17th Russbach School on Nuclear Astrophysics

## Cross section measurement of the <sup>92,94</sup>Mo(a,n) and <sup>92</sup>Mo(a,p) reactions by γ-spectroscopy

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Ν

		°"Cd	° <sup>si</sup> Cd <sub>8+</sub>	°€Cd ₽+	°7Cd	°ªCd ₽+	°°Cd ®*	10ºCd B+	<sup>101</sup> Cd <sub>B+</sub>	102Cd	<sup>103</sup> Cd <sup>8+</sup>	¹º℃d ₽+	¹º⁵Cd ₽+	106Cd 28+	<sup>107</sup> Cd 8+	<sup>108</sup> Cd 28+	<sup>109</sup> Cd e-cepture	110Cd Stable	11°Cd Stable	112Cd Stable	<sup>™</sup> Cd ₽	111°C 20
	°²Ag <sub>₿+</sub>	°³Ag	°*Ag	⁰⁵Ag ₽+	⁰éAg 8+	<sup>97</sup> Ag β+	SSAC	) <del>~</del> [î		<u>l</u> e	1º2Ag	<sup>103</sup> Ag 8+	104Ag 8+	105Ag	<sup>106</sup> Ад в+	<sup>107</sup> Ag	<sup>108</sup> Ag	109Ag Stable	<sup>110</sup> Ag ₽	<sup>111</sup> Ag ₽	<sup>112</sup> Ag ₽	<sup>113</sup> Д ө-
⁰Pd ₽+	<sup>91</sup> Pd	°²Pd ®+	°³Pd ®+	°"Pd	<sup>98</sup> Pd 8+	<sup>96</sup> Pd ₅+	°7Pd	⁰ªPd ₅+	<sup>99</sup> Pd s+	<sup>100</sup> Pd e-capture	<sup>101</sup> Pd 8+	<sup>102</sup> Pd 28+	<sup>103</sup> Pd e-capture	<sup>10</sup> *Pd Stable	105Pd Stable	<sup>106</sup> Pd stabie	107Pd	<sup>108</sup> Pd Stable	¹º⁰₽d ₽	110Pd 28-	<sup>™</sup> Pd ₽	112P 8-
°Rh ₽Ŧ	°°Rh ®†	<sup>91</sup> Rh ₽+	°2Rh 8+	°³Rh ®+	°"Rh ₽+	°⁵Rh ₅+	° <sup>s</sup> Rh ₽+	<sup>97</sup> Rh	<sup>sa</sup> Rh ₅+	"Rh	100Rh 8+	<sup>101</sup> Rh e- capture	¹º²Rh ⊮	105Rh Stable	¹⁰"Rh ₽	¹º⁵Rh ₽	¹º⁵Rh ₽-	107Rh	¹ºªRh ₽	¹⁰⁰Rh ₽	<sup>110</sup> Rh ₽	111 8-
®Ru ₽+	<sup>ss</sup> Ru ₅+	<sup>∞</sup> Ru ₅+	⁰'Ru ₽+	92Ru 8+	<sup>93</sup> Ru 8+	°4Ru ₽+	PIRU B+	96RU 28+	97RU 8+	<sup>68</sup> RU Stable	<sup>20</sup> Ru Stable	<sup>100</sup> RU Stable	<sup>101</sup> RU Stable	<sup>102</sup> Ru Stable	103Ru 8-	<sup>104</sup> Ru 29-	¹ºªRu ⊮	¹ºªRu ₽	¹ºĩRu ₽	<sup>108</sup> Ru ₽	¹º⁰Ru ₽	119 8-
"Tc ₽+	B+	<sup>во</sup> Тс <sub>в+</sub>	<sup>90</sup> Тс 8+	91TC 8+	<sup>92</sup> Тс <sub>8+</sub>	°²Tc Bt	<sup>94</sup> Тс <sub>вт</sub>	°ªTC Bt	<sup>98</sup> Тс <sub>в+</sub>	°7TC er capture	°°TC °°	°°Tc ₽	<sup>100</sup> Тс в	<sup>101</sup> Тс в	<sup>102</sup> TC P	<sup>109</sup> ТС в-	<sup>104</sup> Тс в-	<sup>109</sup> ТС в-	<sup>108</sup> TC ₽	<sup>107</sup> Тс э	°°TC ₽	109 8-
