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CHARGE-STATE DISTRIBUTIONS OF 100, 175, 275, AND 352 MeV GOLD IONS EMERGING FROM THIN CARBON FOILS*

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Ion charge-state distributions were measured for 100, 175, 275 and 352 MeV gold ions emerging from thin carbon foils. The 90° double-focusing energy analyzing magnet of the Holifield Heavy Ion Research Facility 25 MV tandem accelerator was used to separate the charge-states. Carbon foil thicknesses of 10, 20, 40, and 80 $\mu g/cm^2$ were used depending on the beam energy. At least two different foil thicknesses were used at each energy to insure that equilibrium distributions were measured. The measured mean charge was compared with the predictions of the Sayer, Nikolaev-Dmitriev, and Shima et al. semi-empirical charge-distribution formulas. The measurements are in general agreement with the semi-empirical predictions at 100 MeV but were systematically lower at the higher energies. The largest discrepancy was -4.9 charge-states at 352 MeV. These results are especially significant for the design of booster accelerators for large tandem accelerators and for the design of coupled cyclotron systems.

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INTRODUCTION

These measurements were undertaken as a consequence of our failure early this year to accelerate Au^{+46} ions in the Oak Ridge Isochronous Cyclotron using an injected beam of 352 MeV $^{197}Au^{+17}$ from the 25 MV tandem accelerator. Following that unsuccessful test, we made a preliminary measurement of the charge-state distribution of 352 MeV ^{197}Au ions emerging from a carbon foil using the bending magnet that is a part of the cyclotron beam injection system. The measured mean charge was ~ 38.5, about 4.5 charge-states lower than predicted by the Sayer[1] semi-empirical formula. The measurements reported here were done more precisely and systematically confirm that preliminary result.

METHOD OF MEASUREMENT

Charge separation was accomplished using the 90°, 1.69 m-radius, double-focusing energy analyzing magnet which follows the tandem accelerator. The object slit settings were ± 2.5 mm in both the bending plane and normal to the bending plane. Image slit settings were ± 11.4 mm in the bending plane and ± 8.9 mm normal to the bending plane. The stripping foil was placed 5 cm downstream from the object slit. A beam profile monitor just before the image slit was used to assure that the beam could be accommodated by the image slits without appreciable loss. Current measurements were made using two Faraday cups, the first located just after the stripping foil and the second located beyond the image slit of the analyzing magnet. Current measurements were made with both cups for each point measured. Measurements were made at 100, 175, 275 and 352 MeV with various foil thicknesses to assure that at least one equilibrium charge distribution was measured. Foil thicknesses of 10, 20, 40, and 80 μg/cm^2 were used. The 20, 40, and 80 μg/cm^2 foils were commercial vapor-deposited foils. The 10 μg/cm^2 foils were prepared in our laboratory by the glow-discharge method; the thickness quoted is based on measurement of similarly prepared foils.

RESULTS

Table 1 summarizes the results of 12 separate measurements or runs. The charge transmission percentage is the ratio of the sum of the currents measured following the analyzing magnet image slit for the several charge-states divided by the current measured in the Faraday cup just downstream from the stripping foil. Ideally the charge-transmission ratio would be 100% but the measurements show values ranging from 132.5% at 352 MeV with a 20 μg/cm^2 foil down to 88.9% at 275 MeV with a 40 μg/cm^2 foil. This result is not understood but may result from incomplete suppression of electrons from the foil by the suppressor (1000 volts) of the cup located just beyond the stripping foil. This matter will be addressed in future measurements. Charge-distribution curves for a given energy, normalized to 100% transmission, are essentially identical for all of the thicker foils. This result suggests that the variation in transmission ratio is not significant and that equilibrium distributions were measured. In Table 1 the approximate total dispersion (base-width of peak) measured with the beam scanner is also listed. For all measurements, the dispersion is less than the 2.3 cm image slit width of the analyzing magnet. One centimeter of dispersion corresponds to a $\Delta E/E$ of approximately 3×10^{-3}. Charge distributions are shown for run No's. 1, 6, 10, and 11 in Figs. 1-4. The data plotted in these figures is given in Table 2.

