Radiation Properties of Ions and Exotic Nuclei at Relativistic Energies

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- Theoretical method
- Main results
- Summary

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Introduction

TABLE I: Nuclear effects in atomic transitions

Nuclear property	Effect on atomic structure
Charge $+Ze$	Binding energy
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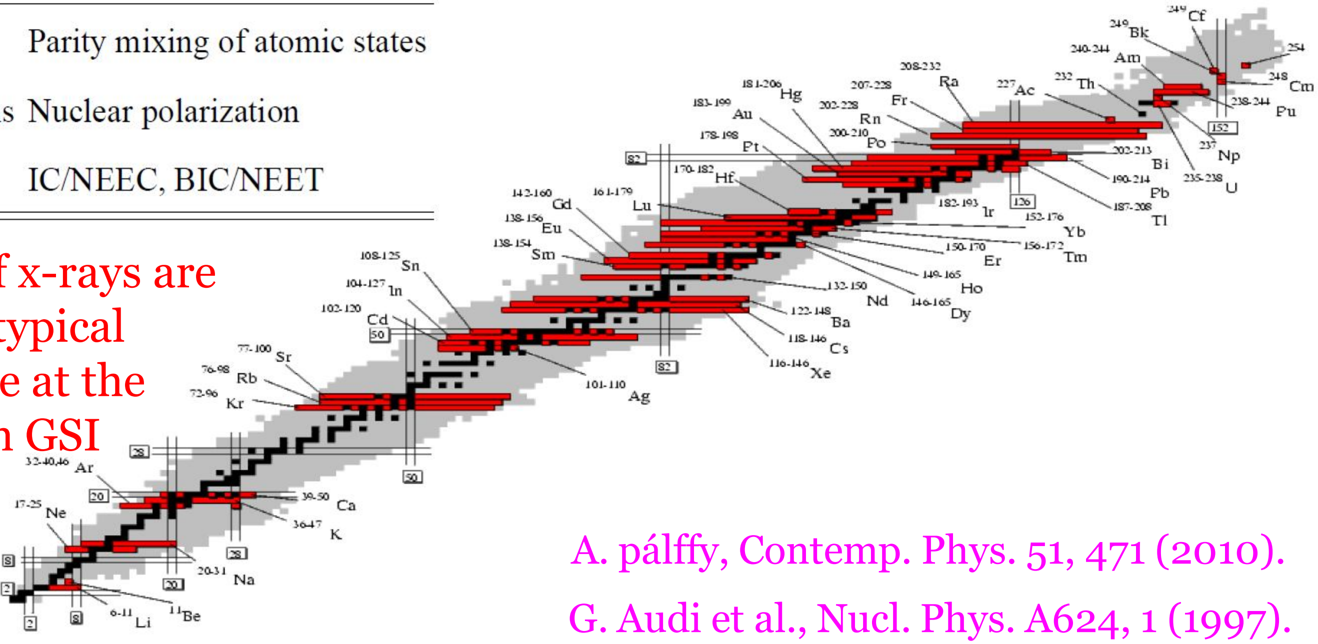
The nuclear effects in atomic structures and transitions have been studied for many years.

These effects on atomic structures and transitions are not very large. Compared to total decay rates, the angle-resolved properties are much more sensitive.

The angular distributions of x-rays are extensively studied. A very typical measurement has been done at the experimental storage ring in GSI following the REC of HCIs.



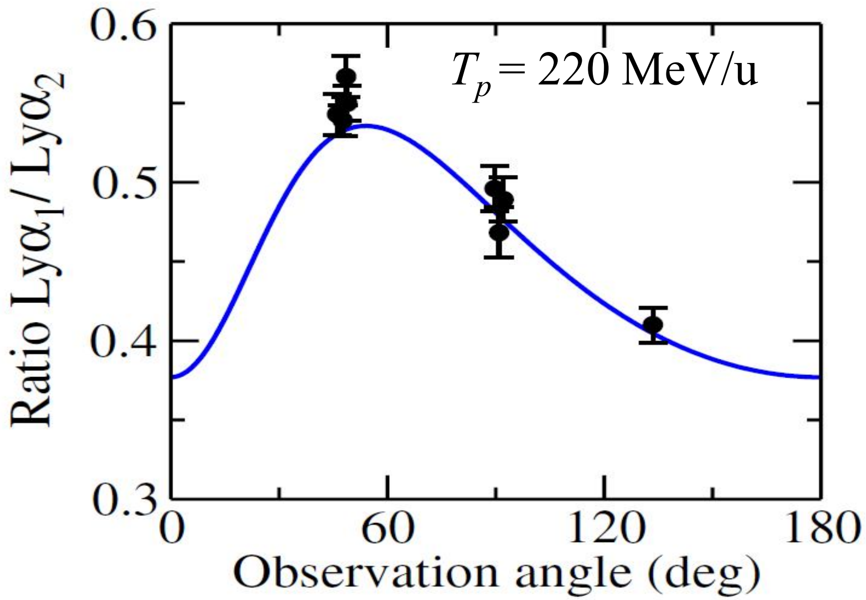
A. pálffy, Contemp. Phys. 51, 471 (2010).