Mo ₽+	<sup>87</sup> Мо <sub>81</sub>	88 84 84	89M0 8+	°°Mo ®+	91MC 8+	92MO 28+	<sup>93</sup> M¢ + captu	94MO Stable	<sup>95</sup> MO Stable	<sup>96</sup> MO Stable	97MO Stable	<sup>98</sup> MO 20 <sup>5</sup>	°Mo ®	<sup>100</sup> MO 28⁺	<sup>101</sup> MO ₽	<sup>102</sup> Мо в-	<sup>103</sup> MO 8-	<sup>104</sup> Мо в-	<sup>109</sup> MO ₽	<sup>106</sup> Мо в-	<sup>107</sup> Мо в	108 8-
Nb ₽+	<sup>86</sup> Nb ₽+	<sup>₽7</sup> Nb <sup>β+</sup>	<sup>88</sup> Nb 8+	<sup>89</sup> Nb 8+	<sup>so</sup> Nb <sup>s+</sup>	er capture	<sup>92</sup> Nb ₿+	<sup>22</sup> ND Stable	°Nb °	⁰ªNb ₽	°ªNb ₽	°'Nb °	°ªNb ₽	°⁰Nb ₽	109Nb	<sup>103</sup> Nb ₽	102Nb 8-	103Nb 8-	⁰"Nb ₽	<sup>109</sup> Nb	¹º⁰Nb ₽	107 0-
<sup>₽</sup> Zr	<sup>89</sup> Zr	<sup>86</sup> Zr ₽+	<sup>87</sup> Zr ₿+	<sup>88</sup> Zr e- capture	<sup>®</sup> Zr ₽+	<sup>90</sup> Zr Stable	<sup>91</sup> Zr Stable	92Zr Stable	٥ºZr	94Zr 28-	°ªZr º-	°€Zr ₂⊳	°Zr ®	۶ºZr	°°Zr	100Zr 8-	<sup>101</sup> Zr 8-	102Zr	¹ººZr ₽	™Zr ₽	¹oªZr ₽	10eZ 8-
ε9γ 87	84¥ 8+	89Y 8+	<sup>ве</sup> ү <sup>в+</sup>	εγ 8+	88¥ 8+	89 <b>Y</b> Stable	90¥ 9	۹۲ ه	°2Y p	90 р-	°4Y 0-	vəY p-	96Ү 0-	۳Y	98Y 9	°°ү в-	100 <b>Y</b> 8-	101¥ 8-	102¥ 8-	103¥ 8-	10 <b>°Y</b> 8*	108 8-
<sup>12</sup> Sr capture	<sup>83</sup> Sr 87	84Sr 28+	85Sr e-capture	857 3804	SING ST	<sup>83</sup> Sr Stable	<sup>89</sup> Sr	°Sr P	°'Sr ®	°2Sr P	°3Sr °-	°"Sr ®	°⁵Sr ₽	⁰*Sr ₽	⁰"Sr ₽	°⁰Sr ₽	°°Sr ®	100Sr 81	<sup>101</sup> Sr e	102Sr 8-	103Sr P	104 <u>0</u> 8-
°Rb ₽+	<sup>≈2</sup> Rb ₽+	<sup>83</sup> Rb e- capture	<sup>84</sup> Rb ₽+	<sup>89</sup> Rb 5864	≌Rb ₽	®Rb ₽	≌Rb ₽	*Rb	<sup>≈</sup> Rb ₽	°¹Rb ₽	≌Rb ₽	°ªRb	°"Rb	₽₽Rb	°*Rb P	°'Rb	<sup>∞</sup> Rb ₽	°°Rb ₽	100Rb	<sup>101</sup> Rb ₽	102Rb	103 <mark>R</mark> 8-
°Kr	<sup>81</sup> Kr e-capture	<sup>82</sup> Kr 514544	<sup>83</sup> Kr 5466	<sup>84</sup> Kr 5404	<sup>ss</sup> Kr ₽	<sup>86</sup> Kr 28-	®Kr ₽	≊Kr ₽	<sup>so</sup> Kr	°°Kr °	°'Kr °	°²Kr ₽	°°Kr ¢	°"Kr	° <sup>s</sup> Kr °	°⁴Kr ₽	°″Kr ₽	°⁰Kr ₽	°°Kr ₽	109Kr P	<sup>101</sup> Kr	