In Figs. 1-4 the solid curves are approximate fits based on a skewed Gaussian distribution of the form used by Sayer[1]:

$$f_q = f_m e^{-0.5\ t^2/(1+\varepsilon t)}$$

where $t = \frac{q - q_0}{\sigma}$, q_0 is the maximum intensity charge value, σ is the width parameter and ε is the skewness parameter.

In Table 3 we show a comparison of widths, σ, skewness parameters, ε, and mean charges, $\overline{q}$, determined in the fits noted above with those predicted by the Sayer semi-empirical formula. It should be noted that the width and skewness parameters determined by fitting these data do not, in general, agree with the predictions of the Sayer semi-empirical formula.

The mean charge derived from these measurements is plotted in Fig. 5 and compared with the prediction of the Sayer, Nikolaev-Dmitriev,[2] and Shima et al.[3] semi-empirical charge-state prediction formulas. These data agree with the average of the three formulas at 100 MeV but deviate systematically at higher energies. As shown in Fig. 5, data measured at Brookhaven National Laboratory[4] at 235 MeV agrees with the trend of the present results. Thus, the present measurements, in conjunction with the Brookhaven result, show that the often-used semi-empirical heavy ion stripping formulas are inadequate for gold ions at energies greater than 100 MeV.

DISCUSSION

As shown in Table 4, we have compared these measurements for ^{197}Au and the measurements of other groups[4,5-11] for several heavy ions with the charge-state predictions of Sayer, Nikolaev-Dimetriev, and Shima et al. For ^{40}Ar, ^{63}Cu, and ^{84}Kr, the measurements and predictions of mean charge typically agree within 0.5 charge state whereas the measurements and predictions of mean charge for ^{132}Xe, ^{197}Au, ^{208}Pb, and ^{238}U show consistent discrepancies at the higher energies.

We have not attempted to develop a new semi-empirical formula to describe the present measurements and those noted above since we believe that additional measurements are probably needed before an adequate semi-empirical formula can be devised. In the meantime, we note that the currently used charge-state prediction formulas should be used with caution for ions with $Z > \sim 36$ and energies above ~ 1 MeV/amu.

ACKNOWLEDGEMENT

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References

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Figure Captions

Fig. 1. ^{197}Au charge-state distribution at 100 MeV (points). Solid curve is skewed-Gaussian fit.

Fig. 2. ^{197}Au charge-state distribution at 175 MeV (points). Solid curve is skewed-Gaussian fit.

Fig. 3. ^{197}Au charge-state distribution at 275 MeV (points). Solid curve is skewed-Gaussian fit.

Fig. 4. ^{197}Au charge-state distribution at 352 MeV (points). Solid curve is skewed-Gaussian fit.

Fig. 5. Comparison of mean-charge derived from these measurements with the prediction of Sayer, Nikolaev-Dmitriev, and Shima et al. semi-empirical formulas.

Table 1 - Summary of ^{197}Au Charge-State Distribution Measurements

Run No.	Energy (MeV)	Foil Thickness (μg/cm^2)	Charge Transmission (%)	$\bar{q}$	Dispersion (cm)
1	352	40	117.4	38.3	
2	352	40	110.2	38.3	1.5
3	352	80	105.6	38.2	1.8
4	352	20	132.5	37.8	
5	275	40	88.9	35.3	~2
6	275	40	109.9	35.3	1.5
7	275	20	112.8	35.6	1
8	175	20	97.1	31.9	1
9	175	10	97.2	31.4	1
10	175	20	95.5	31.8	
11	100	20	97.7	28.0	1
12	100	10	117.0	27.6	1

Table 2. Charge-state Distributions for ^{197}Au Ions

Ion Charge q	Ion Energy (MeV)			
	100	175	275	352
	Charge Fractions F_q (%)			
45				0.4
44				1.3
43			0.3	2.7
42			0.5	5.2
41			1.1	8.0
40			2.6	11.8
39			5.1	14.8
38		0.4	9.2	16.2
37		1.1	13.3	15.2
36		2.8	16.3	11.0
35		6.3	17.5	7.5
34	0.4	11.2	14.7	4.2
33	1.2	16.0	10.0	1.8
32	3.0	19.1	5.5	
31	7.0	17.7	2.6	
30	12.0	13.2	1.0	
29	18.0	7.6	0.2	
28	19.1	3.3		
27	16.4	1.2		
26	11.5			
25	6.5			
24	3.1			
23	1.3			
22	0.5			
21				

