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Isotope yields with a solenoid-based fragment mass analysis system - prospects for exotic isotope studies in the $10 \leq Z \leq 30$ range*

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Abstract

Yields of neutron-rich and other ions in the region of $10 \leq Z \leq 30$, produced by a 30 MeV/u $^{136}Xe^{24+}$ beam on a thick ^{nat}C target, are presented. The ions were collected and identified with the University of Michigan 7-Tesla solenoid device 'BigSol' at 1.36 Tm. The yields are sufficient to make feasible gamma- and/or beta-decay studies of lifetimes and nuclear structure at the solenoid's focal position, or alternately with the fragments transported away for low-background studies. Small but usable amounts of ions close to or including the most n-rich ions produced anywhere to-date are produced and it is shown that if particle-by-particle identification is not continuously required, that the yields may be increased by over two orders of magnitude.

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1 Introduction

Currently there is considerable interest in the production and study of very neutron-rich isotopes at or near the limits of nuclear stability, as novel nuclear characteristics have been found in such nuclei. These include the observations of low-density nuclear 'halos' [1] and neutron 'skins' [2], violations of expected shell closings, etc. However, at present the neutron-rich limit of nuclear stability (the so-called 'neutron drip line') has been experimentally mapped out only up to Z $\approx$ 10(^{33}Ne). In the region immediately beyond of, roughly, 10 $\leq$ Z $\leq$ 30, one is generally constrained to the use of on-line isotope separator (ISOL) or projectile fragmentation (PF) methods. The PF method is hampered, amongst other things, by the empirical fact that, as one proceeds stepwise in the attempt to produce ever-more-neutron-rich isotopes, production cross sections are found to drop off by approximately one order of magnitude per each further step in amu [3]. In this situation, devices with high solid-angle acceptance and which are able to handle high-intensity primary beams yet resolve the products are preferred.

With these issues in mind, we investigated the yields of PF-produced isotopes in the region 10 $\leq$ Z $\leq$ 30 using the University of Michigan's 7-Tesla superconducting solenoid magnet 'BigSol' [4] as a reaction-product collector and fragment mass-analysis system at the National Superconducting Cyclotron Laboratory (NSCL).

2 Two Modes of Solenoid Use

Superconducting solenoid devices have been and are being used to good effect to produce intense beams of radioactive nuclei (RNBs) including nuclei in isomeric states [5-7]. However, to date much of this work has generally involved exploiting low energy transfer reactions with light heavy ions ($2 \leq Z \leq 10$) to produce short-lived beams (e.g.: ^{6}He, ^{8}Li of astrophysical interest [5]. These beams are focused and collected by the solenoid onto secondary targets where nuclear-reaction and/or spectroscopic studies are subsequently conducted. In the present case, however, a superconducting solenoid was employed to collect fragments produced from a highly asymmetric entrance channel reaction (^{136}Xe^{24+} on $^{\mathrm{nat}}$C) at a relatively higher beam energy of 30 MeV/u. For asymmetric reactions this is at the boundary line between the regime of complete projectile-target fusion and that of incomplete fusion [8-9]. Unlike reactions at low energies, in reactions with very heavy projectiles in the energy/nucleon range of the present experiment, it is typical for $\geq$ 200 isotopic species to be simultaneously produced. In addition, the reaction products of interest may emerge at energies where they are not completely stripped of electrons (10

$<$ MeV/u < 35). Ions in a wide distribution of charge states are difficult to identify with any magnetic-selection device, as these select ions according to their A/q (mass-to-charge) ratio, and there is often a charge-state ambiguity as to the correct A-identification.

In spite of these experimental and practical constraints we have shown that a solenoid device can not only focus yields of exotic isotopes sufficient for various reaction studies, but that it is possible to satisfactorily identify individual products and determine their yields. Lastly, the data were taken at $0.7 \leq \theta_{\rm lab} \leq 6.2^\circ$ ($\theta_{\rm lab} \leq 3.1^\circ$ shown here), as solenoids are not constrained to angles near zero degrees. This feature may prove fortuitous, as a recent study of PF yields of new neutron-rich isotopes indicates that their production in this energy range may be concentrated at the classical grazing angle [10].

