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Application of the FLUKA Monte-Carlo Transport Code to Lunar and Planetary Exploration

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Abstract – *Lunar and planetary exploration necessarily involves a need to understand the primary particle radiation and secondary albedo production for space environments such as the surface of the Moon and Mars. These surface radiation environments contain a full spectrum of particle types, including relativistic nuclei produced in heavy-ion collisions. That radiation background influences the design of science payloads, power generation systems, and human* *habitation requirements. FLUKA is a well-known Monte Carlo transport code used as a simulation tool for the analysis of such particle radiation backgrounds in high-energy physics. Our NASA-funded collaboration is adapting FLUKA for use in science and engineering design of planetary surface systems as well. We will present some of the applications that such a simulation tool provides, with an illustration of the FLUKA-predicted neutron albedo for nuclear-based power systems in planetary exploration.*

I. INTRODUCTION

The prospect of new exploration initiatives in space is a reminder that much remains to be done with regard to developing the appropriate tools and basic understanding necessary for designing long-duration robotic and human missions into outer space. For physicists working around particle accelerators and nuclear power systems, the problem of a complex radiation environment is a familiar one. One of the characteristic properties describing the space environment beyond the Earth's atmosphere is that it is bathed by a complex, hostile nuclear radiation environment. Hence, particle physicists are well-prepared to cope with this element of exploration system design. However, the entire field of research into high-energy nuclear collisions at Earth-based accelerators is constantly changing and this work will necessarily complicate space radiation physics in the future.

After 48 years of space exploration much remains to be done. The fundamental tool used in physics for the study of energetic charged particle environments is the Monte Carlo transport code, sometimes referred to as a "mathematical experiment." Many varieties of Monte Carlo exist, and the focus of this presentation will be on FLUKA [1-5], a product of recent and current research at CERN in Geneva and INFN in Italy.

The motivation for space exploration, of course, is a common and mutual one. The physicists want to take a number of their Earth-based experiments and conduct them in places better suited than the Earth for certain kinds of fundamental physics research. The exploration engineers want to build safe havens on other planets for an ever-expanding human society. Only together can they make this a reality. The physicists can contribute by converting their standard accelerator tools into mathematical instruments for space radiation analysis. That is the subject of our presentation.

II. A BRIEF INTRODUCTION TO FLUKA

One can hardly summarize the contents of the Monte Carlo transport code FLUKA in a brief fashion. However, the purpose here is to introduce it to the larger audience interested in planetary exploration. In this respect, we will begin by highlighting some of its features that are particularly useful for studying the space radiation environment on a generic planetary surface. Later in Sect. V and VI specific details about the physics and ongoing development of FLUKA will be presented for the specialist.

Basically, this transport code simulates the physics of radiation processes in response to a set of inputs introduced by the user. These inputs define the geometry and environment of a radiation transport problem of interest along with the desired outputs that define what the user wants as results. FLUKA's user manual [3] is very helpful and is available at its INFN website [4].

II.A. FLUKA in a Nutshell

FLUKA is a fully-integrated particle physics Monte Carlo simulation package, with applications in high-energy experimental physics, engineering, shielding, detector and telescope design, cosmic-ray studies, dosimetry, medical physics, radiation biology, and many more [3-5]. Having been successfully corroborated with well-established experimental physics (called benchmarking), it is known to preserve correlations within interactions as well as among particle shower components, from thermal neutrons to very high energies. Successful benchmarking means FLUKA has predictivity where no experimental data is directly available.

FLUKA simulation represents the interaction and propagation through matter of some 60 different types of particles with high accuracy. This includes photons and electrons from 1 keV to thousands of TeV, charm production of neutrinos, muons of any energy, hadrons of energies up to 20 TeV (extended to 10 PeV by linking FLUKA with the DPMJET code), as well as all of the corresponding antiparticles and heavy ions.

The FLUKA collaboration investigates particle physics in support of CERN experiments such as ALICE [6] and ATLAS, as well as Gran Sasso experiments such as MACRO and ICARUS. Research topics include astrophysics [7, 8], air showers, and even NASA cosmic-ray payloads such as ATIC [9].