Table 3. Comparison of mean charge, distribution width, and distribution skewness from the Sayer formulas[1] with these measurements

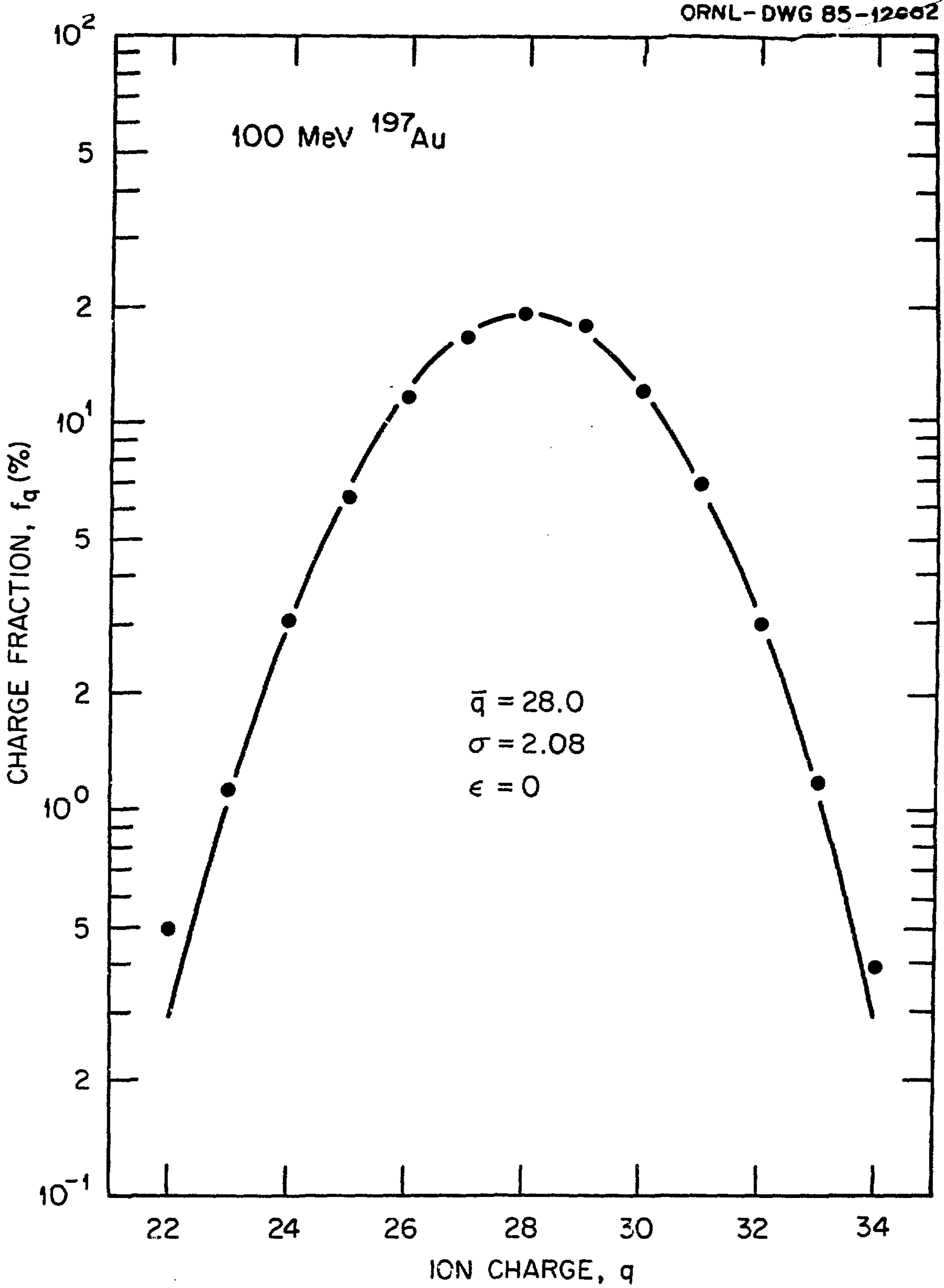
Ion Energy (MeV)	Sayer			These Measurements		
	$\bar{q}$	σ	ε	$\bar{q}$	σ	ε
100	28.8	2.34	0.08	28.0	2.08	0.0
175	34.9	2.38	0.06	31.8	2.08	0.052
275	40.3	2.39	0.04	35.3	2.30	0.074
352	43.2	2.39	0.03	38.2	2.48	0.070

