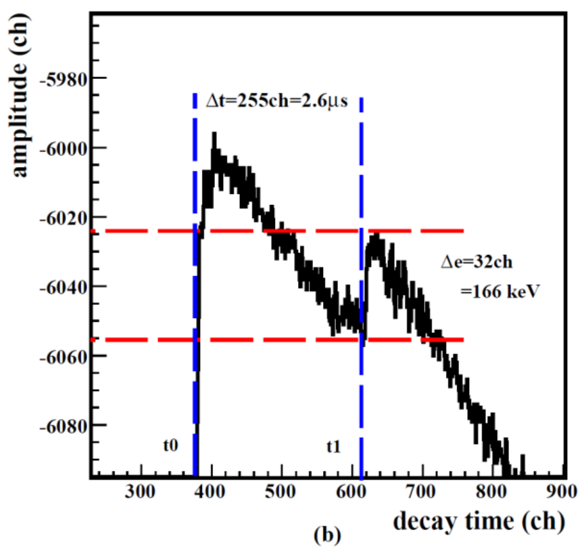

Figure 4: A conversion electron pile-up event following the implantation of a ^{254}Rf recoil into the same DSSD quasi-pixel.

The research with AGFA will be focused on very heavy nuclei. However, a gas-filled separator can be also used to study exotic proton-rich nuclei produced in fusion-evaporation reactions. In particular, very low cross sections for the most exotic cases preclude the use of the FMA due to its lower transport efficiency. The challenges caused by less separation between reaction products and unreacted beam particles in a gas-filled separator can be overcome by a carefully designed beam stopper, beam slits and beam dump. In fact, several experiments aiming at exotic proton-rich nuclei have been successfully carried out with the gas filled separator RITU at the University of Jyväskylä in Finland as will be discussed in more detail in Sect. I.b.1.

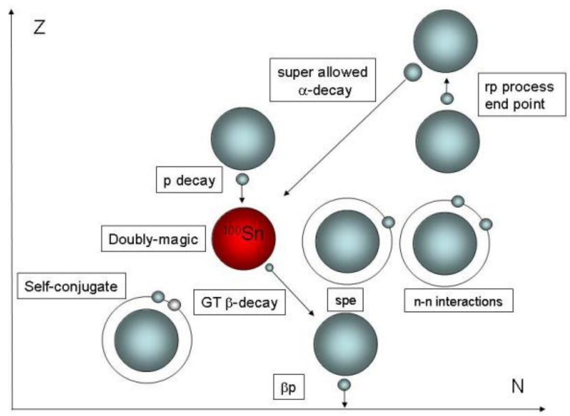

Figure 5: Physics phenomena observed in the ^{100}Sn region

Another exciting opportunity would be to produce exotic proton-rich nuclei using in-flight radioactive proton-rich beams from the AIRIS separator, which is currently under development, and select them in AGFA. In this case AGFA would collect almost all reaction products and the limited beam suppression and high implantation rate would not be an issue.

Possible applications of AGFA in the ^{100}Sn region, for the studies of highly-deformed proton emitters in the middle of the Z=50-82, N=50-82 major shells, and for the search for heavy proton emitters above Z=82 are discussed below.

I.b.1 The ^{100}Sn region

The region around the self-conjugated doubly-magic ^{100}Sn is located where the N=Z line and the proton drip-line crosses and is rich in interesting physics topics as illustrated in Fig. 5.

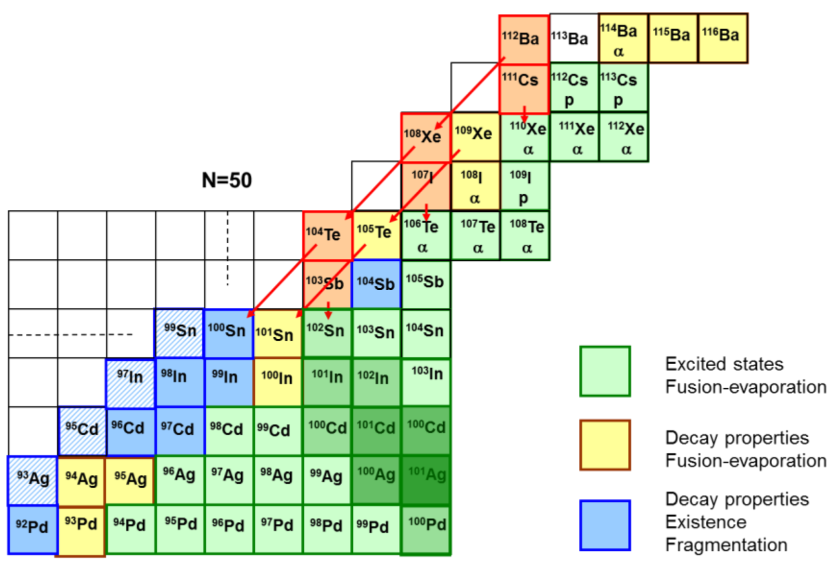

Figure 6: Experimental status of nuclei in the ^{100}Sn region. The nuclei and the decays marked in red can potentially be studied with AGFA.

Nuclei with Z>50 and N>50 close to ^{100}Sn form an island of alpha emission. An overview of the region is given in Fig. 6. The most proton-rich odd-Z nuclei among them decay via proton emission. This offers a unique opportunity to tag γ-ray transitions in these exotic nuclei.

This is true in particular for fast activities. For example, in-beam studies of the 0.5 microsecond α emitter ^{105}Te, which is relevant for the order of the $d_{5/2}$ and $g_{7/2}$ single-neutron states at ^{100}Sn, should be feasible with AGFA. Another example is the super-allowed α-emitter chain ^{112}Ba(~10 ms)→^{108}Xe(~1 ms)→^{104}Te(~100ns)→^{100}Sn where participating nuclei can be viewed as consisting of α particles coupled to the ^{100}Sn core. The yet unobserved fast proton emitters ^{103}Sb, ^{107}I and ^{111}Cs could also be within reach. In these cases, the expected life times are much shorter than the time of flight through the separator and the protons emitted from the ground state would be detected at the target position and tagged by the decays of the daughter nuclei (^{106}Te, ^{110}Xe) at the focal plane.