FLUKA's radiation biology research is equally broad in scope, ranging from shielding dosimetry for NASA to flight-crew exposure on the Air Bus [10-12]. Benefiting from its use in atmospheric cosmic-ray calculations, a vast amount of benchmarking with muon, hadron, and electron data in the Earth's atmosphere has been conducted [8, 13-14]. Once again, its hadronic interaction modeling makes it an ideal instrument for this field. Recent progress in the Monte Carlo simulation of human trabecular-bone and porous-lung tissue by the collaboration [15] has provided yet another analytical tool in radiation biology.

FLUKA can handle very complex geometries, using an improved version of the well-known Combinatorial Geometry (CG) package. The latter is faster, more flexible, more user-friendly, and has also been designed to track charged particles correctly (even in the presence of magnetic or electric fields). FLUKA includes an advanced 3-D graphics geometry package [4], used in conjunction with an object-oriented (OO) physics analysis infrastructure that is currently evolving at CERN known as ROOT [16]. FLUKA with a ROOT-based interface is known as FLEUR (FLUKA-Executing-Under-ROOT).

FLUKA simulation packages are usually launched on a Linux-based architecture. PAW (Physics Analysis Workstation) can be used to generate the output plots. FLUKA plays a part in the virtual Monte Carlo concept at CERN's ALICE. The AliROOT system [9] allows differing transport engines such as FLUKA and GEANT to interface geometry databases with one another.

II.B. How does one obtain FLUKA?

FLUKA is available in the form of a pre-compiled object library for a number of computer platforms [4]. The library comes bundled in a tar file, which includes additional files required to run the program. In the case of Linux, the version of the system C library and the FORTRAN compiler are of importance. Any current Linux distribution with a compatible set should work. For the other supported platforms, it is sufficient if the Operating System version is at least as new as those indicated in the release notes.

II.C. Biasing in FLUKA

Biasing is a powerful feature of this transport code used (a) to reduce excessive calculations such as the amount of computer overhead needed to arrive at a solution; or (b) to make very rare events (e.g., hadronic interaction of photons) equally probable with more common events. Deep penetration problems, such as massive shielding or even atmospheric showers, can hardly be managed without biasing. Biasing is based on rigorous mathematical tools, but its application is delicate. Wrong biasing parameters can even lead to an increase of computation time, or to large statistical fluctuations. For this reason, biasing should be applied with care. Thanks to its unique capability to perform both biased and normal (or "analog") calculations, FLUKA can be used with success both in pure physics research and in applied physics and engineering .

III. PLANETARY EXPLORATION

With the brief introduction of FLUKA above, we can proceed and address how it is useful for analyzing scientific as well as engineering design problems in planetary exploration. Figure 1 illustrates most of the environmental features of a given planetary surface problem.

III.A. The Planetary Surface

When one speaks of a planetary surface, several subjects come to mind. First of all, the surface is not the Earth. Second, the surface is comprised of some form of regolith and topology. Third, the planet may or may not have an atmosphere. All of these characteristics must be addressed in defining the surface environment where FLUKA is to be asked to calculate the fluence, dose, and energy spectra for a user-specified source plus geometry.

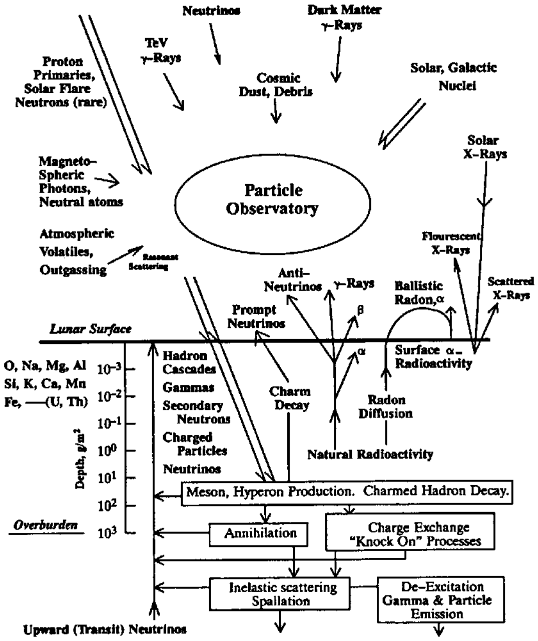

Fig. 1. Space radiation environment of a lunar or planetary surface with no atmosphere [17].