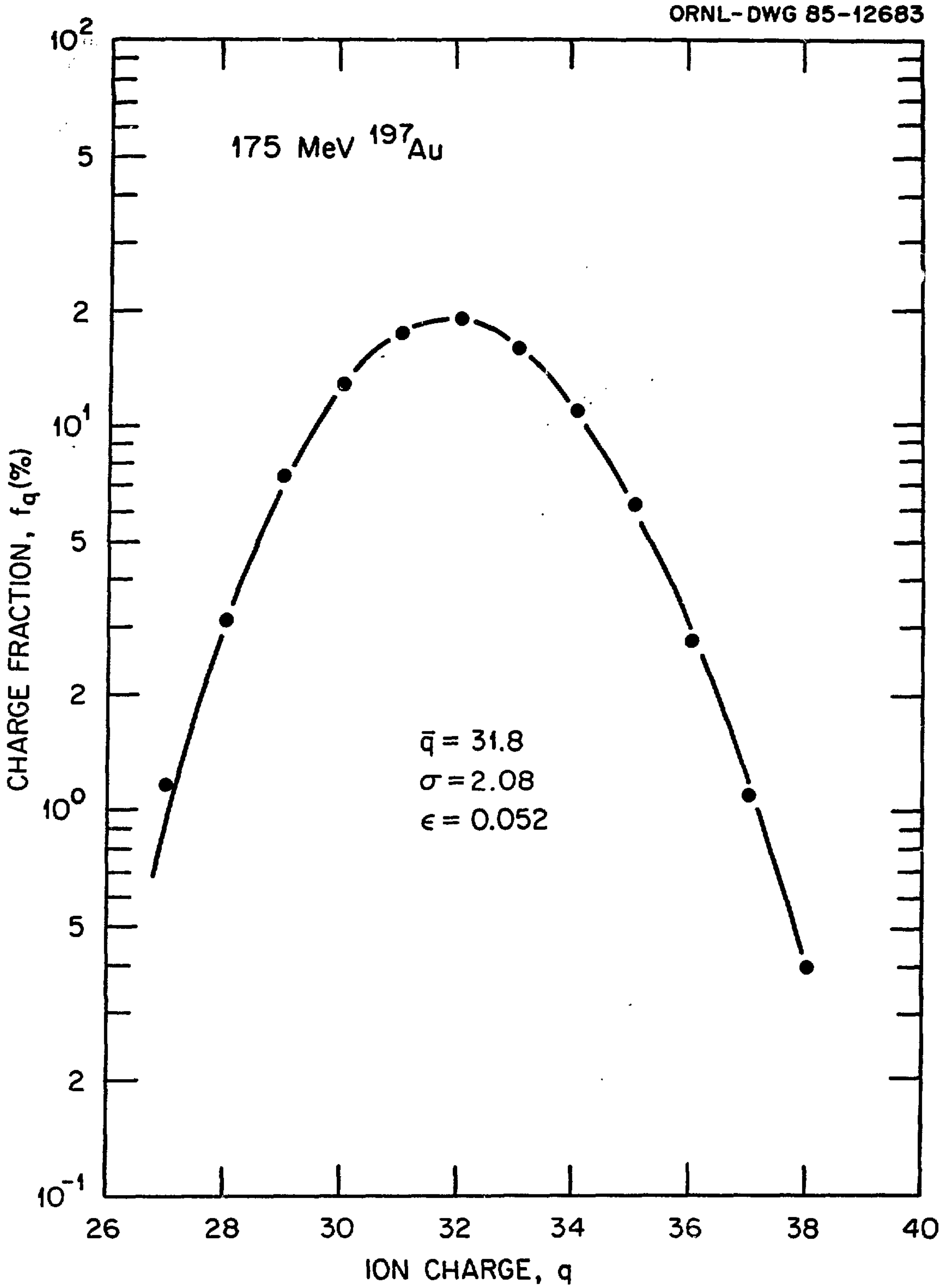
Table 4. Comparison of other measurements with charge-state formula predictions