G. Audi et al., Nucl. Phys. A624, 1 (1997).

Fig.2.1.1: Chart of nuclei showing the isotopes for which optical spectroscopy has been performed in long isotopic chains or on nuclei far from stability.

Angular distributions of the Ly-α$_1$ and *K*α$_1$ emissions

$$\begin{aligned} U^{92+} + e^- &\longrightarrow U^{91+}\ (2p_{3/2}) \\ &\longrightarrow U^{91+}\ (1s_{1/2}) + \mathrm{Ly}\alpha_1 \end{aligned}$$



➢ A strong anisotropic angular distribution.

Th. Stöhlker *et al.*, ***Phys. Rev. Lett.* 79**, 3270 (1997);

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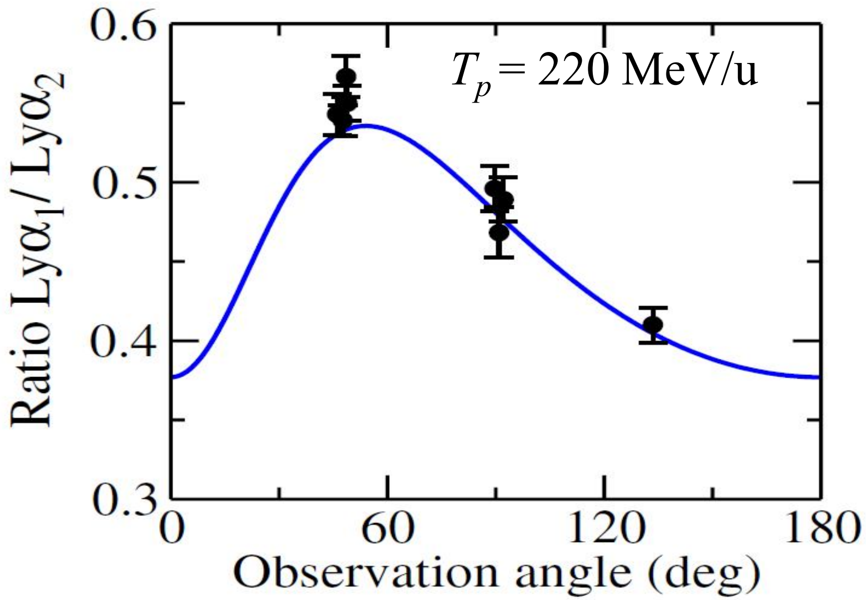

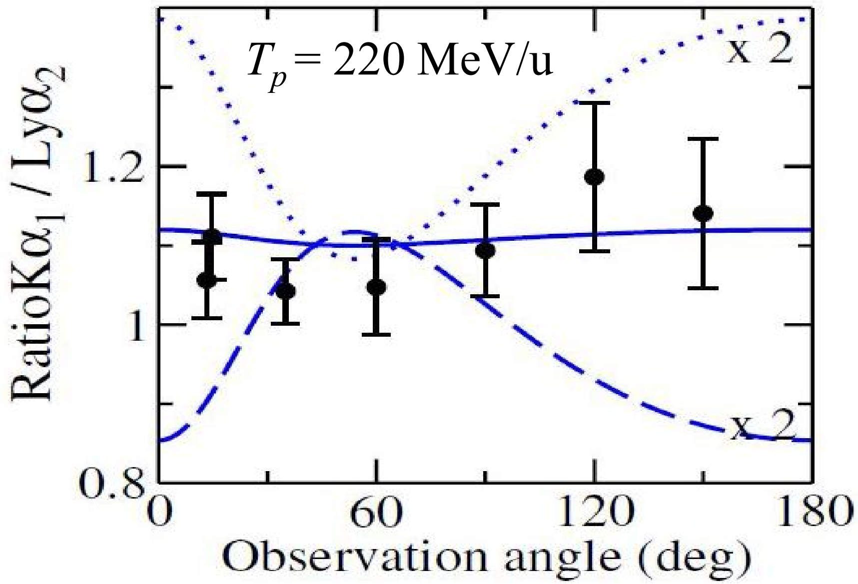

$$\mathrm{U}^{91+}\ (1s) + e^- \longrightarrow \mathrm{U}^{90+}\ (1s2p_{3/2}\ {}^{1,3}P_{1,2}) \longrightarrow \mathrm{U}^{90+}\ (1s^2\ {}^1S_0) + K\alpha_1$$

- A strong anisotropic angular distribution.
- The $K\alpha_1$ emission is almost isotropic.