3 Experimental Method and Ion Identification

For the data we present here, a rather thick target was used (114 mg/cm^2), viz. sufficient to stop the primary ^{136}Xe beam, yet thin enough to allow the relatively lighter reaction products of interest to emerge. As a result, at the field setting and asymmetric geometrical image-distance/object-distance arrangement of the solenoid 'lens' which was chosen, ions with Z $\geq$ 33 were largely suppressed from reaching the focal plane. Furthermore, the primary Xe beam intensity was attenuated to ≈ 4.6 enA (1.2e + 09 particles/s) out of 43 enA (10.2%) available from the NSCL cyclotron. This was done so as to limit the rate at the entrance PPAC detector to below 50 kHz when running in the particle-by-particle, time-of-flight (ToF) identification mode.

In a typical run 5.8e + 06 events were collected at the focal plane during 3.3 h of beam time. Temporarily reducing the effective size of the focal plane aperture with a software gate placed on the centroid of a spectrum derived from the Si PSD (position-sensitive detector) reduced the magnetic acceptance, $\Delta(B\rho)/B\rho$, to $\leq 1.5\%$, passing 2.8e + 05 events ($\approx 1/20$). This allows Z resolution to emerge from the ΔE signal (Fig. 1a), and A/q resolution from the ToF signal (flight path 6.1 m, Fig. 1b).

The 2-5 groups into which each Z-hyperbola of Fig. 1a are broken-up indicate the presence of multiple charge states for each Z. Therefore, to unambiguously identify isotopic mass groups, the data are further reduced. Fig. 2 is a Z-identifier vs. A-identifier plot. The Z-identifier is formed from the product of ΔE $E_{\rm total}$, while the A-identifier is formed from a relativistic calculation of each ions' amu from its $E_{\rm total}$, ToF and the length of its flight path. Atomic-mass and atomic-number resolution of isotopes is now evident. No restrictive gates have been set on Z-bands or A/q groups, etc., as is often done in PF analysis to provide 'separation' and identification of isotopes. Hence no data are excluded, nor were q or A values rounded to nearest integers.

4 Production Rates

Fig. 3 shows binned (summed) data derived from the particle identifier of Fig. 2 for a few selected element groups, plotted on a log scale. The axis labeled 'yield' represents the counts of each isotope collected within the software gate set in the 2-D PSD spectra during the 3.3 h run. Taking into account that this gate passed 1/20 of the events, and that only 10.2% of the total available beam of the A1200 cyclotron was used, then a yield more than 200 times greater is available.

Table 1 shows rates (counts/h) predicted from the present results for producing some moderately n-rich RNBs. These rates show promise for conducting exotic-isotope experiments of the type described in the Introduction. The table also indicates, for each element shown in Fig 3, the most n-rich isotope produced here vs. the most n-rich yet reported in the literature [11]. Although the rates of the most n-rich isotopes produced here are very low (1-3 $\times$ 10^{-3} counts/s), these isotopes are close to the most n-rich isotopes which have yet been produced.

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5 Figure Captions

Fig. 1. (a) ΔE vs. E_{total}, and (b) ΔE vs. time-of-flight spectra, for focal plane limit $\Delta(B\rho)/B\rho \leq 1.5\%$. Resolution of q-states, atomic number and isotopic mass is evident.

Fig. 2. 2-D particle identification spectra with charge-state ambiguity removed. Data shown represents $23 \leq \text{amu} \leq 81$ and $12 \leq Z \leq 33$.

Fig. 3. Tallied (binned) yields of isotopes as indicated (log scale), as derived from data shown in Fig. 2 (resolved isotopes). Available yields are $200\times$ these values (see text Section 2 and Table 1 for details), with $0.7° \leq \theta_{\text{lab}} \leq 3.1°$ and $\Delta\phi_{\text{lab}} \approx 2\pi$.