Ion	Reference	Energy (MeV/amu)	Mean Charge					
			Measured Values	Predicted Values			Average of Predictions	Measured Minus Avg. Prediction
				Sayer	N-D	Shima, et al.		
$^{40}_{18}Ar$	5	1.04	11.9	12.0	12.3	12.0	12.1	- 0.2
		4.13	15.6	15.6	15.5	16.1	15.7	- 0.1
		7.00	16.6	16.5	16.3	17.4	16.7	- 0.1
		8.00	16.7	16.7	16.4	17.6	16.9	- 0.2
		9.00	17.0	16.9	16.6	17.7	17.1	- 0.1
		9.6	17.2	16.9	16.6	17.8	17.1	+ 0.1
$^{63}_{29}Cu$	6	0.56	15.1	14.6	14.6	14.5	14.6	+ 0.5
		0.96	17.7	17.1	17.3	17.0	17.1	+ 0.6
		1.52	19.8	19.2	19.6	19.2	19.3	+ 0.5
		1.84	20.6	20.1	20.4	20.1	20.1	+ 0.5
		2.32	21.7	21.1	21.4	21.2	21.2	+ 0.5
$^{84}_{36}Kr$	5	1.04	19.3	20.5	20.8	20.4	20.6	- 1.3
	7	1.39	21.8	22.2	22.5	22.1	22.3	- 0.5
	8	4.44	28.9	28.6	28.8	29.0	28.8	+ 0.1
	8	5.28	30.4	29.5	29.6	30.1	29.7	+ 0.7
	8	6.57	31.1	30.5	30.4	31.3	30.7	+ 0.4
$^{132}_{54}Xe$	7	1.39	29.5	30.5	30.5	30.0	30.3	+ 0.2
	9	3.6	37.0	38.4	39.0	38.4	38.6	- 1.6
$^{197}_{79}Au$	*	0.51	28.0	28.8	27.2	28.1	28.0	0
	*	0.89	31.8	34.9	34.0	34.2	34.4	- 2.6
	4	1.19	33.7	38.4	37.9	37.7	38.0	- 4.3
	*	1.40	35.3	40.3	40.0	39.6	40.0	- 4.7
	*	1.79	38.2	43.3	43.3	42.7	43.1	- 4.9
$^{208}_{82}Pb$	7	0.58	31.1	31.0	29.4	30.2	30.2	+ 0.9
	7	1.00	35.0	37.3	36.4	36.5	36.7	- 1.7
	7	1.39	37.8	41.3	41.0	40.6	41.0	- 3.2
$^{238}_{92}U$	7	1.39	40.9	45.0	43.3	44.1	44.1	- 3.2
	10	5.9	63.1	65.8	66.6	65.6	66.1	- 3.0
	11	16.3	77.9	78.5	78.4	80.9	79.3	- 1.4