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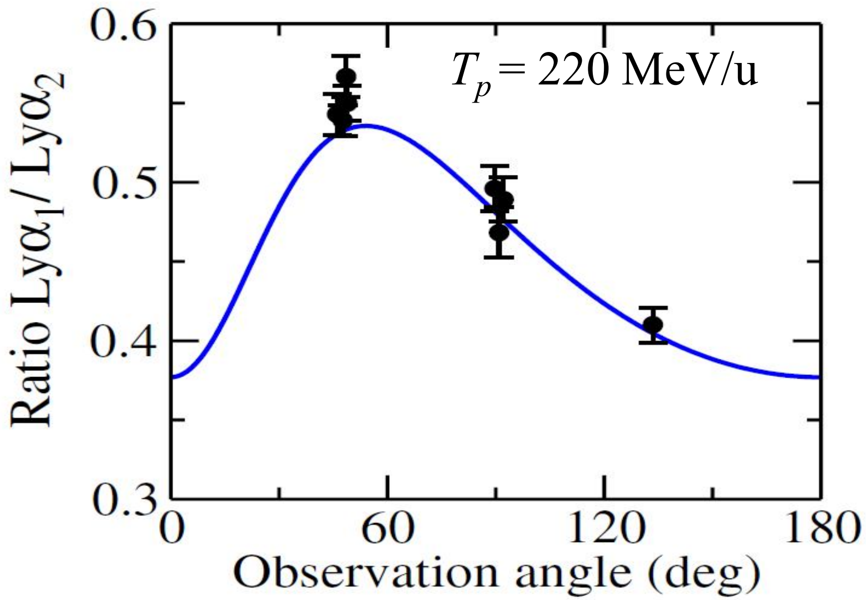

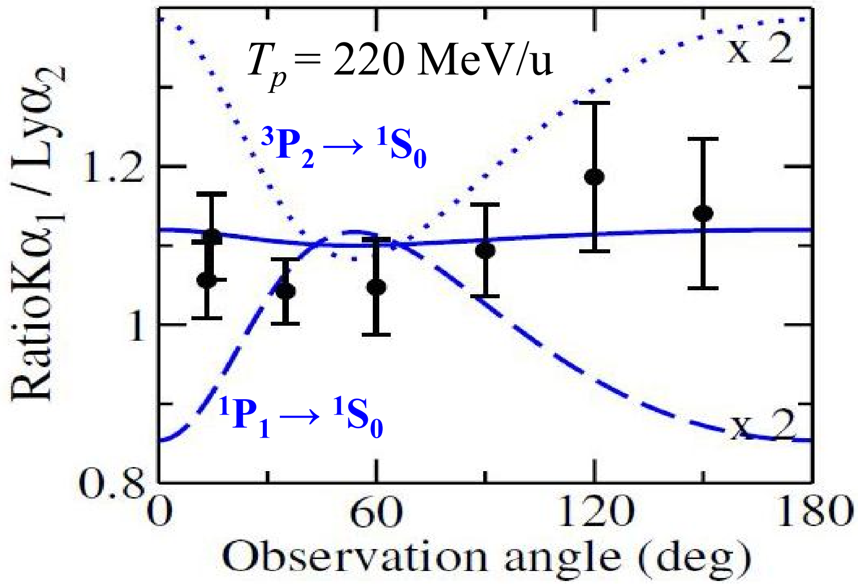

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- Such an isotropy caused by the mutual cancellation.

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Motivation

The present angular distribution of the $K\alpha_1$ emission was displayed for uranium ions with ***zero nuclear spin*.**

However, for ***nonzero-spin isotopes***, the fine-structure levels will split into more hyperfine components which all contribute to the $K\alpha_1$ emission.

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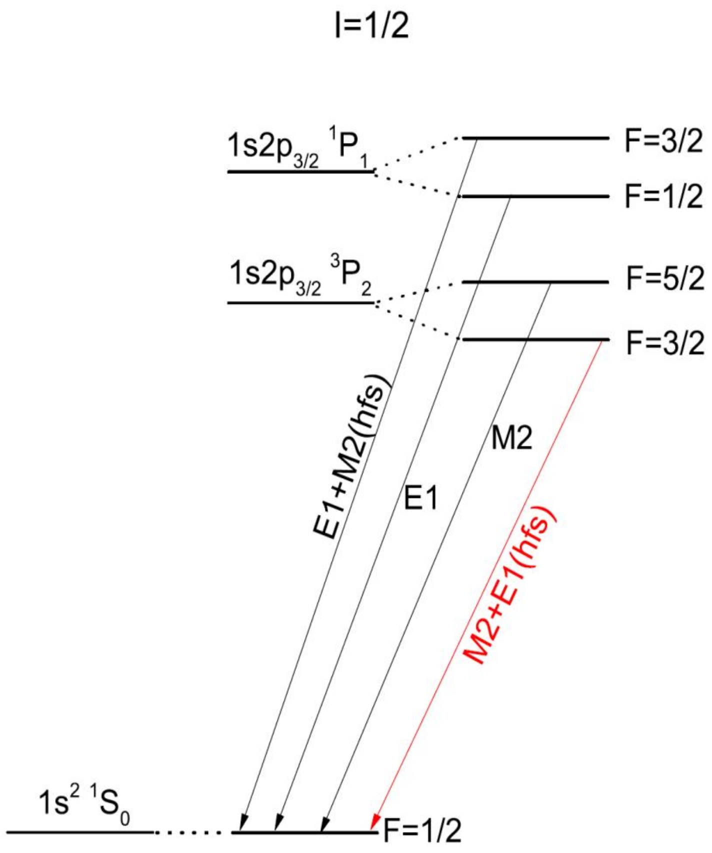