The p-nuclei mainly synthetized via photodisintegration. However, the rp- and  $\nu$ p-process can give a contribution to their abundance.

 $\gamma$ -process

#### Reaction network calculations

>10 000 reaction on ~ 1 000 (mostly radioactive) nuclei



#### Motivation

 $^{92,94}$ Mo are the most abundant p-isotopes  $\rightarrow$  experimental knowledge on  $^{92,94}$ Mo involved reactions is important



### Thick target yield measurement

Radioactive product  $\rightarrow$  Activation technique  $\rightarrow$  Irradiation and counting separately

$$N_{det}(E) = \sigma(E) \cdot \Phi \cdot N_{targ} \cdot \epsilon \cdot I \cdot \frac{\left(1 - e^{-\lambda \cdot t_i}\right)}{\lambda} \cdot e^{-\lambda \cdot t_w} \cdot \left(1 - e^{-\lambda \cdot t_c}\right)$$

- 0.5 mm thick, natural isotopic composition molybdenum targets.
- The  $\alpha$ -beam stops in the target material.
- Reactions takes place with all energies between the initial and threshold energy.
- The cross section can be determined by subtraction:

$$\sigma(E_{eff}) = \frac{[Y_{TT}(E_2) - Y_{TT}(E_1)] \cdot \overline{\epsilon_{eff}}(E_1; E_2)}{E_2 - E_1}$$

Reaction properties								
Target	92	Мо	<sup>94</sup> Mo	<sup>100</sup> Mo				
bundance	14.5:	±0.3%	9.2±0.9%	9.8±0.3%				
Reaction	<sup>92</sup> Mo(α,n)	<sup>92</sup> Mo(α,p)	<sup>94</sup> Mo(α,η)	<sup>100</sup> Mo(α, Α [Sze21]				
Product	<sup>95</sup> Ru	<sup>95</sup> Tc	<sup>97</sup> R	103 RL				
T <sub>1/2</sub>	1.6033±0.0044 h [Sze20]	19.258±0.026 h [Sze20]	2.84+201 d	39.242-9.013d				
Gammas		E <sub>v</sub> [keV] (I <sub>v</sub>	%])	S				
	336.4 (69.9±0.5)	765.8 (93.8±0.3)	2157 (85.6±1.3)	497.1(91.0±1.2)				
	626.8 (17.8±0.5)	947.7 (1.95±0.02)	324.5 (10.79±0.17)	610.3(5.76±0.06)				
	1096.8 (20.9±1)	1073.7 (3.74±0.4)						

[Sze20] T.N. Szegedi et al., Eur. Phys. J. A 56, [Sze21] T.N. Szegedi et al., Phys. Rev. C, 104, 182 (2020).

#### Irradiation

- $\alpha$ -beam was provided by the cyclotron accelerator of Atomki between 9.5 13 MeV energy range
- Length of irradiation varied between 30 min and 12.5 hours
- Current measurement
  - Faraday-cup  $\rightarrow$  Determination of the number of incident  $\alpha\text{-particles}$
  - Multichannel analyzer
  - Secondary electron suppression voltage U = 300 V
  - Water cooling
  - Typical beam current: 0.3 2  $\mu A$





#### γ-counting setup

- Cross section measurement is based on measuring the yield of  $\gamma$ -radiation following the  $\beta$ -decay of the radioactive isotopes  $\rightarrow$  HPGe detectors
- Absolute detection efficiency was measured by calibration  $\gamma$  sources (60Co,  $^{133}Ba,\,^{137}Cs,\,^{152}Eu)$



Parameters	Detector						
	DET1	DET2					
Relative efficiency*	50 %	100 %					
Shielding	Pb (50 mm)	Cu-Cd-Pb (1-1-100 mm)					
Far counting geometry	21 cm	27 cm					
Close counting geometry	$5~{ m cm}$	1 cm					

\* Absolute efficiency of a 3" diameter, 3" high cylindrical NaI detector.



#### Data analysis



2. Peak area

3. Thick target yield  $(Y_{TT}(E))$ 

4. Cross section





#### Preliminary results 10<sup>3</sup> <sup>92</sup>Mo(α,n)<sup>95</sup>Ru $10^{2}$ Cross Section [mbarn] 10 Rapp et al. [Rap08] McFadden Esterlund et al. [Est65] Demetriou I 10<sup>0</sup> Graf et al. [Gra74] Demetriou III Denzler et al. [Den95] Avrigeanu Levkovski et al. [Lev91] Atomki-V1 Present work Non Smoker 10<sup>-1</sup> 9.5 10.0 10.5 9.0 12.0 12.5 11.0 11.5 13.0

E<sub>eff.</sub> [MeV]

### $^{92}$ Mo( $\alpha$ ,p) $^{95}$ Tc method

- ${}^{92}Mo(\alpha,n)$  and  ${}^{92}Mo(\alpha,p)$  channels are open
- $\sigma(\alpha,n) \approx 10 \cdot \sigma(\alpha,p)$ , but different half-lives
- By applying the Bateman equation the counts corresponding to the (a,n) channel can be subtracted from the measured yield

Data Analysis Is In Progress!







Nemzeti Kutatási, Fejlesztési És Innovációs Hivatal

# Thank you for your attention!

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