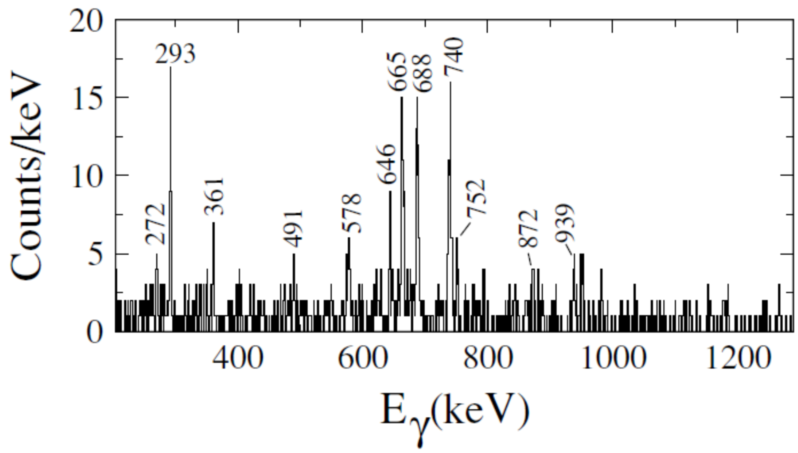

Figure 7: Prompt γ-ray spectrum from ^{106}Te tagged with α-decays at the RITU focal plane.

The feasibility of in-beam spectroscopy in the ^{100}Sn region with a gas-filled separator has been demonstrated by the results obtained with RITU for ^{106}Te [19], ^{108}Te[20] and ^{110}Xe [21]. The ^{106}Te nucleus, which is the most exotic case, was produced with the cross section of only 25 nb using the ^{54}Fe(^{54}Fe,2n)^{106}Te reaction. The experiment ran for 5 days and the beam intensity was about 10 pnA. It resulted in collecting about 500 ^{106}Te alpha particle decays which was enough to tag prompt in-beam gamma ray transitions detected in the JUROSPHERE array of Ge detectors. The ^{106}Te gamma ray spectrum measured in Ref. [18] is shown in Fig. 7.

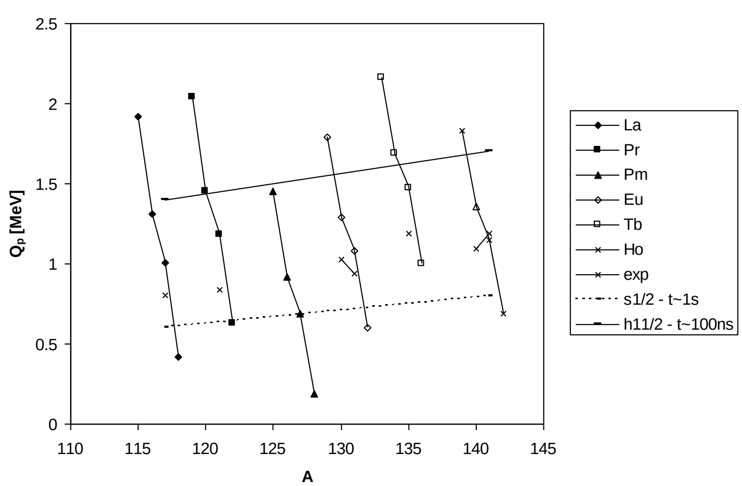

Figure 8: Proton decay Q-values for highly-deformed proton emitters as a function of the mass number. The measured values, represented by crosses, are compared with the calculations of Liran and Zeldes [23]. The solid and the dashed line represent Q-values for which the $h_{11/2}$ state would have a lifetime of about 100ns and the $s_{1/2}$ state would have a lifetime of about 1s, respectively.

The required separation between beam and reaction products was achieved by using a carefully designed beam dump and slits which were placed inside the RITU separator. A similar approach is planned for the AGFA separator. In order to accommodate even higher beam currents an already existing large-area high-granularity DSSD capable of handling higher implantation rates will be used with AGFA.

1.b.2 Highly-deformed proton emitters

Several models of proton decay from deformed nuclei were developed over the years. In the early adiabatic approach of Esbensen and Davids [22], the Coriolis interaction was not included and pairing was added in an *ad hoc* fashion to account for level occupancies. This approach gives good results for band heads of deformation-aligned (strongly-coupled) bands. The most recent and most comprehensive non-adiabatic model by Fiorin, Maglione and Ferreira [24], which treats both the Coriolis and pairing force in a consistent way and extends the theoretical reach to partially aligned and rotationally aligned (weakly-coupled) band heads. This model predicts that protons are emitted from the $7/2^-$ member of the partially decoupled $h_{11/2}$ band in ^{121}Pr [25]. This is at variance with Ref. [26], where adiabatic calculations [9] support the $3/2^+$[422] or $3/2^-$[541] assignment. A similar prediction for ^{117}La appears to be inconsistent with the in-beam study of ^{117}La [27]. These discrepancies reflect uncertainties in the choice of parameters such as the Coriolis attenuation or the pairing strength. More detailed studies of known deformed proton emitters in this region combined with searches for new cases would provide a further constraint for these parameters and improve the predictive power of theory.

Searches for even more exotic highly-deformed proton emitters are hampered by both small cross sections and lifetimes shorter than the time of flight through a recoil mass separator. Figure 8 shows the proton Q-values of known highly-deformed proton emitters as a function of the mass number. For comparison, proton Q-values calculated using the Liran-Zeldes model [23] are included. The Liran-Zeldes model is known to reproduce decay Q-values along the proton drip line rather well although the experimental proton decay Q-values in Fig. 8 are on average lower by ~300 keV. The area between the line corresponding to the $s_{1/2}$ emission with a lifetime of about 1 sec and the line corresponding to the $h_{11/2}$ emission with a lifetime of about 100 ns represents Q-values that are experimentally accessible. Close examination of Fig. 8 indicates that the ^{125}Pm, ^{139}Eu, ^{139}Ho odd-Z, odd-Z even-N and ^{116}La, ^{120}Pr, ^{134}Pr odd-Z, odd-N fast deformed proton emitters could still be within experimental reach. AGFA, with its high efficiency and