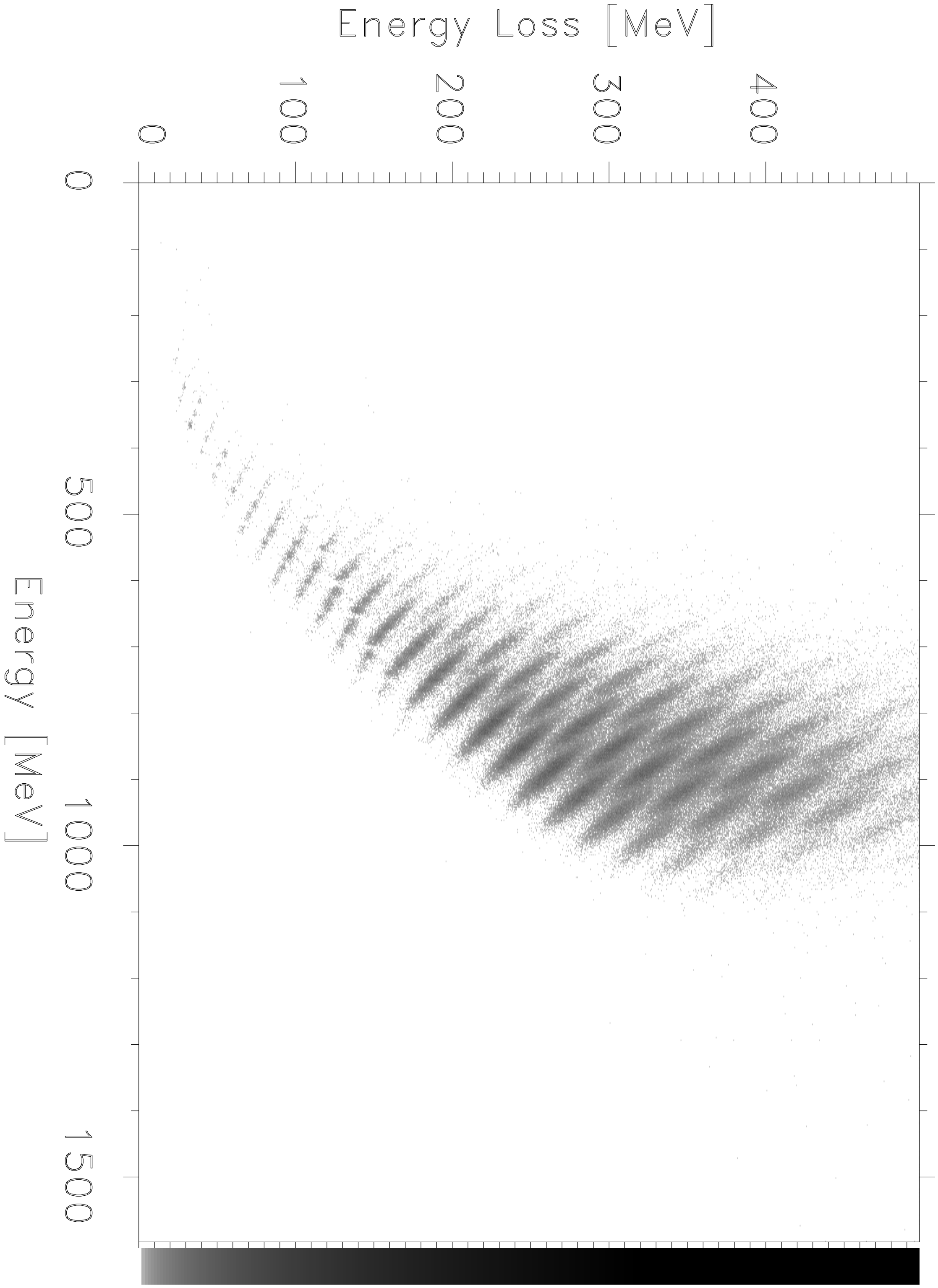

Fig. 1. (a) ΔE vs. E_{total}

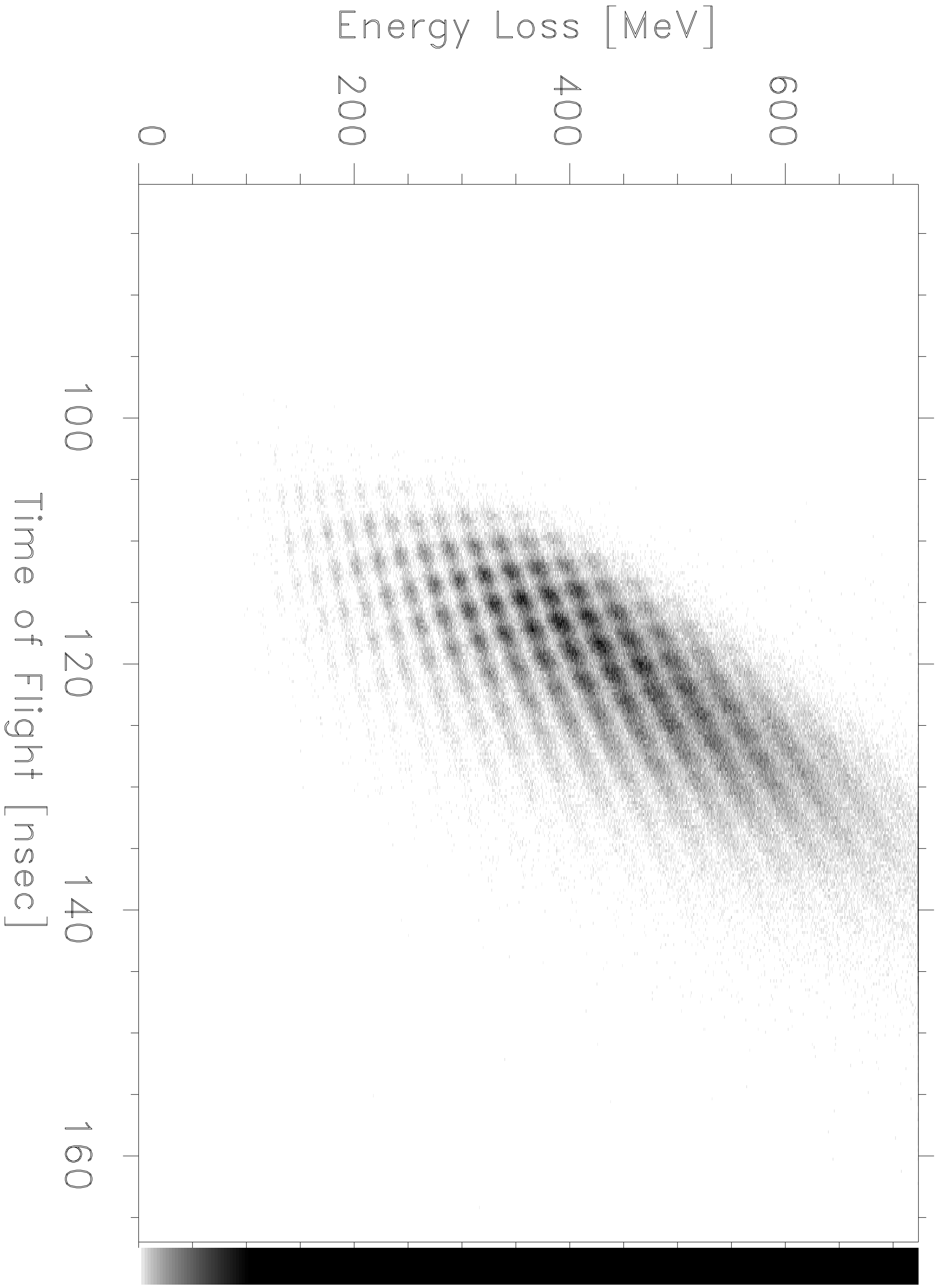

Fig. 1. (b) ΔE vs. time-of-flight spectra, for focal plane limit $\Delta(B\rho)/B\rho \leq 1.5\%$. Resolution of q-states, atomic number and isotopic mass is evident.