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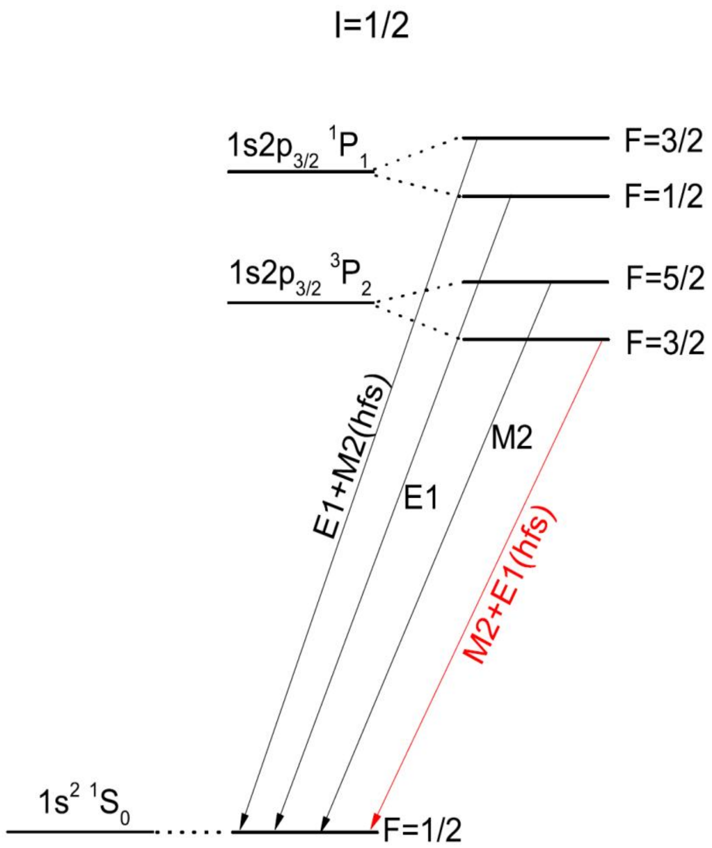

In this case, how does the hyperfine splitting affect the (hyperfine- and fine-structure-averaged) angular distribution of the $K\alpha_1$ emission ?

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Angular distribution of hyperfine-resolved decay photons

Within the density matrix theory, the angular distribution of hyperfine-resolved decay photons is given by

$$W_{if}(\theta) = \frac{1}{4\pi}[1 + \mathcal{A}_{20}(\beta_i F_i)\ f_2(\beta_i F_i, \beta_f F_f) P_2(\cos\theta)]$$

A_{20} denotes the alignment parameter; f_2 the structure function; $P_2(\cos\theta)$ the second-order Legendre polynomial.

A. Surzhykov *et al*., ***Phys. Rev. A* 87**, 052507 (2013); Z. W. Wu *et al*., ***Phys. Rev. A* 89**, 022513 (2014).

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$$\mathcal{A}_{k0}(\beta_i F_i) = (-1)^{J_i + I + F_i - k}\,[J_i, F_i]^{1/2} \times \begin{Bmatrix} F_i & F_i & k \\ J_i & J_i & I \end{Bmatrix} \mathcal{A}_{k0}(\alpha_i J_i)$$

For the two fine-structure levels $1s2p_{3/2}\ {}^1P_1$ and ${}^3P_2$ of our interest following the REC process

$$\mathcal{A}_{20}({}^1P_1) = \sqrt{2}\,\frac{\sigma_{|1,\pm1\rangle} - \sigma_{|1,0\rangle}}{2\sigma_{|1,\pm1\rangle} + \sigma_{|1,0\rangle}},$$

$$\mathcal{A}_{20}({}^3P_2) = -\sqrt{\frac{10}{7}}\,\frac{\sigma_{|2,0\rangle} + \sigma_{|2,\pm1\rangle} - 2\sigma_{|2,\pm2\rangle}}{\sigma_{|2,0\rangle} + 2\sigma_{|2,\pm1\rangle} + 2\sigma_{|2,\pm2\rangle}}$$

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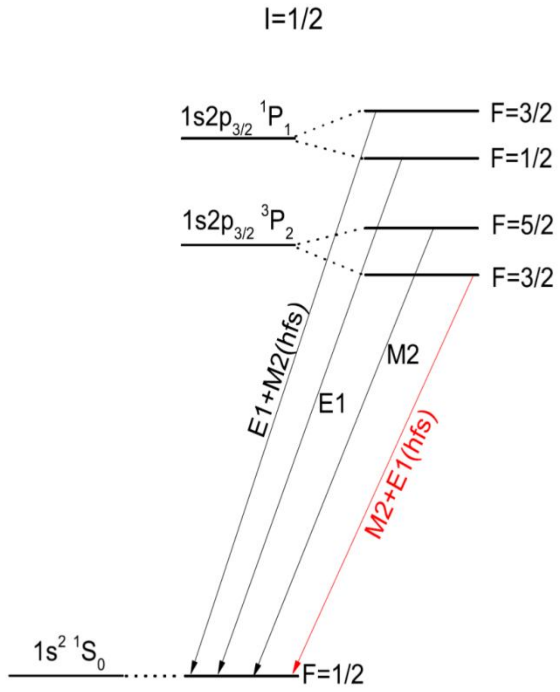
Angular distribution of the $K\alpha_1$ emission

$$W_{J=1,2}(\theta) = \frac{\sum_{F_i F_f} N_{if} W_{if}(\theta)}{\sum_{F_i F_f} N_{if}}$$