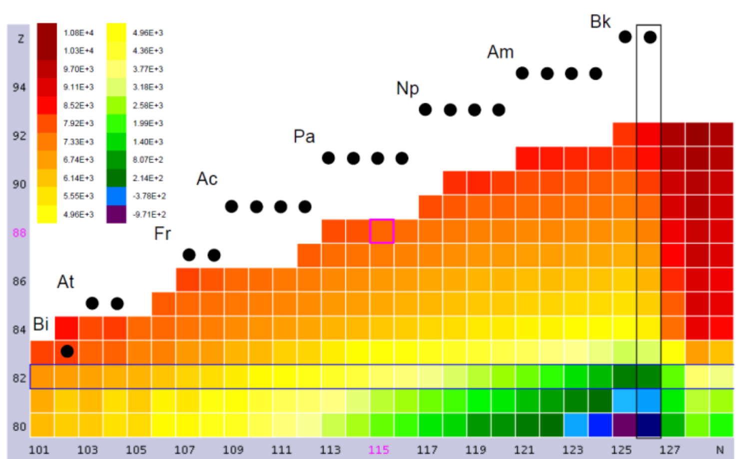

Figure 9: The Z>82, N<126 corner of the chart of nuclides. Proton emitters predicted by the Liran-Zeldes mass model are marked by full circles. The measured α-decay Q-values are given by the color map.

short flight path would be well suited for such experiments.

I.b.3 Heavy proton emitters

All known proton emitters, except one, have atomic numbers between 55 and 83. The heaviest known proton emitter, ^{185}Bi, which was observed at ATLAS, is the only one located above the Z=82 major shell. Multiple proton emitters are expected to exist for elements heavier than Bi (see Fig. 9).

Proton Q-values calculated using the Liran-Zeldes model, which reproduces ^{185}Bi very well, indicate that in ^{188,189}At, ^{194,195}Fr, and ^{200,201}Ac proton emission is an important decay mode. Proton emitters in this region are predicted to transition from spherical shapes close to Z=82, such as in ^{185}Bi, to deformed shapes with addition of protons to the Z=82 core. Interestingly, Möller and Nix [28] predict high prolate deformation of β_2~0.35 for the two former elements and a substantial oblate deformation of β_2~-0.26 for the Ac isotopes. If confirmed, ^{200,201}Ac isotopes would be the first cases of proton emission from an oblate state. This region is also known of shape coexistence offering a possibility of observing proton emission from states with different shape in the same nucleus.

The most proton-rich nuclei observed in this region, such as ^{191}At, ^{199}Fr, or ^{207}Ac were studied via xn reaction channels using A~40-50 beams and A~140-170 targets. At ATLAS, intense A~80-90 beams are available, which can be combined with A=100~120 targets in order to reach the candidate proton emitters via pn and p2n channels. The pxn reaction channels were successfully exploited in the studies of lighter proton emitters in the past. Since reactions leading to this region of nuclei are dominated by prompt fission, the rates at the AGFA focal plane will be low, even for high beam currents. Simulations also show that suppression of the primary beam will be sufficient such that this will not be a problem.

AGFA, with its high efficiency, combined with intense A~80 beams from ATLAS will allow us to delineate the proton drip line in the corner of the nuclear chart of Z>82 and N<126.

I.c. Weak Deep-inelastic Channels

The primary use of the proposed gas-filled separator is for research in the area of heavy and super-heavy nuclei. Given the intense stable beams of heavy nuclei at ATLAS, up to and including uranium, additional research opportunities exist. One which appears as rather unique is the access to very neutron rich heavy nuclei near the N=126 shell gap by deep inelastic processes in nucleus-nucleus collisions at energies up to perhaps twice the Coulomb barrier. These nuclei are of great interest for nuclear structure and nuclear astrophysics, but difficult to reach otherwise. They are too neutron-rich to be populated in fusion evaporation reactions; they are too heavy to be populated in fission of the actinides; fragmentation yields with high-energy uranium beams fall off about one order of magnitude per neutron when moving away from the valley of stability and are expected to become too small to be observed for these nuclei. An intriguing possibility for reaching into this region is by the use of deep-inelastic processes. Because of their stochastic nature, these processes have been observed to reach out with a less precipitous fall-off [29].

The science interest in this region, on the other hand, has increased considerably because of important questions in nuclear physics and astrophysics. It is through this region of the nuclear chart that rapid-neutron capture (the r-process) proceeds to produce the heaviest nuclei in the universe. A detailed understanding of the r-process is not possible without measurements of the properties of these nuclei near the N=126 waiting point. It plays a critical role for nuclear model predictions for the synthesis of the heaviest r-process nuclei. It also places stringent constraints on the astrophysical scenario embedding the r-process due to the requirements of highest neutron density to form the corresponding r-process abundance peak. The beta decay properties of these nuclei are themselves of great interest because Gamow-Teller and first-forbidden transitions compete in this unique mass region due to the shell evolution. It opens an interesting domain in nuclear physics in that the forbidden transitions become competitive with the (suppressed) allowed transitions and thus beta decay half-lives are very difficult to predict.

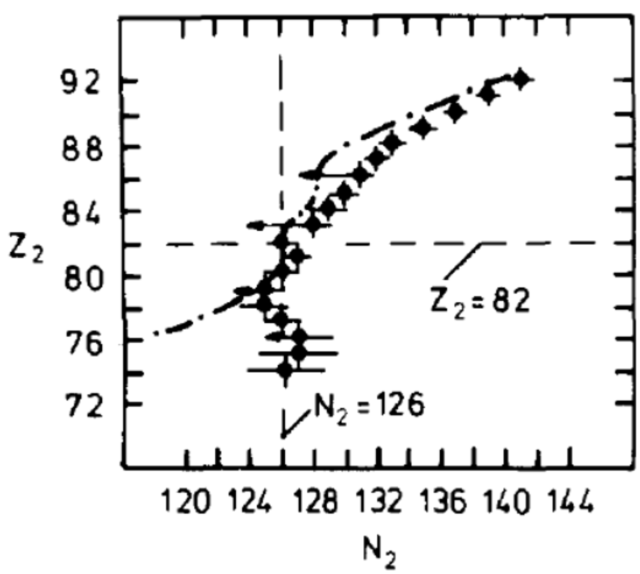

Figure 10: Experimentally measured centroids for the most probable neutron number are plotted for each nuclear charge Z for both the palladium-like and the uranium-like reaction products.