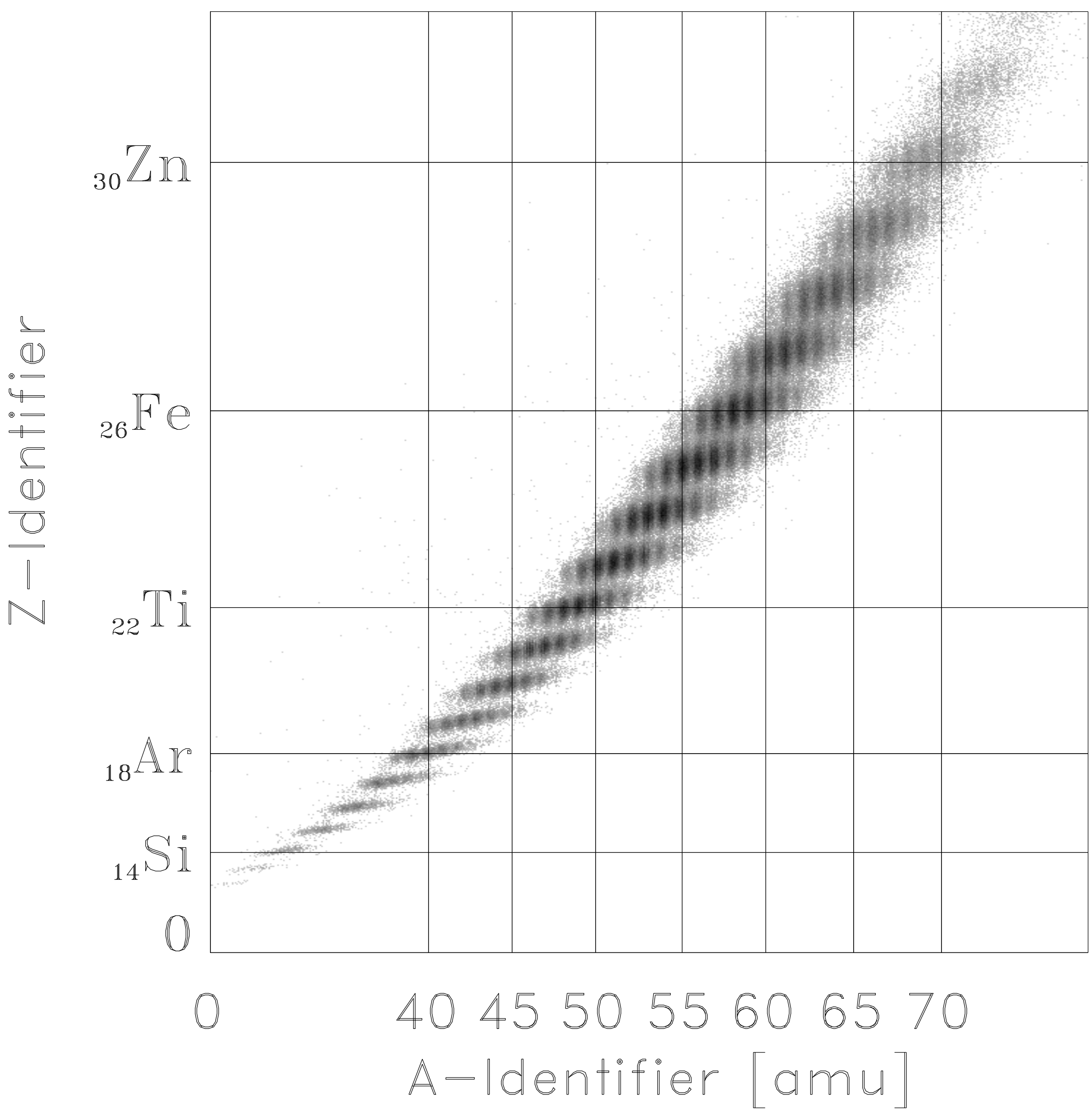

Fig. 2. 2-D particle identification spectra with charge-state ambiguity removed. Data shown represents $23 \leq \text{amu} \leq 81$ and $12 \leq Z \leq 33$.

