New charge state distribution tool

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1 Introduction

The ATLAS charge state tool is used to estimate the charge state distribution of an ion beam after it passes through a stripping foil. After the existing tool was transferred to the alpha server, it was tested to ensure nominal functionality, and newly calculated predictions compared to its documented predictions in a number of prior experiments. While it did match previous predictions, it was noted that those predictions were often 3-6 charge states removed from the measured value. In the interest of greater accuracy, other models were explored and a new charge state tool was developed.

2 Models

Five models for calculating the mean charge state, $\bar{q}$, were evaluated against 13 ATLAS experiments in which an ion beam was stripped to a higher charge state using 50μg/cm^2 carbon foils. The fractional population for each charge state around $\bar{q}$ follows a normal distribution with the parameters $x = \bar{q}$ and σ uniquely determined in each model. Therefore, using a model that calculates $\bar{q}$ close to the historically measured values with minimal error is a desirable starting point.

The models evaluated were:

- the existing charge state tool created by Richard Pardo and bearing similarites to models developed by N. Bohr and at GANIL,
- the ETACHA4 module in the LISE++ software [1],
- three individual semi-empirical models, developed by H. Betz [2], G. Schiwietz [3], and V. Nikolaev and I. Dmitriev [4].

All models used are stated to be valid for the mass and energy ranges typical of ATLAS experiments. Three of the models—the existing tool, Schiwietz, and ETACHA4—account for foil thicknesses and material, and with the exception of Schiwietz (being a semi-empirical model), calculate energy loss. The Betz and Nikolaev-Dmitriev models assume an equilibrium charge state distribution, which is reasonable given the foil thicknesses (50μg/cm^2 and up), ion masses, and energies used in ATLAS.

3 Comparison

For each historical experiment, estimates of $\bar{q}$ were calculated using each of the models. For the existing charge state tool the estimates were compared to the estimate generated for the original experiment to check that they matched (they did). In some cases, the beam energy used to calculate the estimate during the experiment was different from the experiment's measured unstripped beam energy. Therefore in the interest of reducing error, care was taken in all cases to use the most accurate possible energy measurement, and energies in documentation were cross-referenced with Time-of-Flight (ToF) energies recorded in Paradox.

For each model, the differences between the estimated values for $\bar{q}$ and the measured mean charge state were calculated for each experiment in the set. To determine if some models worked better within certain ion mass or energy ranges, the error ($\bar{q}_{estimated} - \bar{q}_{measured}$ in the model estimates were plotted vs atomic mass (Figure 1a) and against energy per nucleon (Figure 1b). No correlation was observed.

However, there were observable differences in the magnitude of the errors generated by different models; for example the Pardo tool and Nikolaev-Dmitriev model consistently overestimated the charge state, and most models tended to produce both very small and very large relative errors. The Betz model stood out, first for its avoidance of the extremes of error for each experimental case, and second for its relative simplicity of calculations, which makes it less tedious to encode and less prone to encountering human error in application. Therefore, it was selected for use in a new charge state estimator tool.

4 Betz Model

Since the Betz model assumes an equilibrium distribution, its calculation of $\bar{q}$ is only a function of the incident ion atomic number, Z, and particle velocity, v where v_0 is the Bohr velocity of the electron and is equal to $\frac{e^2}{h} = 2.18 \times 10^6$ m/s (Equation 1)

$$\bar{q}(Z, v) = Z \cdot [1 - 1.041 \exp(-0.851 \cdot Z^{-0.432} \cdot (\frac{v}{v_0})^{0.847})], \quad (1)$$

and σ is a function of Z alone (Equation 2)