There exists some evidence that this region of nuclei can be reached using the deep-inelastic reaction mechanism. Figure 10 shows the experimentally measured centroids for the most probable neutron number, plotted for the uranium-like reaction products [1] [29]. In addition to the strong influence of the N=126 closed neutron shell on nucleon flow, the results indicate that nucleon transfer populates heavy neutron-rich nuclei far beyond the last stable isotope in this mass region. This is expected to further increase with bombarding energy. We have confirmed this with calculations using the deep-inelastic model code by Feldmeier [30]. Increasing the collision energy also moves the reaction products to more forward angles. At about 50% above the Coulomb barrier (*i.e.* around 10 MeV/u) the deep-inelastic events are centered at zero

[1] Note that Z and A of the heavy fragment were not measured directly in this experiment, but inferred from the coincident light fragment measurement. The authors do not discuss any correction for neutron evaporation from the heavy, very neutron-rich fragments of interest here. It is therefore possible that the heavy fragments in the Z=72-80 range are somewhat less neutron-rich than indicated in Fig. 10.

degrees, since the multi-nucleon exchange results in sticking and rotation of the two reaction partners to the forward angles.

Based on the model calculations, matching to the experimental data at 6 MeV/u and using the model calculations to extrapolate to the 10 MeV/u, we find that at the latter energy a nucleus as exotic as ^{196}Yb might be produced with micro-barn cross sections. Considerably higher cross sections should be expected for reaction products less removed from the beam species.

Advantages of the gas-filled separator over other arrangements, such as that employed in Ref. [29], arises from the fact that the gas-filled separator is dispersing in $A/Z^{1/3}$. This will help to select the most neutron-rich products which are of interest in these studies.

Although somewhat speculative, we find that there may be a unique opportunity for nuclear spectroscopy and nuclear astrophysics in a scientifically very interesting, but otherwise perhaps not accessible, region of the nuclear chart. This approach has three key components: 1) the gas-filled separator as proposed here, 2) high beam intensity, and 3) high beam energies resulting from the Energy and Intensity Upgrade that is presently being implemented.

II. Important design parameters

The AGFA separator design has been optimized for use with a 4π array of Ge detectors, such as Gammasphere or Greta, and for experiments with intense beams from ATLAS after the Energy and Intensity Upgrade to study decay properties at the focal plane of the separator. The emphasis is on efficiency, flexibility, reliability, and ease of use. The separator will be located at the former APEX beam line next to the FMA. This beam line was used in the past for stand-alone Gammasphere experiments and as a general-purpose beamline. There is sufficient space to accommodate both Gammasphere and the gas-filled separator at this beam line as shown in Fig. 11.

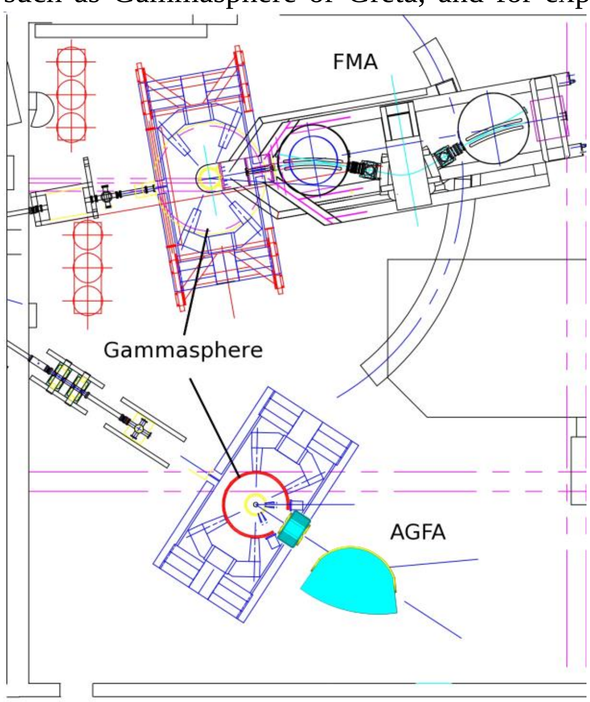

Figure 11: Floor plan of ATLAS Area IV shoving the FMA, AGFA and Gammasphere in front of either instrument.

The most important property is the transmission of the device, *i.e.*, the integral of the acceptance function weighted by the emission distribution of the reaction being considered. A solid angle of >22 msr would assure a competitive transmission at a reasonable cost.

To accommodate a 4π Ge array, sufficient space is required between a target and a separator. A distance of 80 cm is sufficient to accommodate all but the most forward Gammasphere detector rings, similar to the geometry with the FMA. We thus envisage two different target positions relative to the first quadrupole: 80 cm for experiments with Gammasphere and 40 cm for experiments at the focal plane. To avoid a solid-angle penalty imposed by the large 80 cm separation, it is necessary to use a large-bore quadrupole.

Good beam suppression will be achieved by designing a large magnetic dipole chamber, equipped with an external beam dump shaped in order to eliminate beam scattering into the detector and the possibility to insert slits after the dipole exit to intercept beam particles. In order to further improve the beam suppression, it is planned to provide for the insertion of a Faraday cup at 0^o at a location between the quadrupole and the main dipole of AGFA. Depending on the specific experimental conditions it is expected that a factor of ~100 or more in beam suppression can be achieved in this way without significant loss of transport efficiency of the evaporation residues. This technique is especially important for the near-symmetric reactions needed to study nuclei in the ^{100}Sn region.

The separator will be filled with He gas. Typical experiments with heavy nuclei require a pressure of about 0.5-1.0 Torr and a maximum magnetic bending power of Bρ=2.5 Tm is needed to account for most fusion-evaporation reactions. Transport of super-heavy nuclei requires Bρ values of 2.0 – 2.2 Tm, based on average charge states estimated with an empirical relationship from Ref. [31]. The flight path through the separator should be minimized to reduce multiple scattering in the gas and to achieve a short flight time required for detection of rapidly decaying nuclei. To achieve high γ-ray detection efficiency at the focal plane using *e.g.* the existing X-array consisting of five HPGe clover detectors, a relatively small ~64 mm×64 mm implantation area, corresponding to the largest single wafer DSSD, is required.