III.B. Lunar and Martian Regoliths

Another aspect of particle radiation environments is the importance of the albedo or backscatter produced by a primary radiation source such as cosmic rays. This secondary radiation is often neglected completely, tantamount to declaring that everything above the surface in Figure 1 does not exist except the Galactic Cosmic

Rays (GCRs) and Solar Particle Events (SPEs). In some circumstances the secondary radiation is more significant than the primary radiation.

Table I. Elemental Abundances in Lunar Regolith.

Element	*Atomic Weight*	*Z*	*Percent Weight*
Si	28.09	14	20.86
O	16.00	8	43.47
Ti	47.88	22	1.46
Al	26.98	13	9.63
Cr	52.00	24	0.22
Fe	55.85	26	9.08
Mn	54.94	25	0.16
Mg	24.31	12	5.54
Ca	40.08	20	8.93
Na	22.99	11	0.32
K	39.10	19	0.15
P	30.97	15	0.09
S	32.07	16	0.09
Total			100.00

The model of the Moon's surface is taken to be the chemical composition of soils found at various landing sites during the Apollo and Luna programs [18], averaged over all such sites to define a generic regolith.

Table II. Martian regolith simulant models.

Constituent	*Viking-1 %Weight*	*Viking-2 %Weight*	*Pathfinder* %Weight	*JSC-Mars-1 %Weight*
SiO_2	43.0	43.0	44.0	43.5
Al_2O_3	7.3	7.0	7.5	23.3
TiO_2	0.7	0.6	1.1	3.8
Fe_2O_3	18.5	17.8	16.5	15.6
MnO	n/a	n/a	n/a	0.3
CaO	5.9	5.7	5.6	6.2
MgO	6.0	6.0	7.0	3.4
K_2O	<0.15	<0.15	0.3	0.6
Na_2O	n/a	n/a	2.1	2.4
P_2O_5	n/a	n/a	n/a	0.9
SO_3	6.6	8.1	4.9	n/a
Cl	0.7	0.5	0.5	n/a
Total	89.0	89.0	89.5	100.0

The resulting weight percentages by element are given in Table 1. Neglecting biogenic elements (H, C, and N), these are the 13 elemental abundances measured to be present on the Moon with more than a trace, having atomic number Z. The lunar surface model is assumed to have a mean density of 2.85 g cm^{-3} and a negligible magnetic field.

For the case of Martian regolith models, these are summarized in Table II. In view of the current robotic MER mission activity on the Martian surface, these will probably change soon. Note that the principal author (Richard V. Morris) of the JSC-Mars-1 simulant is involved in the MER rover program for NASA [19].

The elemental composition by weight-percent is introduced into FLUKA as an execution-input file. Alternatively, the user can define chemical compounds such as those appearing in Table II.

III.C. Martian Atmosphere

The Martian atmosphere has been studied in several contexts, Mars-GRAM (Global Reference Atmospheric Model) being the one suggested here [20]. As mentioned earlier, FLUKA is well-known for the accuracy of its Earth-atmospheric analysis, giving the correct muon flux at sea-level. FLUKA astrophysical studies of Earth-based atmospheric neutrinos are still in progress [7,8]. Hence, it should prove useful in the study of the Mars atmosphere and particle radiation environment.

At least two groups are presently using FLUKA to analyze the Martian atmospheric model Mars-GRAM 2005. These Marshall Space Flight Center and the University of Houston.

III.D. Backscatter Albedos using FLUKA

FLUKA is particularly suited for back-scatter problems in physics [9]. Naively, a pedestrian has difficulty understanding how firing a bullet-like object down the nadir into the surface in Figure 1 can produce something flying backwards into the zenith. This misconception needs to be overcome.