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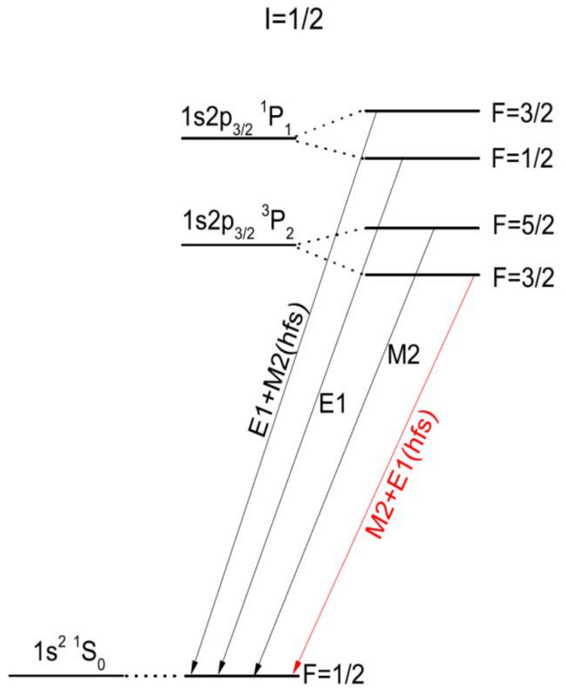

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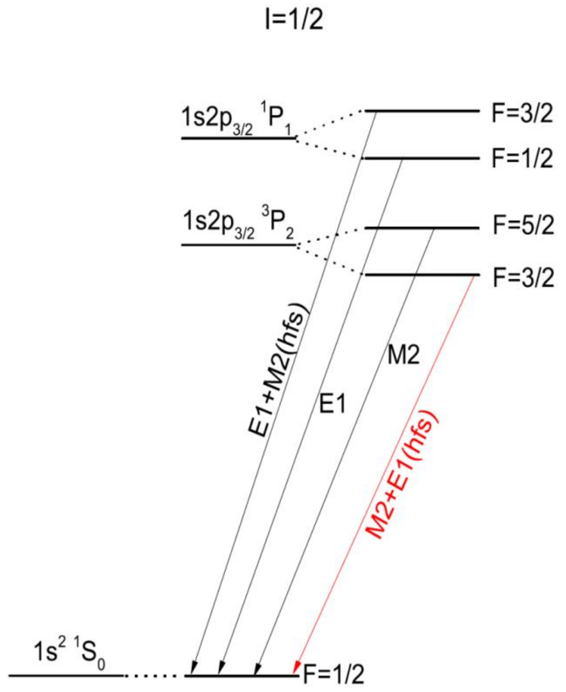
$$W_{K\alpha_1}(\theta) = \frac{1}{4\pi}\left[1 + \beta_2^{\text{eff}}(K\alpha_1)\, P_2(\cos\theta)\right]$$



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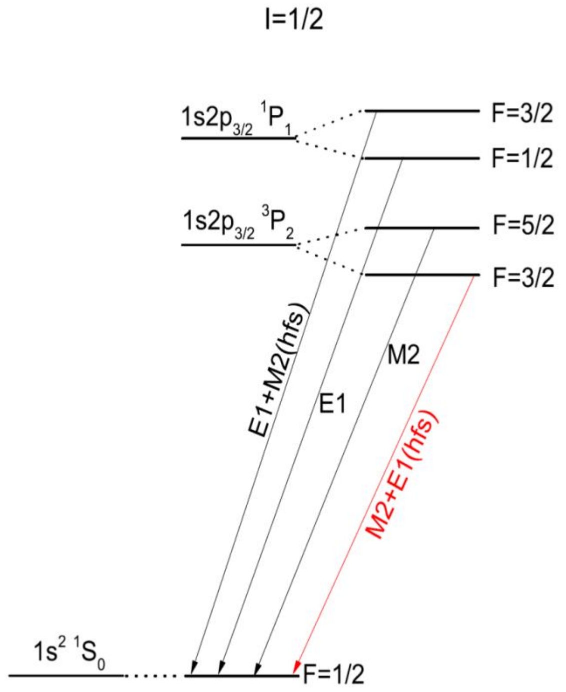

$$\beta_2^{\rm eff}(K\alpha_1; I = 1/2) = \frac{1}{3\sqrt{2}} N_{J=1} \mathcal{A}_{20}(^1P_1) + \frac{2}{5}\sqrt{\frac{7}{5}} N_{J=2} \mathcal{A}_{20}(^3P_2) \times \left(\frac{\sqrt{6}}{2}\frac{a_{\rm E1}}{a_{\rm M2}} - \frac{\sqrt{2}}{4} - \frac{3\sqrt{2}}{7}\right).$$

$$\beta_2^{\rm eff}(K\alpha_1;\; I = 0) = \frac{1}{\sqrt{2}} N_{J=1}\, \mathcal{A}_{20}(^1P_1) - \sqrt{\frac{5}{14}}\, N_{J=2}\, \mathcal{A}_{20}(^3P_2)$$

The same routes for isotopes with I > 1/2 …

Z. W. Wu *et al*., ***Phys. Rev. A* 89**, 022513 (2014).

Calculations of alignment and transition amplitudes

In the present calculations, the RATIP and GRASP92 codes based on the multi-configuration Dirac-Fock (MCDF) method were used to produce the required alignment parameters and hyperfine-structure transition amplitudes.