III. Design solution

In order to achieve a compact design with large solid angle, acceptance, and good resolution at the focal plane that could fit together with Gammasphere, an innovative Q_vD_m design was chosen. This design consists of a large bore (220mm bore x 470mm length) single quadrupole magnet, which focusses in the Y-direction followed by an ~20 ton combined-function dipole which provides a horizontal bend of 38 degrees as well as strong horizontal (X) focusing. The X-focusing of the dipole is provided by a linear dependence of

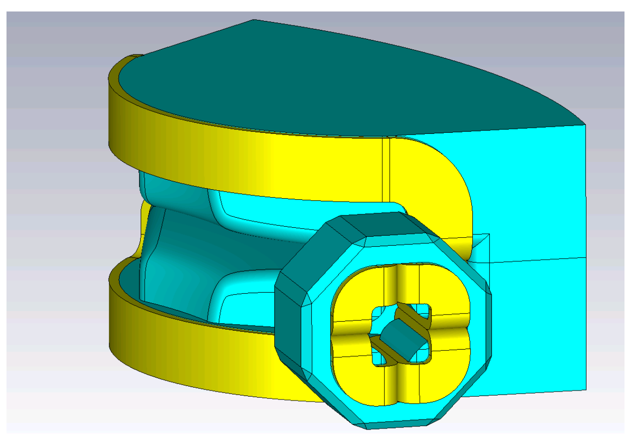

Figure 12: Computer-aided design rendering of the magents of the AGFA separator showing the single quadrupole (front) and the dipole/multipole main magnet (back) including coils in yellow.

the magnetic field on X and by the 36° tilt of the field boundaries with respect to normal incidence. This dipole also has substantial higher-order components to the magnetic field for aberration correction. Modeling of this dipole in 3D has verified the viability of maintaining the required field profile over the necessary dynamic range of magnetic rigidity. This compact layout, consisting of just 2 optical elements, leads to a short total path length from target to focal plane which has benefits in terms of minimizing the small angle multiple- scattering of reaction products in the gas and the ability to measure short-lived products. The focal plane is located 89 cm downstream from the exit of the dipole leading to a total length of central trajectories of 4.2 m with the 80 cm target-to-quadrupole distance mode. A computer-aided design rendering of the two magnetic components of AGFA is given in Figure 12. Conventional water-cooled copper coils are shown in yellow.

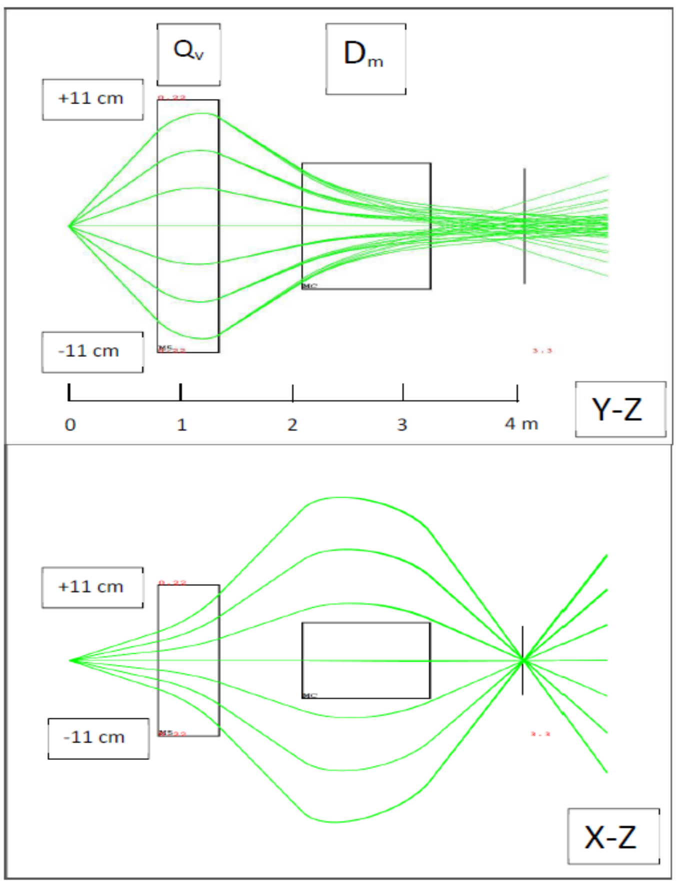

Figure 13: Vacuum optics of the AGFA separator, showing the Y-Z (top) and X-Z (bottom) planes, each with 7 rays spanning ±102 mr and ±52mr, respectively. The trajectories were calculated with the COSY program. Note that the scales in the vertical and horizontal directions are in cm and m. The left and right boxes represent Q_v and D_m. The case is shown for a flight path of 0.08 m between the target and Q_v, which accommodates Gammasphere.

In Fig. 13, we show ray-traces through the separator in vacuum mode, which illustrate the fact this design achieves an excellent focus in the dispersive X-direction, whereas the Y-focus is less concentrated. We consider this a good design compromise since it allows for an optimal separation of beam and recoils in the X-direction at the focal plane.

IV. Performance simulations

The performance of the separator has been simulated and optimized for the ^{208}Pb(^{48}Ca,2n)^{254}No reaction using a beam energy of E_{beam}=220 MeV with a distance of 80 cm from the target position to the quadrupole, which can accommodate Gammasphere at the target position. To accurately simulate the performance of AGFA when filled with a gas, a special Monte-Carlo code was written, adapted from prior work [32]. To our knowledge, this is the first gas-filled separator design that is based on such detailed simulations. This code numerically integrates the path of ions through the fields of the magnets, while simulating the charge-changing interactions with the gas, as well as multiple scattering and energy loss. At each step, the ion is checked against a 3D model of the magnet apertures and discarded if it hits a wall. Charge changing collisions are simulated as single charge-changing events, with cross sections chosen to preserve a Gaussian charge-state distribution and an average cross section. With 1 Torr He gas in AGFA we find that ~89% of the recoiling ^{254}No products are transported to the focal plane, whereas ~71% of the products fall within a 64 x 64 mm^2 area of a large Double-Sided Si-strip Detector (DSSD) of the size routinely used at the FMA in this type of experiments. For this reaction the acceptance of the spectrometer, including the implantation in the DSSD, is ~22 msr.

The relevant parameters for the simulation of the ^{208}Pb(^{48}Ca,2n)^{254}No reaction are given in Table. I.