A heavy-ion cosmic ray is an atom stripped of its electrons and travels at nearly the speed of light. Some have the impact energy of a high-speed tennis ball, concentrated in an $\approx 10^{-39}$ times smaller volume. Upon penetrating the surface in Figure 1, the cosmic ray fragments explosively and comes apart, depositing its kinetic energy there. Part of that energy is deposited inside atomic nuclei, and heats them up. The result is that nuclei in the surface begin "to boil" nucleons much like a pot on a kitchen stove. As the neutrons heat up they begin to evaporate, hence their name *evaporation neutrons*.

In the rest-frame of the surface there is no *up* or *down* for the evaporation neutrons. These can be imagined as a cloud or gas of particles expanding isotropically in their own rest-frame about the point of impact. The excitation or perturbation of the impacting heavy-ion cosmic ray thus creates particles of secondary radiation rising up out of the surface. The surface of the Moon is thus bathed by this cloud of GCR- and SPE-induced albedo neutrons. By the same arguments, other backscatter particles are likewise produced including photons.

Neutron physics is one of the fortes of FLUKA, and now we are prepared to discuss a specific example exhibiting FLUKA's neutron physics using PAW as the GUI interface.

IV. NUCLEAR POWER SYSTEMS

We take as a simulation example the nuclear power system, an application of interest to the nuclear science community. This is related to the neutron albedo problem just discussed, but for a nuclear power source sitting on the planetary surface in Figure 1 involving both primary and secondary radiation production. Neutron mitigation is obviously of much concern and appropriate shielding designs are necessary in order to protect the livelihood of personnel, equipment, and scientific instrumentation. To this question we can add the calculation of dose about the perimeter of such a facility or device.

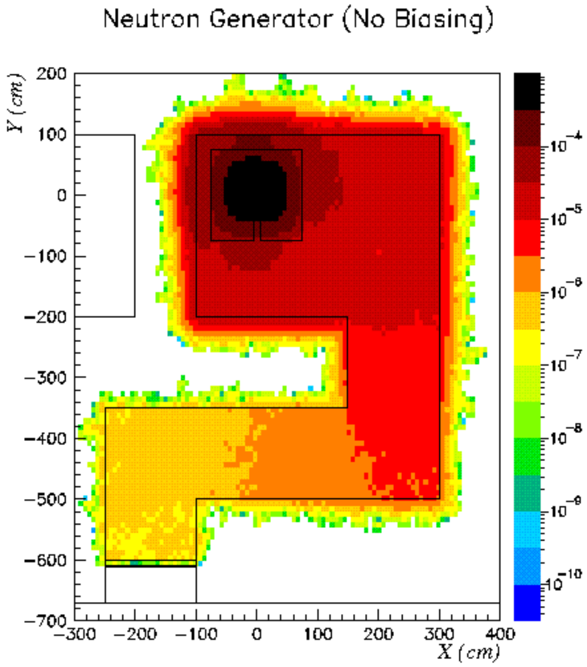

Fig. 2. Neutron fluence example from FLUKA using PAW.

IV.A. An Example from FLUKA

As yet, FLUKA has not been enlisted to address a specific planetary-exploration architecture, like the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) and Sterling Isotope Generator (SRG) being discussed at this conference or the Radioisotope Power System (RPS) concepts appearing in U.S. Department of Energy (DoE) designs for deep-space NASA missions. To illustrate what FLUKA can accomplish, an Earth-based example will be presented instead.

One of our collaborators (Vasilis Vlachoudis) has investigated the neutron fluence surrounding a neutron source at the Aristotle University of Thessaloniki. The results from FLUKA are given in Figure 2.

The fluence shown is produced as a color image superimposed over the architectural layout of the facility that houses the neutron source. Color binning is defined by the right-hand ordinate axis (log color-scale: particles/cm^2). The user-input file defines the walls and doors of the facility, including its elemental composition such as concrete, borated paraffin, stainless steel, lead, and so forth.