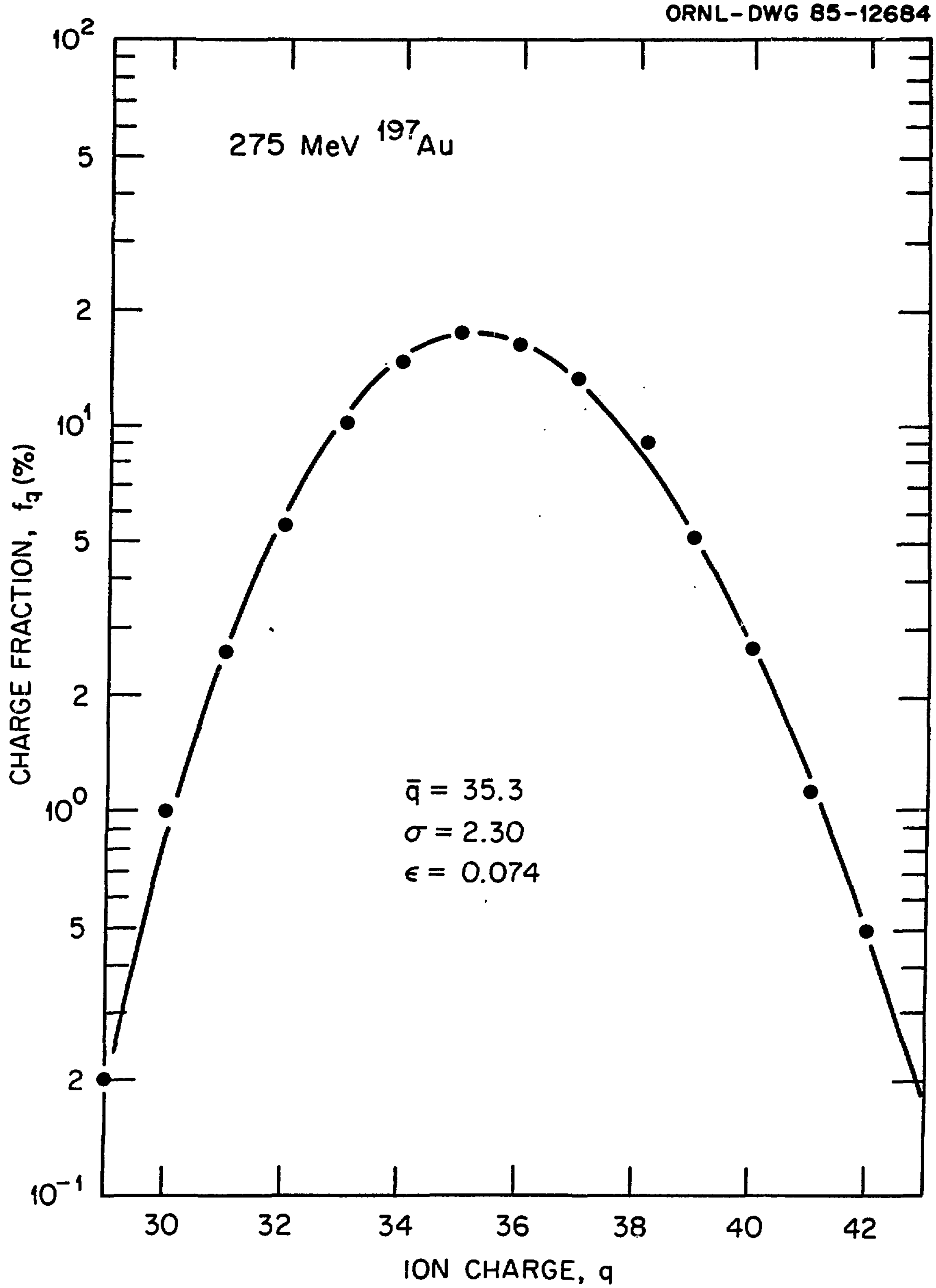
*These measurements.