Reaction	**Beam energy**	**E_{recoil}(initial)**	**Q_{recoil}(initial)**	**Target thickness**
^{208}Pb(^{48}Ca,2n)^{254}No	220 MeV	37 ±2 MeV	19±2	0.5 mg/cm^2
Beam profile	**σ_x**	**σ_y**	**$\sigma(d_x/d_z)$**	**$\sigma(d_y/d_z)$**
	2.1 mm	0.85 mm	0.036	0.036
Magnetic rigidity	**^{4}He gas press.**	**Target-Q1 dst**		
2.09 Tm	1 Torr	80 cm		

Table I: Parameters used in the simulation of the ^{208}Pb(^{48}Ca,2n)^{254}No reaction.

This design will surpass (or equal) that of current or planned gas-filled separators for both key parameters of AGFA relative to those for existing gas-filled separators.

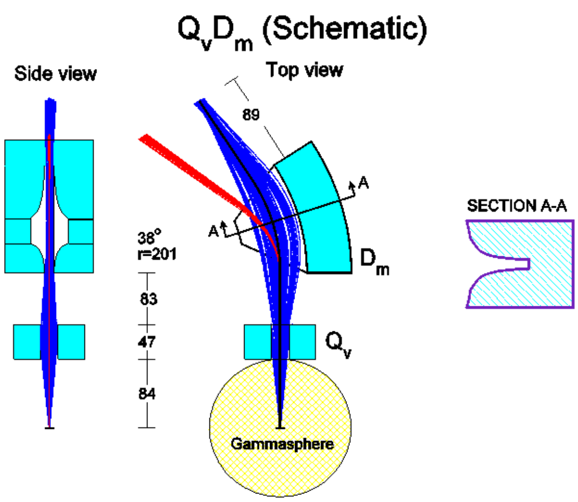

Figure 14: Schematic view of AGFA from the side (left) and the top (right) showing the trajectories for ^{254}No recoils (blue) and the beam (red).

The trajectories of ^{254}No recoils are shown as blue traces in Fig. 14. The primary beam trajectories, shown as red traces, experience substantially larger bend angles and are well separated from the No recoils. The image at the focal plane for the ^{254}No products is shown in the left panel of Fig. 15, where the grey area represents the size of a 64x64 mm^2 DSSD. The right panels show the horizontal (lower) and vertical (upper) distributions. In total, 71% of the ^{254}No products produced in this reaction are transported and implanted into the DSSD.

The successful use of gas-filled separators to isolate and study heavy nuclei, such as the example chosen here, is well documented [1-3]. Despite the challenge of separating the fusion evaporation residues that are produced with sometimes extremely small cross sections from the intense beam particles, these reactions benefit from a large difference in mass and energy between the these two components, which leads to a large spatial separation in the focal plane. A strong beam suppression factor is therefore possible for these cases. In fact, it has often been reported that the main background comes from back-scattered target nuclei or the target-like products of transfer reactions, which have properties more closely resembling those of the fusion evaporation residues. However, the main fraction of the reaction cross section leads to fission or quasi-fission fragments that are relatively easily separated from the evaporation residues.

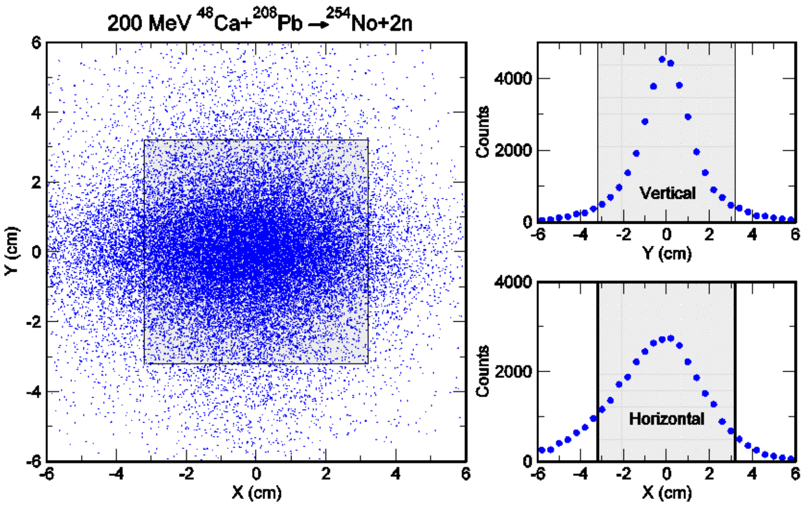

Figure 15: Left: X-Y image of ^{254}No recoils at the focal plane. The grey area corresponds to that a covered by a 64x64mm^2 DSSD. Right: Projections onto the horizontal (lower panel) and vertical (upper panel) where the grey area indicates the extent of the DSSD.

Typically, in these reactions the beam energy is chosen such that the main fraction of the evaporation cross section is associated with a single reaction channel, in this case the (2n) channel.

However, in order to ascertain the suitability of AGFA to address the second scientific area of interest, namely the study of exotic proton-rich nuclei, we have performed a second set of simulations for the entrance channel symmetric reaction ^{54}Fe+^{54}Fe→^{106}Te+2n. The result of this simulation are shown in Fig. 16 in terms of the X-Y distribution of ^{106}Te recoils at the focal plane (left panel) and the vertical and horizontal distributions (right panels). The implantation area covered by a 64x64 mm^2 is indicated by shading. We observe that the majority ~95% of the ^{106}Te products are implanted into the focal-plane DSSD. The relevant parameters used for this simulation are listed in Table II.