The neutron source is located at the origin of the x-y coordinate system. Typically, neutron generators produce neutrons (n) by means of deuterium-deuterium (D-D) and deuterium-tritium (D-T) target reactions

$$\mathrm{D} + {}^{2}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \mathrm{n}$$
$$\mathrm{D} + {}^{3}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \mathrm{n}$$

where the neutrons produced have energy of ~2.5 and ~14.1 MeV respectively. An isotropic neutron distribution, however, was used in creating the result illustrated in Figure 2. Biasing was also conducted for this example (but is not illustrated) to demonstrate that when properly used, considerable time can be saved in obtaining the result but with only small variations in the peripheral fluence bins of the plot. Once again, biasing works by providing the user several means for improving the statistical significance in selected phase-space regions, at the expenses of those phase-space regions that are not specifically germane to the desired result. Gamma-rays were not requested in the Figure 2 study, although they could have been.

A natural question follows from this FLUKA example. What is the correct or preferred way for calculating dose equivalents for gamma and neutron radiation outside the shield walls in the same problem? The most common way is folding of fluence with fluence-to-dose equivalent conversion factors. If folding is performed off-line one will need energy spectra that can be scored. On the other hand (and this is usually more convenient), one can request a scoring and folding online (during FLUKA execution). An existing routine allows one to multiply every entry into the scoring-bin with particle type and energy-dependent factors, e.g. fluence-to-dose equivalent conversion factors. At CERN the energy-dependent fluence-to-dose equivalent conversion factors are produced by a user-input routine written by Stefan Roesler in the FLUKA collaboration.

In closing this section, there needs to be mention of neutron balance plots generated by FLUKA. Neutron balance [9] represents the algebraic sum of outgoing neutrons minus incoming neutrons in a fundamental volume.

V. FLUKA MODIFICATIONS IN PROGRESS

There are a number of areas where FLUKA development is an ongoing process. These include improved event generators and ROOT-derived GUI-based interfaces for the user community, both of which will be summarized in these concluding Sections V and VI. The focus will be for the Monte Carlo specialist.

V.A. Collisional Cross-Section Measurements

Since ion-ion (A-A′) nuclear interactions are not yet thoroughly treated in any Monte Carlo for all energies, FLUKA itself is still under development. This circumstance arises because of the neglect of thorough A-A′ collision data at the onset of relativistic effects around 0.5-to-5.0 GeV/n. It seems that physicists have been more interested in the production of very rare events (because these often produce Nobel prizes as well) than the more common ones in medium- and high-energy physics. A consequence has been a certain degree of uncertainty about what is really going on in collisional nuclear physics at that energy range.

Above this energy range (0.5-to-5.0 GeV/n), FLUKA links the Dual Parton Model (DPMJET). Below, FLUKA uses the Intra-Nuclear Cascade (INC) technique and Pre-Equilibrium Approach to Nuclear Thermalization (PEANUT) model for light ions, and is going to implement the Boltzmann Master Equation approach [5]. The code for each of these models is referred to as an *event generator*.

What is an event generator? Monte-Carlo-type transport codes use total interaction cross-sections to determine probabilistically when a particular type of interaction has occurred. Then, at that point, a distinct event generator is employed to determine the results of that interaction – that is, to simulate the known physics over some energy range.

Basically, the Monte Carlo community is in need of a satisfactory event generator that adequately simulates collisional nuclear physics (A-A′ scattering) in the energy range 0.5-to-5.0 GeV/n.

NASA has recognized the need for addressing this A-A′ experimental measurement problem, in the context of developing adequate transport code models for its Radiation Shielding Program. FLUKA has been identified as one of several transport codes (under Grant NAG8-1901) that will attempt to develop such an event generator, based upon A-A′ collisional data extracted from beamline experiments at the U.S. Brookhaven National Laboratory. That having been said, there is much discussion about the quality of measurements necessary (inclusive versus exclusive measurements) and the associated cost.

V.B. The FLUKA-DPMJET Interface

Above the problematic energy range, FLUKA has a very satisfactory simulation of particle physics derived from what is called the Standard Model. This event generator is known as DPMJET. It is a Monte Carlo code for sampling hadron-hadron, hadron-nucleus, and nucleus-nucleus (A-A′) collisions at accelerator and cosmic-ray energies (E_{lab} from 5-10 GeV/n up to 10^{18}-10^{20} GeV/n), adapted and interfaced with the rest of FLUKA [21]. It has since been upgraded to DPMJET-3 [22]. DPMJET is based on the Dual Parton Model in conjunction with the Glauber formalism.