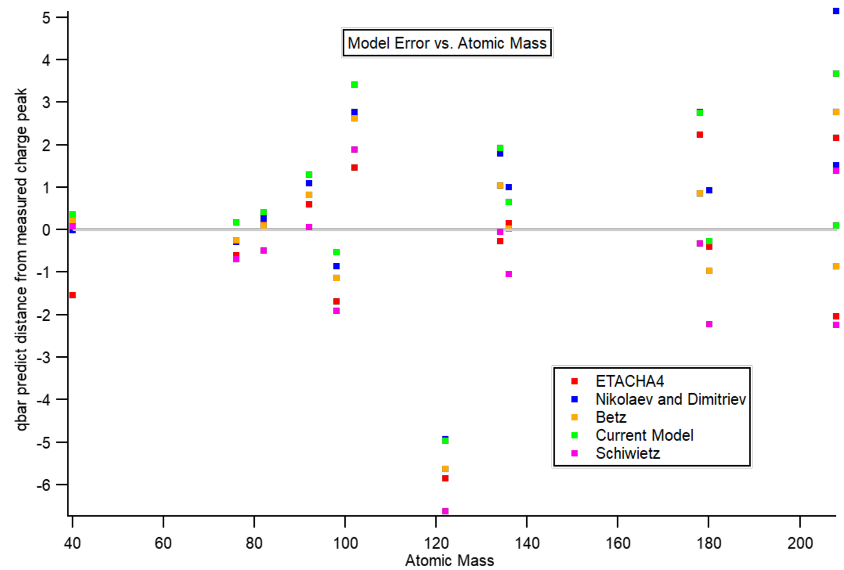
$$\sigma = 0.27 \cdot \sqrt{Z}. \quad (2)$$

v is derived from $E = \frac{mv^2}{2}$, resulting in

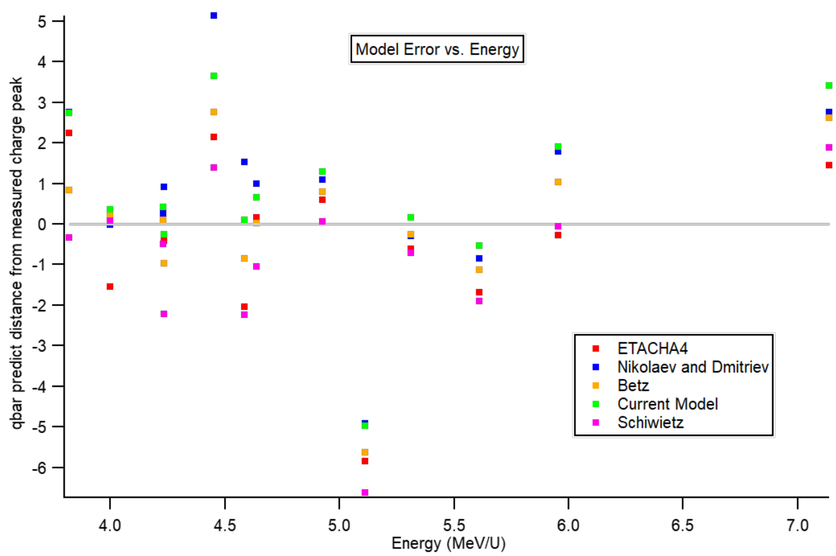
$$v = \sqrt{\frac{1}{2} \cdot \frac{E}{m} \cdot \frac{c^2}{m_{rest}}} \quad (3)$$

where E is the unstripped beam energy in MeV, m is the ion atomic mass in amu, m_{rest} is equal to 931.5 MeV (the rest mass of 1 amu in MeV), and c is the speed of light in a vacuum in m/s.

The fractional populations are then calculated via normal distribution about $\bar{q}(Z, v)$ with standard deviation σ [5]:



(a) $\bar{q}$ error vs. mass



(b) $\bar{q}$ error vs. energy

Figure 1: Error in $\bar{q}$ estimates vs. ion atomic mass and energy per nucleon.

$$P(q) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(q-\bar{q})^2}{2\sigma^2}\right) \tag{4}$$

5 Implementation

A charge state tool using the Betz model was then developed in Excel and Python, which prompts the user for the ion atomic mass (A), number (Z), and energy (E) and calculates $\bar{q}$, σ, and the population distribution $P(q)$ for 10 charge states above and below $\bar{q}$. The Python code was converted for use in the ATLAS control system by Kanesha Jackson.

References

[1] Michigan State University. *LISE++*. Version 12.1.2. URL: http://lise.nscl.msu.edu/lise.html.

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[3] Schiwietz G and Grande P.L. "Improved charge state formulas". In: *Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms* 175 (Apr. 2001), pp. 125–131. DOI: 10.1016/S0168-583X(00)00583-8.

[4] V.S. Nikolaev and I.S. Dmitriev. "On the equilibrium charge distribution in heavy element ion beams". In: *Physics Letters A* 28.4 (Dec. 1968), pp. 277–278. DOI: 10.1016/0375-9601(68)90282-X.

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