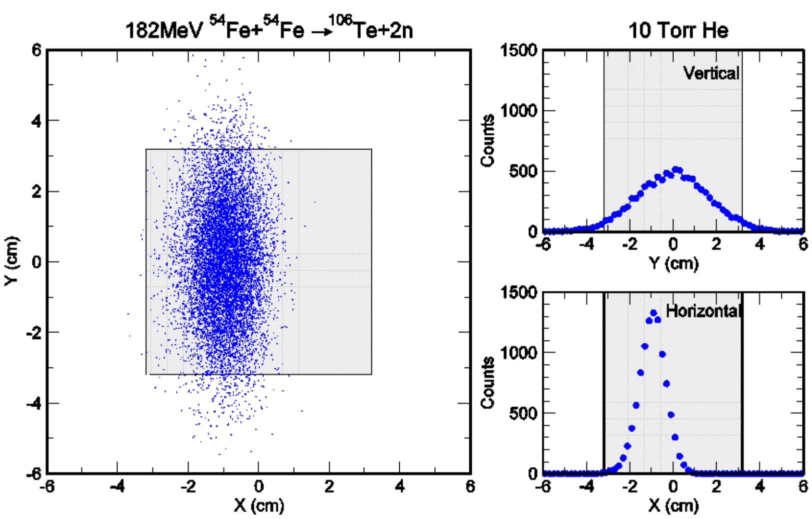

Figure 16: Same as Fig. 15, but for the reaction 182MeV ^{54}Fe+^{54}Fe→^{106}Te+2n with 10 Torr He gas in AGFA.

This type of reaction is probably the most challenging because a large part of the reaction cross section leads to products with less extreme neutron to proton ratio, for which a gas-filled separator can provide only minimal separation. The simulations show, however that the beam itself can be suppressed adequately.

Reaction	**Beam energy**	**E_{recoil}(initial)**	**Q_{recoil}(initial)**	**Target thickness**
$^{54}Fe(^{54}Fe,2n)^{106}Te$	182 MeV	89.4 ±2 MeV	25±2	1.1 mg/cm^2
Beam profile	**σ_x**	**σ_y**	**$\sigma(d_x/d_z)$**	**$\sigma(d_y/d_z)$**
	2.1 mm	0.85 mm	0.018	0.0058
Magnetic rigidity	**^{4}He gas press.**	**Target-Q1 dst**		
0.86 Tm	10 Torr	80 cm		

Table II: Parameters used in the simulation of the $^{54}Te+^{54}Fe \rightarrow ^{106}Te+2n$ reaction.

V. Comparison with other instruments

Table III provides a comparison of the AGFA design and properties with those of competing gas-filled separators. One observes that the AGFA design leads to superior properties in terms of solid angle and flight path (length), especially for the case where the target distance is set to 80 cm in order to accommodate Gammasphere for prompt gamma-ray detection.

Separator and Location	**Config.**	**Solid angle (msr)**	**Bend Angle**	**Max. B-rho (Tm)**	**Length (m)**	**Target Dist. (cm)**
AGFA @ ATLAS	Q_vD_m	22.5	38^o	2.5	4.2	80
AGFA @ ATLAS	Q_vD_m	>40	38^o	2.5	3.7	40
BGS @ LBNL	Q_vD_hD	45	70^o	2.5	4.6	35
TASCA @ GSI	DQ_hQ_v	13	30^o	2.4	3.5	15
RITU @ Jyväskylä	$Q_vDQ_hQ_v$	10	25^o	2.2	4.7	40
Garis II@ Riken	DQ_hQ_vD	20	45^o	2.4	5.1	<40
GFS @ Dubna	DQ_hQ_v	10	23^o	3.1	4.3	<40

Table III: The properties of AGFA are compared with five existing separators that are used for separating fusion reaction products.

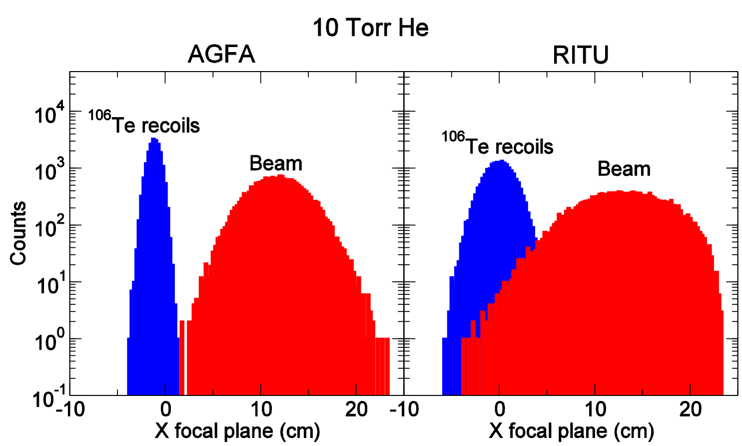

Figure 17: Focal plane distributions of ^{106}Te recoils (blue) and beam particles (red) in AGFA (left panel) and RITU (right panel) for a 10 Torr He gas pressure in both separators.

In order to assess the performance of AGFA in comparison to existing separators we have carried out a detailed simulation for the reaction 182 MeV $^{54}Fe+^{54}Fe$ that was used to study ^{106}Te via the 2n channel with the RITU separator at Jyväskylä [1]. The results of this simulation, which was carried out for both separators using our software, clearly shows that the AGFA apparatus achieves a superior separation between the beam (red histograms) and the ^{106}Te recoils (blue histograms) in Fig. 17. Note that the He gas pressure used in these simulations is substantially higher than typically used (10 Torr vs. 1 Torr). It was found necessary in order to obtain the desired collapse of the charge states for both recoils and beam particles. It is most likely that this aspect of the simulation is associated with inadequate knowledge of the relevant single-charge exchange cross sections for ions in this mass and energy region. We have not attempted to adjust these cross sections in order to reproduce the experimental observation that ~1 Torr is sufficient to achieve this charge-state collapse. However, since the same charge-exchange cross sections were used in both the AGFA and RITU simulations, it is believed that the comparison between the two devices is still valid.

One should also keep in mind that neither instrument provides significant suppression of neighboring decay channels, most importantly the much stronger, but less exotic isobars, in this case ^{106}Sn populated via the 2p exit channel. However, as already demonstrated in Ref. [19], the selective power of the recoil-decay tagging method (RDT) provides the necessary unique assignment as long as the implantation rate in a single quasi-pixel is lower than that corresponding to the life-time of the nucleus under study. In this method, the subsequent characteristic particle (proton or alpha) decays of the recoils implanted in a highly segmented focal-plane double sided Si detector are recorded. The exquisite selectivity of this technique has been demonstrated in numerous experiments over the preceding decade.