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In the MCDF method, an atomic state wavefunction with parity P and total angular momentum J is approximated by linear combination of configuration state functions (CSFs) with the same symmetry

$$\left|\Psi_{\alpha}(PJM)\right\rangle = \sum_{r=1}^{n_c} C_r(\alpha)\left|\Gamma_r(PJM)\right\rangle ,$$

where n_c denotes the number of the CSFs and $c_r(\alpha)$ the configuration mixing coefficients.

F. A. Parpia *et al*., ***Comput. Phys. Commun.*** **94**, 249 (1996);
S. Fritzsche, ***Comput. Phys. Commun.*** **183**, 1525 (2012).

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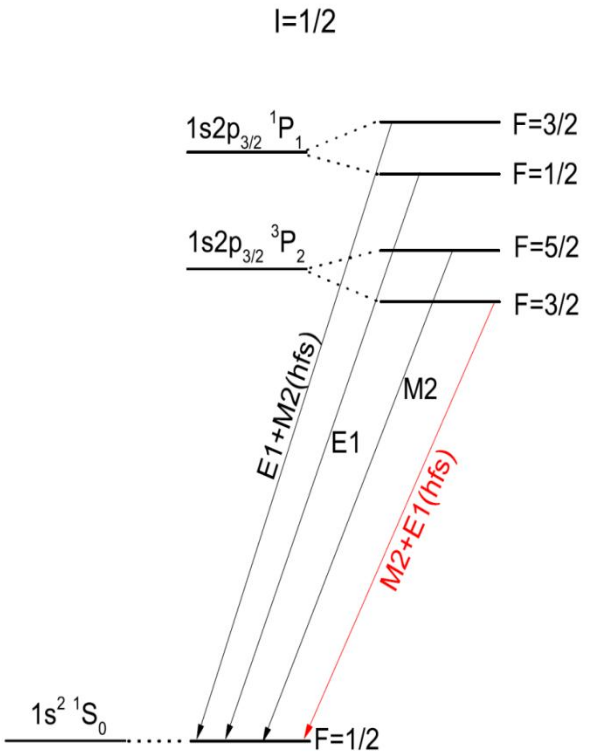
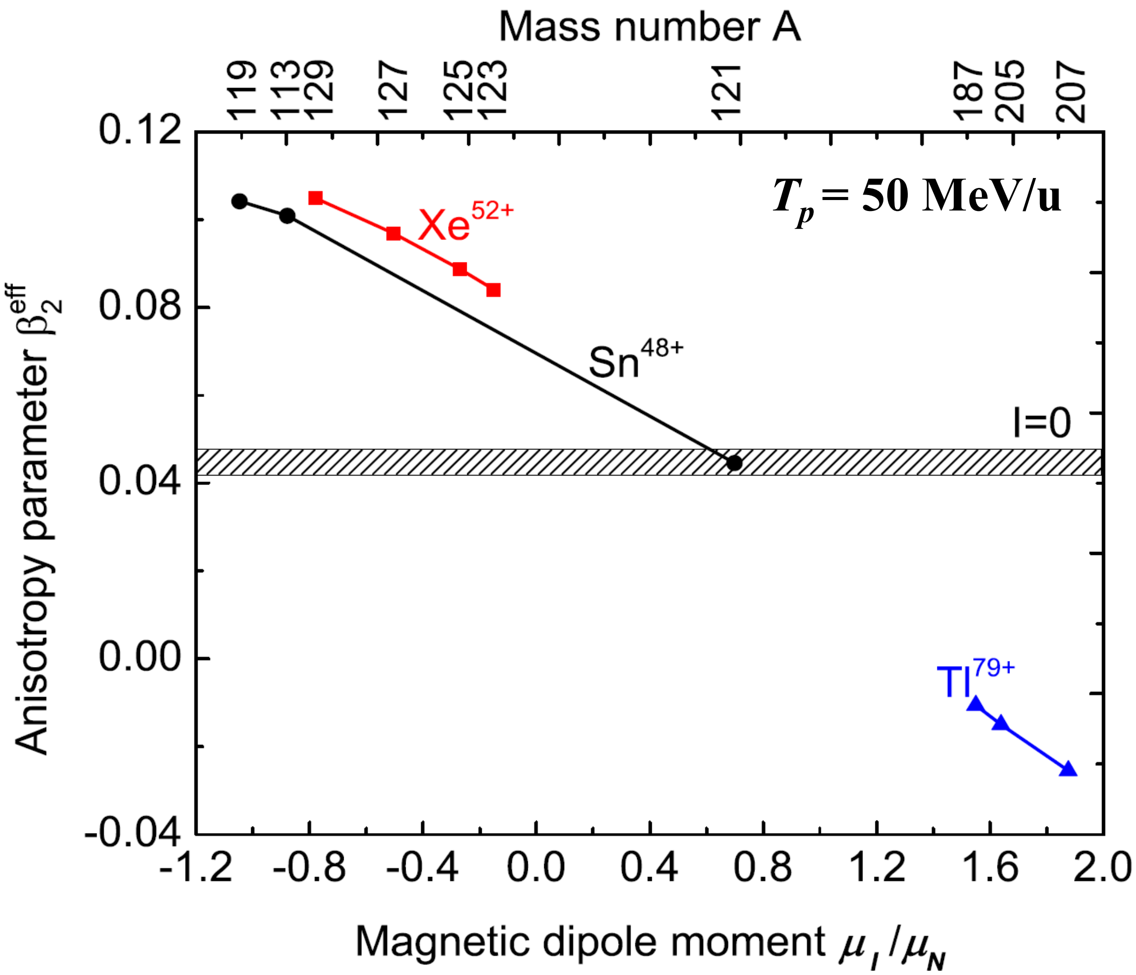
Effective anisotropy parameters of the $K\alpha_1$ emission for selected spin-1/2 isotopes