ORNL-DWG 85-12602

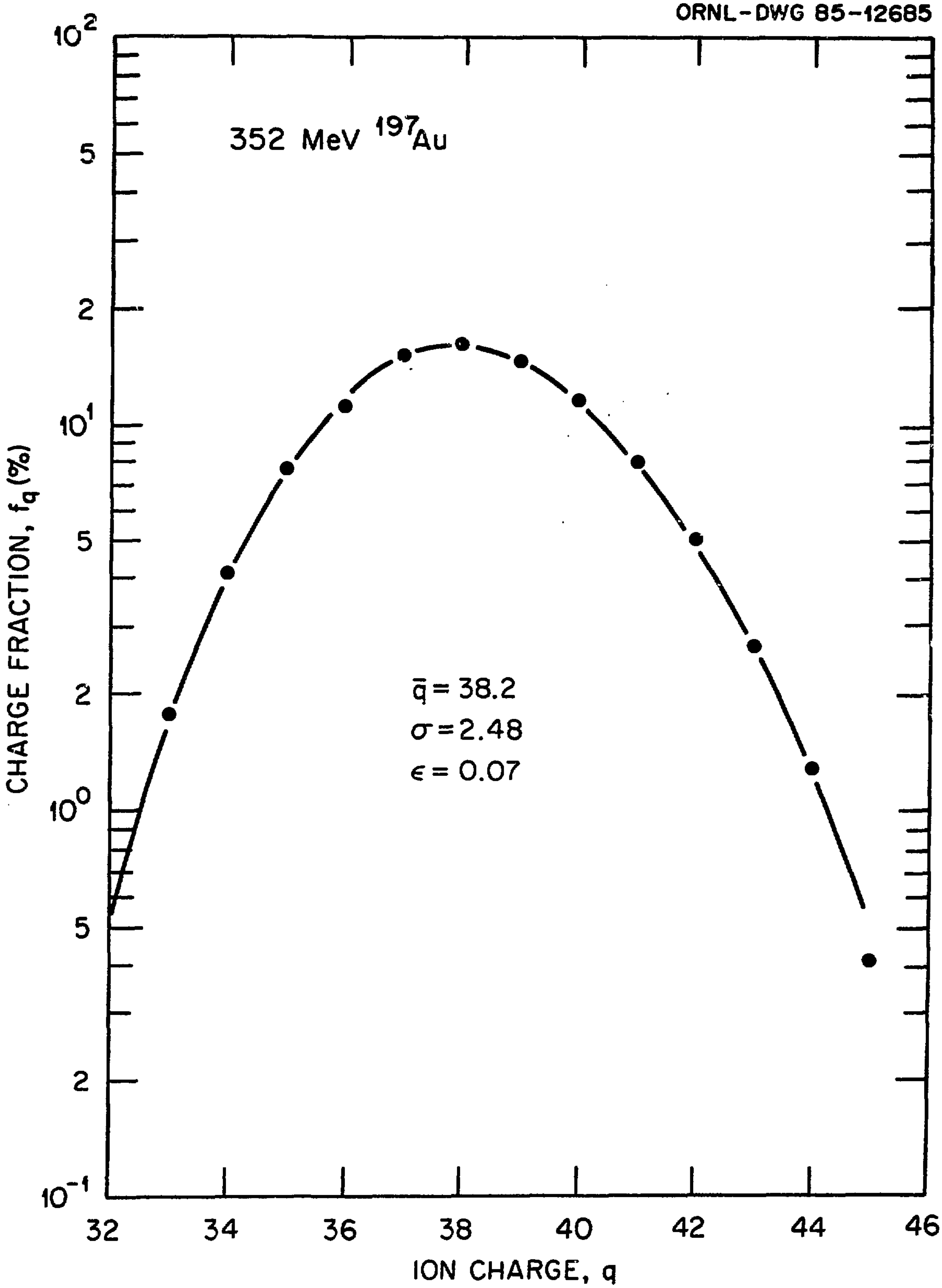


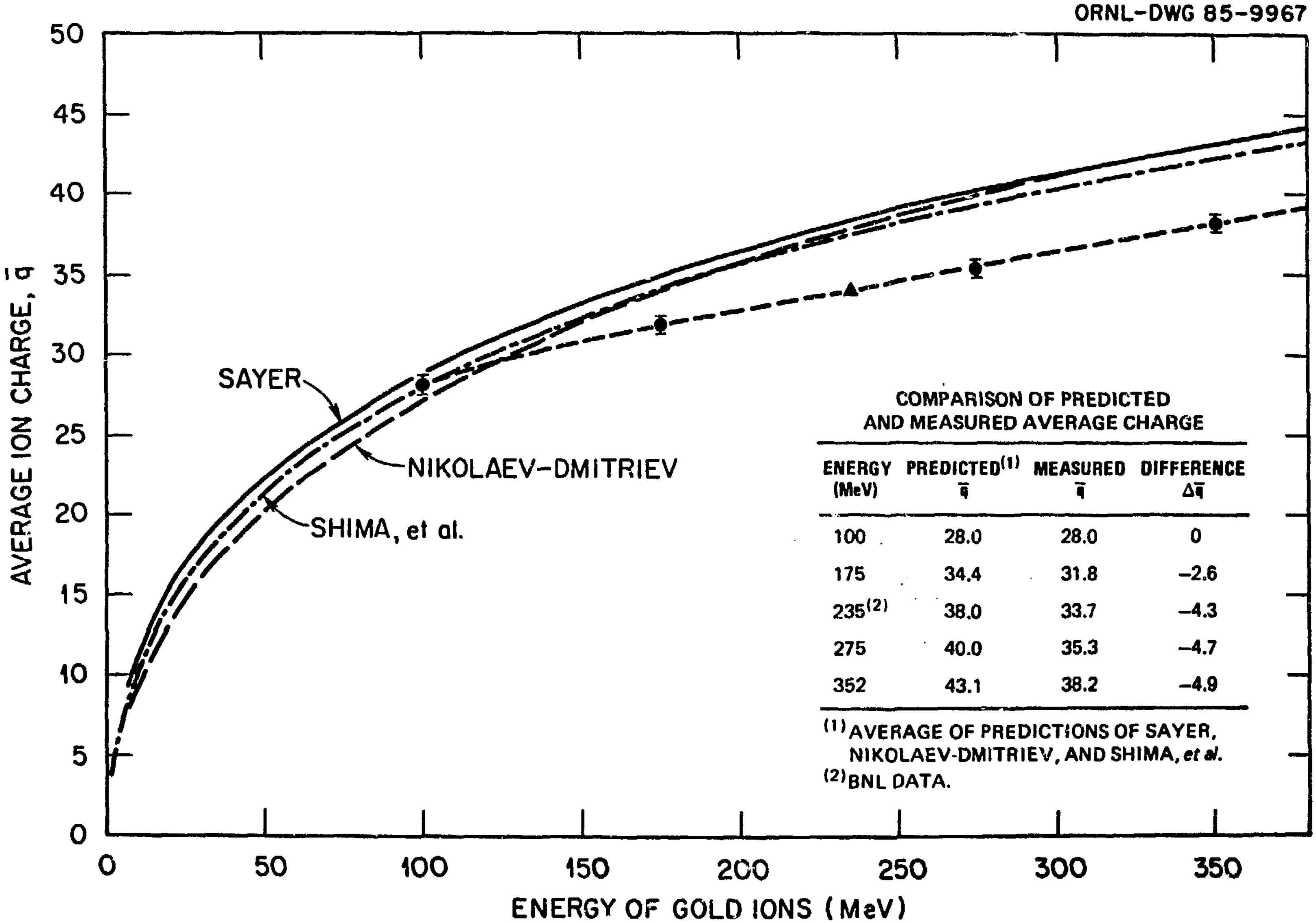


ORNL-DWG 85-12683
175 MeV 197Au
q̄ = 31.8
σ = 2.08
ε = 0.052
CHARGE FRACTION, fq(%)
ION CHARGE, q
10^2
5
2
10^1
5
2
10^0
5
2
10^-1
26
28
30
32
34
36
38
40


275 MeV ^{197}Au
$\bar{q}$ = 35.3
σ = 2.30
ϵ = 0.074
CHARGE FRACTION, f_q (%)
ION CHARGE, q
10^2
5
2
10^1
5
2
10^0
5
2
10^{-1}
30
32
34
36
38
40
42

ORNL-DWG 85-12685





COMPARISON OF PREDICTED AND MEASURED AVERAGE CHARGE

ENERGY (MeV)	PREDICTED[1] $\bar{q}$	MEASURED $\bar{q}$	DIFFERENCE $\Delta\bar{q}$
100	28.0	28.0	0
175	34.4	31.8	–2.6
235[2]	38.0	33.7	–4.3
275	40.0	35.3	–4.7
352	43.1	38.2	–4.9

(1) AVERAGE OF PREDICTIONS OF SAYER, NIKOLAEV-DMITRIEV, AND SHIMA, *et al.*
(2) BNL DATA.

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