Example: Study of the ^{105}Te nucleus using AGFA and Gammasphere

The ^{101}Sn nucleus is the focus of much attention because of the possibility of gaining insight into the single particle structure in the doubly-magic N=Z=50 region. Several experiments have been carried out with this goal. As a result, the single-neutron $d_{5/2}$ and $g_{7/2}$ states were identified but their order remains ambiguous. The AGFA separator coupled to Gammasphere promises to provide more abundant and complete data to address this problem. For example, the knowledge of the structure of ^{105}Te, which α decays to the two single-neutron states in ^{101}Sn could shed light on this issue. Below, we go through some of the relevant parameters for such an experiment in order to prove this point.

^{105}Te can be populated via the ^{54}Fe(^{54}Fe,3n)^{105}Te reaction at a beam energy of 190 MeV (based on recent ^{101}Sn and ^{109}Xe experiments). The total fusion cross section is estimated to be ~200 mb based on the HIVAP code. The 3n channel cross section is ~10 nb (as determined in an FMA experiment). The beam intensity limit for the experiment will be set by the count-rate in Gammasphere, which, however, is currently being upgraded with digital electronics readout that will allow each Ge detector to count at a rate of up to 40 kHz. Assuming an average γ-ray multiplicity of M_γ=20, a raw peak-to-total ratio of 25%, and a γ-energy averaged photo-peak efficiency of 15%, this corresponds to a beam intensity of about 50 pnA on a 0.5 mg/cm^2 target. Furthermore, assuming a conservative 50% efficiency of AGFA, these conditions result in a total implantation rate into the focal plane DSSD (64x64mm^2) of 175 kHz. This rate of course appears to be very high, but the high pixilation of our present detectors for the FMA, which will also be used in these experiments, is 160 orthogonal strips on each side of the detector leading to an average 1100 Hz in each strip, a well manageable rate. The crucial point allowing for the correlation between the implantation of an evaporation residue into the DSSD and the subsequent α-decay (in this case) arises from the high segmentation of the DSSD, which effectively contains 160x160=25600 quasi-pixels. Each quasi-pixel thus sees an average implantation rate of ~175000/25600= 7 implants per second, such that the average period between implants is about 150 ms, which compares very favorably with the 0.6 μs half-life of the ^{105}Te α decay. The fact that the DSSD will not be illuminated uniformly does not change this conclusion.

It is important to note that the fact that AGFA can collect about a factor of ten larger fraction of the ^{105}Te products than the FMA (50% with AGFA vs. 5% for the FMA) allows for this experiment to be performed in a reasonable beam time (say about 1-2 weeks to collect sufficient statistics) and therefore makes this experiment feasible.

The high implantation rate into the DSSD, although manageable, does have the drawback that it leads to radiation damage of the detector over a period that may be comparable with the length of the experiment. In fact, based on tests by H. Livingston et al. [33] the DSSD should last several days without major deterioration in energy resolution. And although the DSSD is relatively expensive, it is not prohibitive to think about replacing it midstream during the experiment if necessary. The cost saving associated with running the ATLAS accelerator for a 10 times shorter period (at about $2k/hour) clearly justifies the possible expenditure.

VI. Cost estimate, funding and schedule

The cost estimate is based on recent experience in building equipment of similar nature, budgetary quotations, and vendor's price lists. The design has only recently become sufficiently concrete to seek cost estimates from vendors for fabricating the two main cost components, the

Component(s)	**Cost (k$)**
Dipole magnet incl. power supply	$500k
Quadrupole magnet incl. power supply	$200k
Vacuum pumps	$125k
Support stand	$100k
Beamline	$50k
Target chamber wheel	$50k
Dipole vacuum chamber	$50k
Detector and focal plane vacuum chambers	$50k
Design – engineering support	$100k
Vacuum gauges, valves, etc.	$75k
Utilities	$50k
Total (no contingency)	**$1350k**
Contingency (30%)	$405k
Total w. contingency	**$1755k**

dipole and quadrupole magnets, but these estimates are not yet available although they are expected soon. It is, however, anticipated that significant cost savings for these two components can be realized by carrying out the detailed design in house and requesting only the actual machining and fabrication from outside companies.

The table below reflects the proposed equipment budget for AGFA submitted to DOE in Feb. 2013. The AGFA project can be accommodated within the Physics Division budget requests for this period. In anticipation of approval, $500k was set aside for AGFA in FY2012 and it is planned to allocate $600k in FY2013, while the completion of the project will require an additional $700k in FY2014.

FY2012	**FY2013**	**FY2014**
$500k	$600k	$700k

Provided that approval for the project is forthcoming, the following schedule still appears feasible as the work on conceptual design and performance simulations has been completed in FY2012. With relatively little additional design work, the main components, the two large magnets can be ordered in FY2013. The remaining work will be carried out as listed below:

FY2013: Procurement of quadrupole and dipole magnets incl. coils.
Design beam line elements and vacuum chambers

FY2014: Procurement of power supplies and remaining smaller items.
Procurement of vacuum equipment.
Third quarter: Magnets arrive.
Fourth quarter: Final assembly starts.

FY2015: First quarter: Final assembly continues
Second quarter: Commissioning
Third quarter: First experiments

VII: User support

The plan to include a gas-filled separator in the suite of instruments available for the ATLAS research program was discussed at the last ATLAS Users Workshop that was held at Argonne, August 8-9, 2009 and all subsequent Users Workshops. This particular issue was debated in sessions on “Nuclear Structure – Focus on Physics” and “Nuclear Structure – Focus on Instrumentation”, “Nuclear Reactions and Nuclear Astrophysics – Focus on Physics”, and “Nuclear Reactions and Nuclear Astrophysics – Focus on Instrumentation”. An excerpt from the 2009 workshop summary reads:

“Finally, the instrumentation required to take full advantage of the ongoing efficiency and intensity upgrade of ATLAS was considered. With this upgrade, and concurrent

development of high-intensity targets, it was emphasized that the ATLAS facility will be placed well for the study of processes with extremely small cross sections. For example, ongoing programs on the study of nuclear structure of (super)-heavy elements and the quest for measuring nuclei near the doubly-magic N=Z=50 shell closure will both benefit from these developments. In order to take full advantage of these capabilities it is recommended that ATLAS management explore optimal designs for a large acceptance recoil separator, possibly of the gas-filled type, that will also be able to accommodate γ-detectors (Gammasphere/Gretina) at the target position and a full range of γ- and particle detectors at the focal plane"

Thus it shows that there is strong national support among ATLAS users for such an instrument.

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