$$W_{K\alpha_1}(\theta) = \frac{1}{4\pi}\left[1 + \beta_2^{\text{eff}}(K\alpha_1)\, P_2(\cos\theta)\right]$$



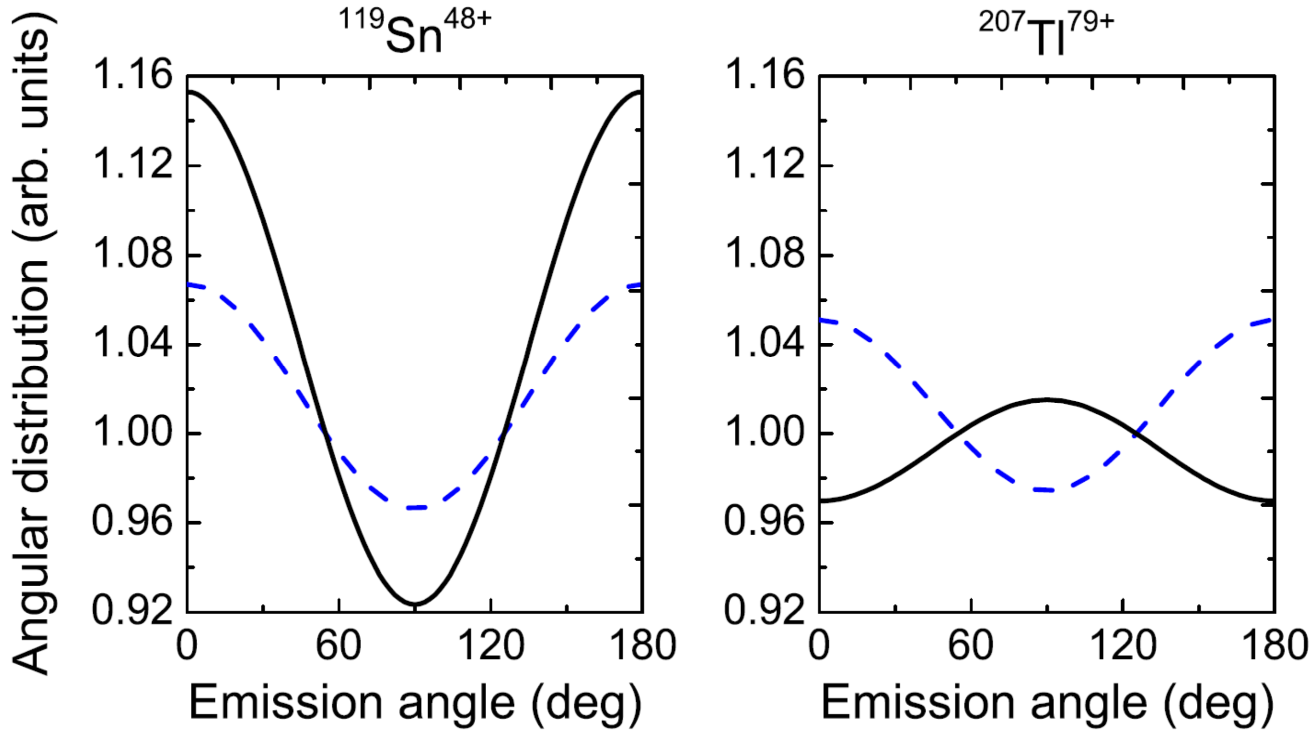


- For $I = 0$, the effective anisotropy parameter is approximately the same.
- For $I = 1/2$, it depends on the sign and magnitude of the magnetic dipole moment.
- A new tool for determining nuclear parameters.