FLUKA internally requires A-A′ production cross-sections in order to select the appropriate nucleus-nucleus interactions. It includes a complete matrix of A-A′ production cross-sections along with the Glauber impact parameter distributions. Owing to the validity of the Glauber formalism, these cross-sections can be safely utilized down to a projectile kinetic energy of ~1 GeV/n. Details of the DPMJET-3 interface with baseline FLUKA are given elsewhere [5].

V.C. Transition to Non-relativistic Energies

Although event generators exist for most of the particle interactions treated by FLUKA, those necessary for A-A′ collisions in the transition region from the Glauber formalism down to non-relativistic energies (from say 5 GeV/n down to 100 MeV/n) are not as well-defined. As stated previously, this is the region of the NASA-funded transport code investigation.

One feature of the physics in this region is momentum-dependent nuclear potentials which are notoriously nonlocal in nature. Nonlocal interactions break Lorentz invariance and this is somehow related to the transition to nonrelativistic dynamics (where Lorentz invariance becomes negligible). A number of computer codes have been created to deal with the nuclear and molecular dynamics in this energy range, but with only marginal success. The first was the nonrelativistic Quantum Molecular Dynamics (QMD) model [23], augmented by limited Poincaré invariance arguments to be pseudo-relativistic, a model known as the Relativistic QMD (RQMD) method [24]. Other molecular-dynamics models have been tried as well [25].

The RQMD model has been widely used over the energy range from 0.1 GeV/n to several hundreds of GeV/n. However, this code does not perform the latest stages of the A-A reaction, and does not always conserve energy.

The FLUKA collaboration has selected several alternatives, addressed in more detail elsewhere [26]. First, the RQMD code *per se* has been scrutinized, adapted to be interfaced with the FLUKA evaporation models and corrected for energy non-conservation, while maintaining its underlying philosophy. Then it has been embedded into the current version of FLUKA while again guaranteeing absolute conservation of energy, an essential requirement for any suitable transport code. Second, alternative QMD [5] and Hamiltonian Molecular Dynamics (HMD) event generators are undergoing development.

V.D. The Modified RQMD Event Generator

The modified RQMD event generator included in the present release as RQMD-FLUKA has been used to prepare fluence plots that will aid in planning for the proposed measurements at Brookhaven National Laboratory for NASA. These are of interest, and two will be shown here. They illustrate FLUKA's existing capability in the suspect energy range below DPMJET's cutoff around 5 GeV/n and above the INC-technique and PEANUT. More comprehensive details and additional fluence plots are given elsewhere [26].

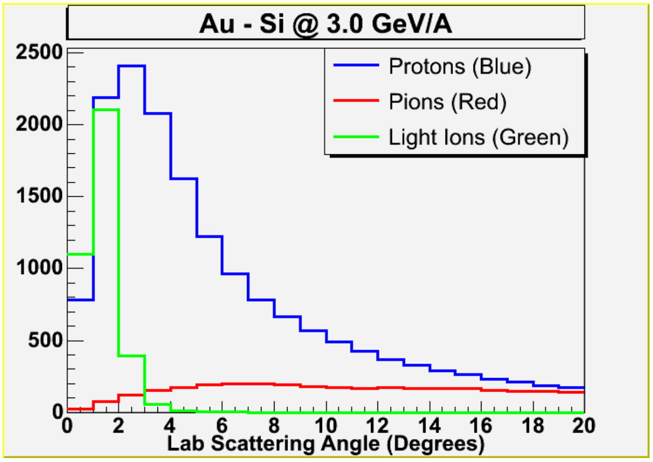

Fig. 3. Laboratory scattering angle distributions for protons, pions and light ions (D-B) per second in one-degree annular bins from a 1 kHz **3.0 GeV/A** Gold (**Au**) beam incident on a Silicon (**Si**) target.

