MeV/uイオンの平衡前電荷分布と 理論断面積ベンチマークへの応用

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今井 誠, 左高正雄, 岡安 悟, 松田 誠, 川面 澄, 高廣克己, 小牧研一郎, 柴田裕実, 西尾勝久, V.P. Shevelko

京都大学原子核工学専攻, 筑波大学,日本原子力研究開発機構,理論放射線研究所, 京都工芸繊維大学,理化学研究所,大阪大学, P.N. Lebedev Physical Institute

東海·重イオン科学シンポジウム, 15-16 January 2020, Tokai.

Ouroboros

日本原子力研究所第一基礎研究部 1957.5.2 2MVバンデグラフ加速器組立完了試運転 1962.10.16 5.5MVバンデグラフ加速器完成 1983.8.24 5.5MVバンデグラフ加速器運転休止 2MVバンデグラフ加速器運転休止 2003

原子分子衝突データ評価

物理部核データセンター 原子分子衝突データの 収集・評価と生産

- 日本原子力研究所物理部 1982.6 タンデム加速器完成
- 定常運転開始 1982.9



物理部原子分子物理研究室 原子衝突の最新トピック研究



Experimental apparatus in Japan Atomic Energy Agency



Charge-state distributions of 2.0 MeV/u S^{*q*+} ions after C-foils



Mean charge-states and distribution widths of 2.0 MeV/u S^{q+} ions after C-foils



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Modeling

with single-electron capture and loss processes only



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Equilibrium and pre-equilibrium charge-state distributions of 2.0 MeV/u C ions after C-foils



Simulation codes

Matrix Method: Charge evolution of swift-heavy-ion beams explored by matrix method, O. Osmani, P. Sigmund, NIM B 269, 813 (2011).

ETACHA: a program for calculating charge states at GANIL energies, J.-P. Rozet, C. Stéphan, D. Vernhet, NIM B 107, 67 (1996).

ETACHA new versions: Extention of charge state distribution calculations for ion-solid collisions towards low velocities and many-electron ions,
E. Lamour, P. D. Fainstein, M. Galassi, C. Prigent, C. A. Ramirez,
R. D. Rivarola, J.-P. Rozet, M. Trassinelli, D. Vernhet, PRA 92, 042703 (2015).

BREIT: Balance Rate Equations for Ion Transport,N. Winckler, A. Rybalchenko, V. P. Shevelko, M. Al-Turany, T. Kollegger,Th. Stöhlker, NIM B 392, 67 (2017).









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ETACHA codes (1996, 2015)

ETACHA: a program for calculating charge states at GANIL energies, J. P. Rozet, C. Stéphan, D. Vernhet, NIM B 107, 67 (1996).

ETACHA23, ETACHA3, ETACHA34, ETACHA4, ETACHA45: Extention of charge state distribution calculations for ion-solid collisions towards low velocities and many-electron ions,
 E. Lamour, P. D. Fainstein, M. Galassi, C. Prigent, C. A. Ramirez,
 R. D. Rivarola, J. P. Rozet, M. Trassinelli, D. Vernhet, PRA 92, 042703 (2015).

Sub-shell (1s, 2s, 2p, 3s, 3p, 3d) oriented rate equations. Capable of treating max. 28 electrons.

-> Max. 60 electrons up to *n*=4 shell.

Processes taken into account:

Electron Capture (NRC Eikonal + REC Bethe-Salpeter for bare ions) Electron Loss (PWBA for H-like ions) -> CDW-EIS Excitations (PWBA) -> Symmetric Eikonal De-excitations (Radiative + Auger)

Valid energy range: 10 – 80 MeV/u

-> down to 0.1 MeV/u





	Case		Cross Se	ections		References		Accuracy
	(1)-(3) BREIT		e-cap. e-loss ex.	OBK relativistic Born relativistic Born		JPB37,201(2004) JETP119,1(2014) NIMB184,295(2001)		50% 30-50% 30-50%
	(4)		e-cap. e-loss ex.	relativis CDW-E symmet	tic Eikonal IS tric Eikonal	PRA32,3291(1985) PMB58,673(2013) PRA52 4972(1995)		Scaling used
С	Case Calculation		Yields Y _i	Density Effect				
(1)			Charge-State		Not involved.		
(2	(2) BRE		EIT MB 392 67 (2017)		$7(C^0 - C^{6+})$		High <i>n</i> states are ionized. JPB38, 2675 (2005)	
(3	3)			CS + n = 1,2-states 18($C^0 - C^{6+}$)		High <i>n</i> states are ionized.		
(4) ETACHA4 PRA92, 042703 (2015)			CS + n/-substate many($C^0 - C^{6+}$)		Shorter collision intervals are involved in the RE.		
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Model calculations using sets of cross sections for charge-state distributions of 2.0 MeV/u C ions after C-foils



Scores for reproducibility of the **equilibrium** charge-state distributions of 2.0 MeV/u C ions after C-foils



Case	Model	Cross Sections	Score1	Score2
(1)	Simple	Better	1602	12.7
(2)	Simple	Better	699	12.7
(3)	Intermediate	Better	138	4.8
(4)	Full	General	776	13.2





Shifted model calculations using sets of cross sections for charge-state distributions of 2.0 MeV/u C ions after C-foils





Shifted model calculations using sets of cross sections for charge-state distributions of 2.0 MeV/u C ions after C-foils



Scores for reproducibility of the **pre-equilibrium charge-state distributions** of 2.0 MeV/u C ions after C-foils

$$Score = \sqrt{\frac{\sum_{i} (y_{i}^{pre-eq,cal} - y_{i}^{pre-eq,exp})^{2}}{N}}$$

N = 97

Case	Model	Cross Sections	Score	Score1	Score2
(1)	Simple	Better	0.0570	1602	12.7
(2)	Simple	Better	0.0792	699	12.7
(3)	Intermediate	Better	0.0282	138	4.8
(4)	Full	General	0.0747	776	13.2



Summary and outlook

- Equilibrium and pre-equilibrium charge-state distributions after C-foil penetration have been measured for 2.0 MeV/u C and S ions as well as 1.0 MeV/u C and W ions.
- Different collision rates for K- and L-shell electrons gave rise to the *quasi*-equilibrium, which can be regarded as an equilibrium in L-shell processes, for C and S ions.
- Applications require not just accuracy of calculated cross sections but also their completeness.
- Experimentalists would like the evaluation of theoretical data to be done with experiments, but in many cases, there exist few experiments directly comparable to theories.
- It would be possible to evaluate set of calculated cross sections (e-capture, loss, excitation, de-excitation) using charge-state evolution data.