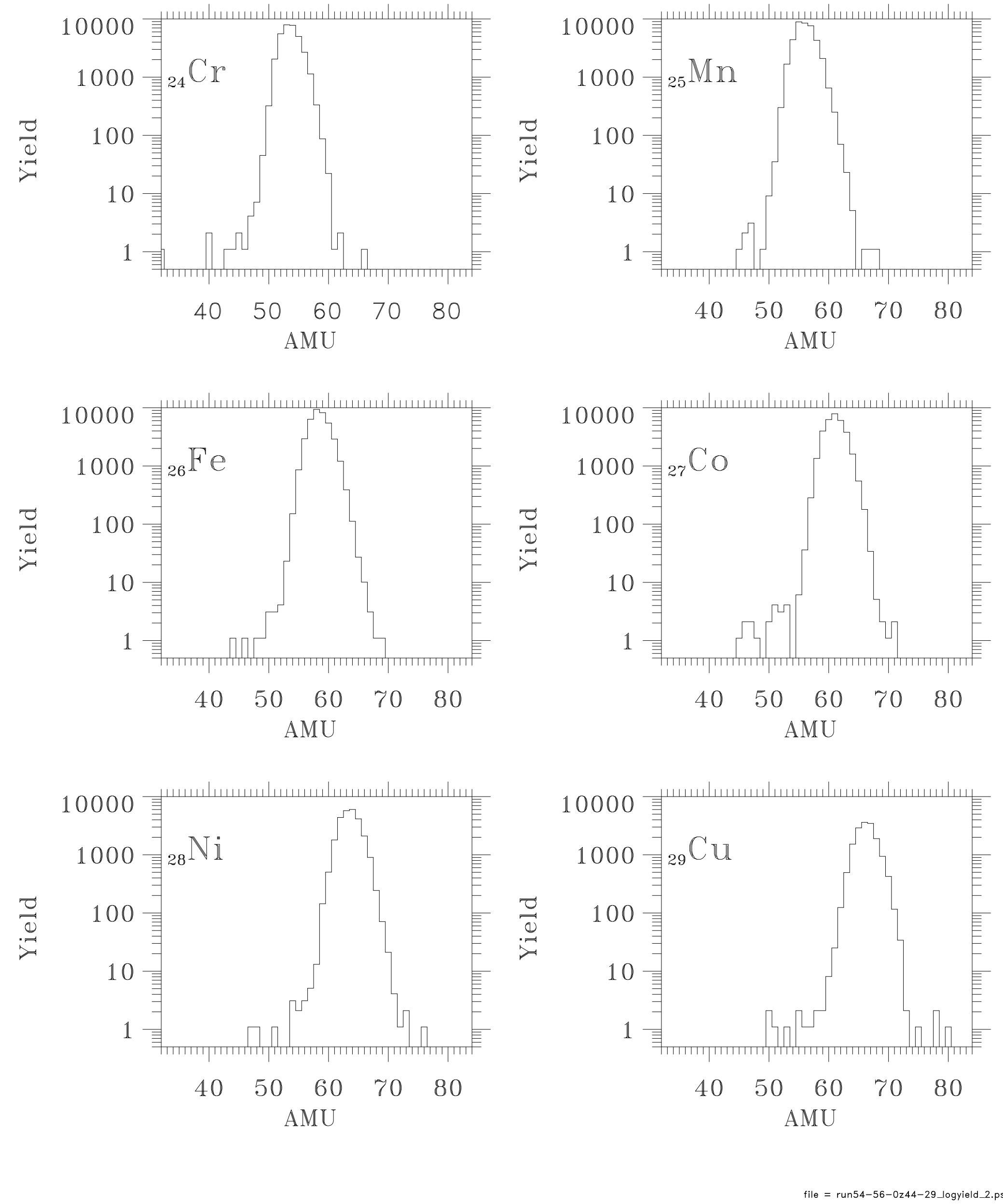

Fig. 3. Tallied (binned) yields of isotopes as indicated (log scale), as derived from data shown in Fig. 2 (resolved isotopes). Available yields are 200× these values (see text Section 2 and Table 1 for detail with $0.7° \le \theta_{\rm lab} \le 3.1°$ and $\Delta\phi_{\rm lab} \approx 2\pi$.

Table 1
Selected neutron-rich isotope yields

Element	BigSol Isotope	Counts/h[a]	Max-A BigSol[b]	Max-A Ref.[11]
Cr	60	$1.3e+02$	66	67
Mn	64	$3.0e+01$	68	69
Fe	66	$6.0e+01$	69	73
Co	68	$3.0e+01$	71	75
Ni	71	$2.4e+02$	76	78
Cu	72	$2.1e+03$	80	80

[a]Predicted rates based on particle-identified yields for 3.3 h run at 1.5% $\Delta(B\rho)/B\rho$ acceptance and scaled up for BigSol 'full-acceptance' mode by 20 $\times$ and 10 $\times$ for maximum beam intensity available at NSCL (see text).
[b]Note that only one or two counts of each maximum-A isotope(s) are seen in Fig. 3, thus statistical uncertainties for these isotopes are very large.