The embedded RQMD-FLUKA provides an option to run in an INC-like mode to reduce computation time in instances where full accuracy is not required. The original RQMD code does not identify complex fragments at the end of the interaction. The strategy adopted is to allow the code to follow an interaction to some intermediate point where all of the hard collisions between constituent particles are over. Then the evolution is stopped in an interim state. At that point, projectile- and target-like nuclei are formed out of the spectator nucleons (i.e. nucleons which did not undergo two-body collisions), and their excitation energy is calculated from the energies of the holes left by the hit nucleons. The remaining particles are next placed in the final-state RQMD-FLUKA event-generator output buffer. The two trial hot-fragments so identified are next run through the FLUKA evaporation/fission/fragmentation module, allowing them to de-excite into surviving fragments since the latter may have boiled-off some of their original constituents in the evaporation process.

Figures 3-4 show some results from the RQMD-FLUKA event generator as it presently exists. These fluence plots (ordinate: number of particles cm^{-2}) depict the laboratory scattering angles in annular angle-bins of one degree for protons above a kinetic energy of 100 MeV in the laboratory, for all charged pions above 50 MeV in the laboratory and for all light ions (Deuterons through Boron) above 100 MeV/n or 100 MeV/A. The ordinates are normalized to the yields from a 1-kHz beam of Gold (Au) incident upon a one-interaction-length thick Silicon (Si) target.

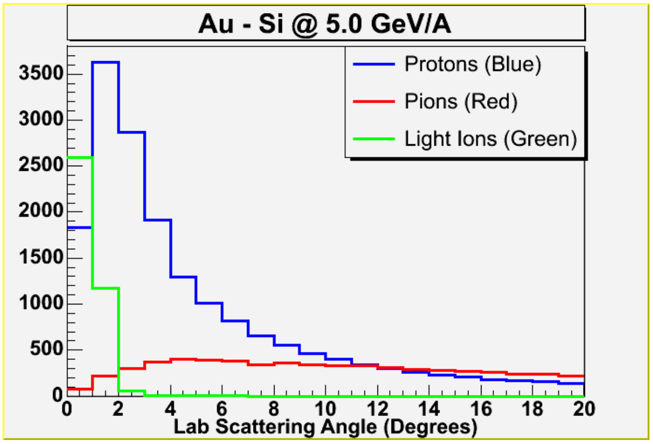

Fig. 4. Same fluence as Fig. 3 except using a 1 kHz 5.0 GeV/A Gold (Au) beam incident on a Silicon (Si) target. Note the dominance of the pions starting at about 13 degrees.

Both of the figures show a similar behavior, having a proton distribution peaking near zero. One of the important differences in the calculations for 5 GeV/A incident projectiles with respect to similar 3 GeV/A interactions is the relative height of the pion distribution at larger angles. The pion scattering-angle distribution rises from low values at small angles, becoming comparable to the proton fluence. In Fig. 4 it begins to exceed the proton fluence around 13 degrees.

V.E. The HMD Event Generator

The additional option under study to complement the RQMD-FLUKA event generator is the HMD model. This event generator derives from the concept of primary and secondary constraints developed by Dirac [27] for relativistic Hamiltonians and derived from Poincaré invariance. It was extended by Komar [28], Todorov [29], and Samuel [30]. When the Hamiltionian exists, this approach to relativistic QMD-type methods has never been implemented successfully in a Monte Carlo and it offers promise in the problematic transition energy range. Its potential application within FLUKA is under consideration as yet another alternative to QMD-FLUKA. More detail on this method is published elsewhere [26].

VI. GUI-BASED TOOLS FOR ENHANCING FLUKA

Figures 3 and 4 are examples of ROOT-derived GUI-based outputs from FLUKA. For some time there has been an effort to provide FLUKA users with additional GUI-based tools that address both the “front-end” or the setting up of FLUKA runs and the “back-end” which includes the analysis of the outputs generated by FLUKA. A portion of these developments [26] will now be discussed.

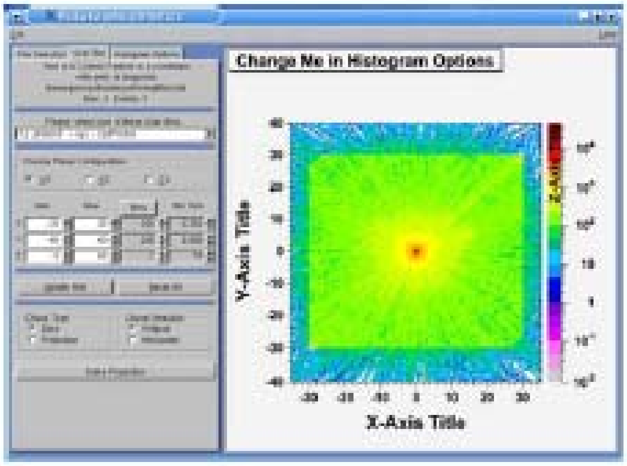

Fig. 5. “USERBIN” ROOT-based GUI Interface.