Angular distribution of the $K\alpha_1$ emission for spin-1/2 isotopes $^{119}Sn^{48+}$ and $^{207}Tl^{79+}$

Projectile energy T_p = 50 MeV/u (dashed --- I=0, solid --- I=1/2)

(I = 1/2 , μ_I = - 1.047μ_N) **(I = 1/2 , μ_I = +1.876 μ_N)**

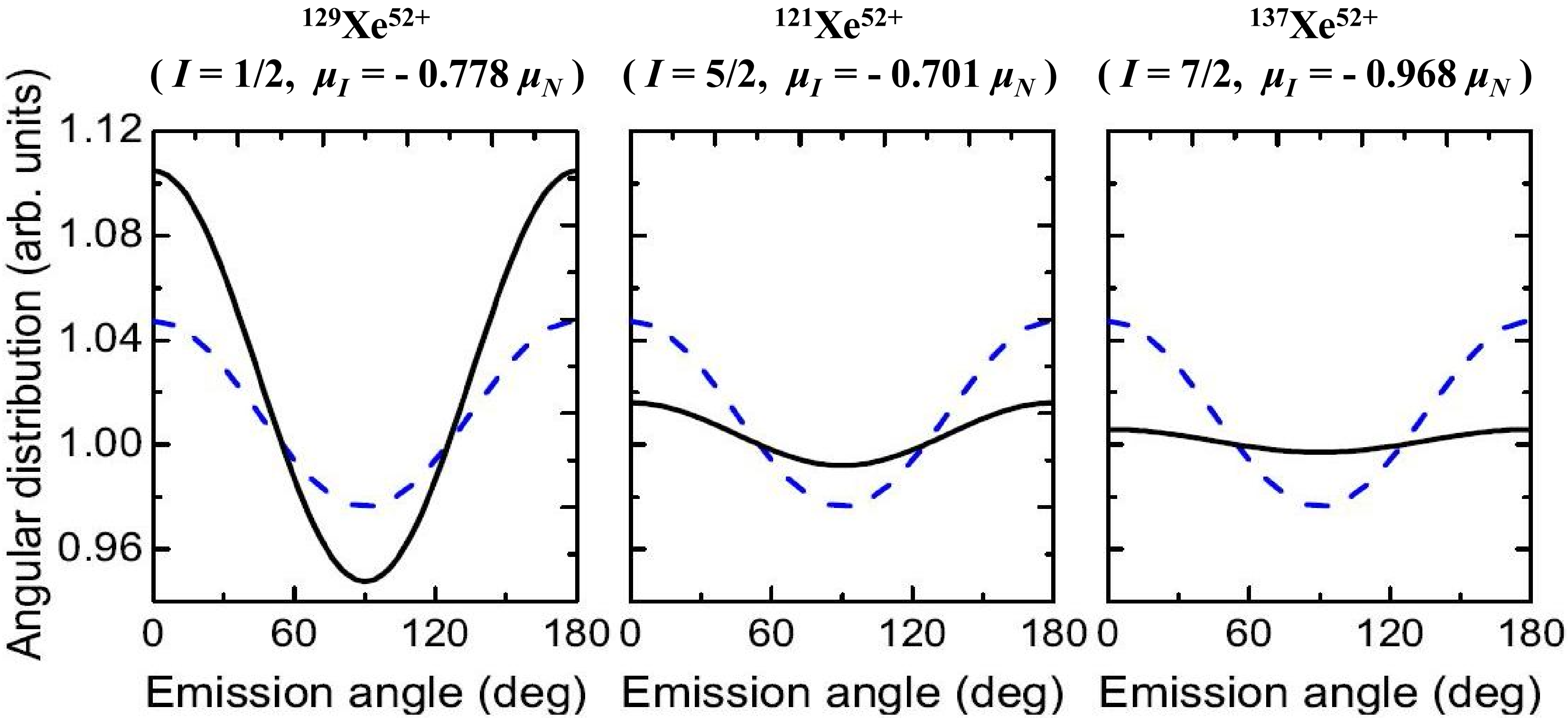


➢ For the case of $^{207}Tl^{79+}$ isotope the qualitative change occurs.

➢ This is the first physics case that the hyperfine interaction results in a qualitatively different angular behavior of emitted x-ray fluorescence.

Angular distribution of the $K\alpha_1$ emission for higher-spin isotopes $^{129}Xe^{52+}$, $^{121}Xe^{52+}$ and $^{137}Xe^{52+}$

Projectile energy T_p = 50 MeV/u (dashed --- I=0, solid --- I=1/2)



- The effect of the hyperfine interaction on higher-spin ions is relatively weak.
- The average over more hyperfine-resolved transitions washes out such effect.

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- The angular distribution of the $K\alpha_1$ emission following the REC of initially hydrogenlike ions has been studied within the density matrix theory and the MCDF method.

- Special attention has been given to the effect of the hyperfine interaction and how the hyperfine splitting affects the overall $K\alpha_1$ emission for nonzero spin isotopes.

- A quite sizable contribution of the hyperfine interaction was found for spin-1/2 isotopes, while this effect is suppressed for isotopes with $I > 1/2$.

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- A quite sizable contribution of the hyperfine interaction was found for spin-1/2 isotopes, while this effect is suppressed for isotopes with $I > 1/2$.

- We hope accurate measurements on the $K\alpha_1$ angular distribution could be utilized as a tool for determining the nuclear parameters, such as the nuclear spin, and magnetic dipole moment.

The End

Thank you for your attention!