While FLUKA will always provide users with the opportunity to do their own “scoring”, the code includes a robust suite of internal scoring capabilities. In the past, there have been various command-line macros along with prescriptions on how to employ them to produce visualizations of these built-in capabilities. In order that users can take advantage of such features, an attempt to provide a ROOT-based GUI tool that includes all of the built-in scoring types is underway. The initial effort has been focussed on the FLUKA fluence scoring associated with the internal “USERBIN” scoring capability.

This effort has progressed to the point where it is possible to examine the interface and anticipate its final form. It includes the ability to select the FLUKA output file directly and it does the conversion of that information into a ROOT file such that it can be viewed and manipulated totally via the GUI interface with fluence plots and GUI-selected profile histograms being directly presented without the need to master either ROOT or command-line capability. On the other hand, the ROOT command-line code produced in the process is user viewable to enable comparison of the details of the needed ROOT C++ commands with the actual outputs in case the user wishes to learn from that example. Figure 5 shows the current GUI tools for this type of analysis.

In addition, integrated ROOT-based tools have been developed that encapsulate FLUKA from the initiation of a run through the setting up of a ROOT-based analysis. The current plans are to continue to extend these capabilities to the point where a GUI tool can be employed both to produce the normal FLUKA input file and to launch a FLUKA run. Then upon completion, the user will be able to open another GUI tool to examine and analyze directly the outputs produced by the standard FLUKA scoring capabilities in a ROOT-based GUI environment.

On the input side, introducing the geometry information for a situation remains a singularly complex task. At present the plans for the GUI input tool will require that a separate geometry input file be prepared independently. Over the longer term, plans exist to develop distinct GUI-based tools to facilitate the input of the geometry information.

VII. CONCLUSIONS

A brief introduction to the Monte Carlo transport code FLUKA has been presented, with application to planetary surface system analysis. Neutron physics was the focus of attention. Several enhancements in FLUKA have been discussed as an illustration of its ongoing evolution, also being presented elsewhere [26, 31-32]. Further bench-marking of FLUKA is in progress [32].

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NOMENCLATURE

ALICE is A Large Ion Collision Experiment destined for the LHC at CERN.

ATLAS is A Toroidal LHC ApparatuS.

CERN is the European Organization for Nuclear Research located in Geneva, Switzerland.

DoE stands for the U. S. Department of Energy.

DPM stands for the Dual Parton Model.

FLUKA is an acronym from the German, for *FLUktuierende KAskade*.

FLEUR is FLUKA-Executing-Under-ROOT, website at http://fleur.cern.ch/~empl/fleur/.

GEANT (GEometry ANalysis Tool) is French for "giant," comprising another Monte Carlo engine at CERN different from FLUKA.

GRAM represents Global Reference Atmospheric Model.

GUI is Graphical User Interface.

ICARUS stands for Imaging Cosmic And Rare Underground Signals.

INC is Intra-Nuclear Cascade.

INFN represents the (Italian) National Institute for Nuclear Physics.

JSC is the Johnson Space Center in Houston.

LHC is CERN's Large Hadron Collider.

MACRO represents Monopole Astrophysics and Cosmic Ray Observatory.

MER is the Mars Exploration Rover mission.

MMRTG is Multi-Mission Radioisotope Thermoelectric Generator.

NASA is the National Aeronautics and Space Administration.

PAW is Physics Analysis Workstation.

PEANUT is Pre-Equilibrium Approach to Nuclear Thermalization.

QMD is Quantum Molecular Dynamics.

RPS is Radioisotope Power System.

SRG is the Sterling Radioisotope Generator.

RQMD is Relativistic QMD.

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