The phenomena of spin rotation and depolarization of high-energy particles in bent and straight crystals at Large Hadron Collider (LHC) and Future Circular Collider (FCC) energies and the possibility to measure the anomalous magnetic moments of short-lived particles (charm and beauty baryons)

V.G. Baryshevsky

INP

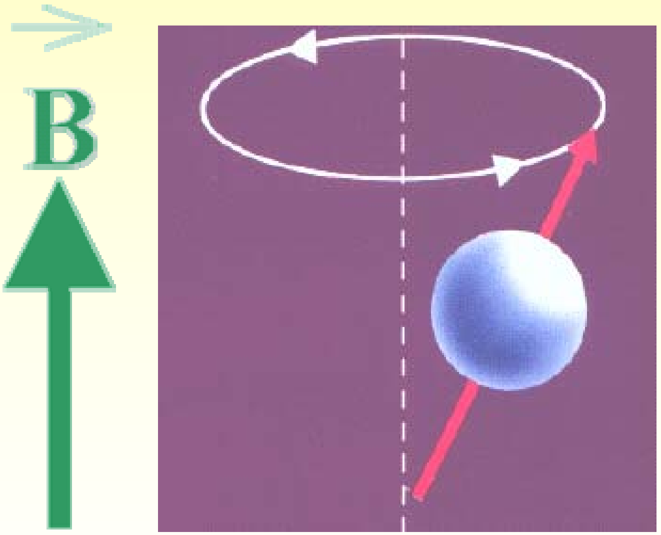
BSU

Institute for Nuclear Problems,
Belarusian State University, Minsk, Belarus

Magnetic moment - important characteristic of the nuclei and elementary particles

$$\mu = \frac{e\hbar}{2mc} gS = \mu_B g S \qquad g \text{ - g factor} \qquad \mu_B = \frac{e\hbar}{2mc}$$

Magnetic moment (spin) precesses in magnetic field .
Precession frequency



$$\Omega = \gamma_S B = \frac{g \mu_B B}{\hbar}$$

$$\gamma_S = g \mu_B = \frac{\mu}{S\hbar} \text{ - gyromagnetic ratio}$$

So we can measure the magnetic moment

Majority of the elementary particles are unstable!

Characteristics

Charmed baryons

$$\Lambda_c^+ : \tau = 0.2 \cdot 10^{-12} s; \quad m = 2286.46 MeV; \quad l_d = l_{decay} = \tau c \gamma = 6cm.$$

$$\Xi_c^+ : \tau = 0.44 \cdot 10^{-12} s; \quad m = 2467.8 MeV; \quad l_d = 13.2cm.$$

$$\Xi_c^0 : \tau = 0.1 \cdot 10^{-12} s; \quad m = 2470.88 MeV; \quad l_d = 3.3cm; \quad \gamma = 10^3$$

$$\Omega_c^0 : \tau = 7 \cdot 10^{-14} s; \quad m = 2695 MeV; \quad l_d = 2.1cm.$$

Bottom baryons

$$\Lambda_b^0 : \tau = 1.425 \cdot 10^{-12} s; \quad m = 5619.4 MeV; \quad l_d = 42.7 cm; \quad \gamma = 10^3.$$

$$\Xi_b^0 : \tau = 1.49 \cdot 10^{-12} s; \quad m = 5788 MeV; \quad l_d = 44.7 cm.$$

$$\Xi_b^- : \tau = 1.56 \cdot 10^{-12} s; \quad m = 5791 MeV; \quad l_d = 44.7 cm.$$

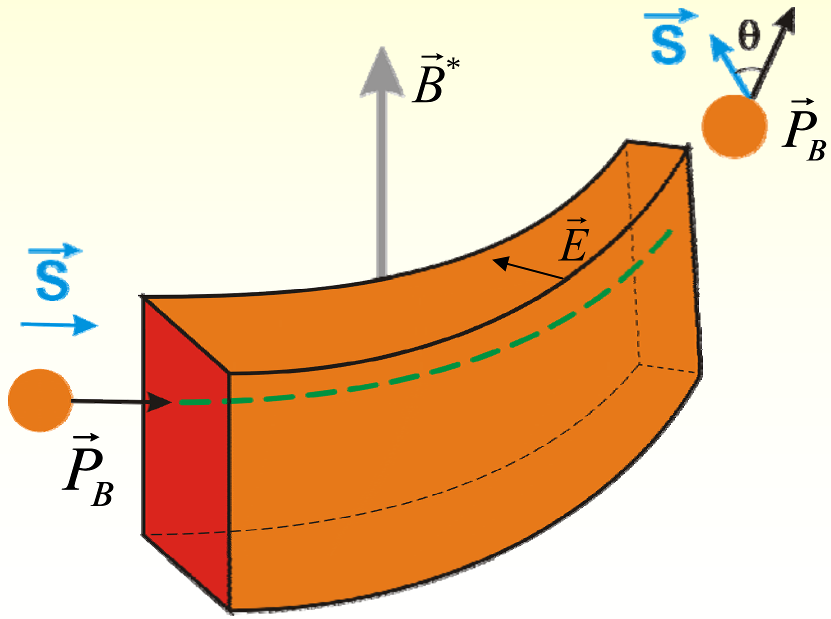
$$\Omega_b^- : \tau = 1.1 \cdot 10^{-12} s; \quad m = 6071 MeV; \quad l_d = 33 cm.$$

When the pass length is small how can we measure μ?

* Baryshevsky V.G., Spin rotation of ultrarelativistic particles passing through a crystal, Pis'ma Zh. Tekh. Fiz., 5, 3 (1979), pp 182-184.

* Baryshevsky V.G., Spin rotation and depolarization of high-energy particles in crystals at Hadron Collider (LHC) and Future Circular Collider (FCC) energies and the possibility to measure the anomalous magnetic moments of short-lived particles, arXiv:1504.06702 [hep-ph]

* Baryshevsky V.G., The possibility to measure the magnetic moments of short-lived particles (charm and beauty baryons) at LHC and FCC energies using the phenomenon of spin rotation in crystals, Physics Letters B, V. 757, 2016, pp 426–429.



Polarized particles spin rotation

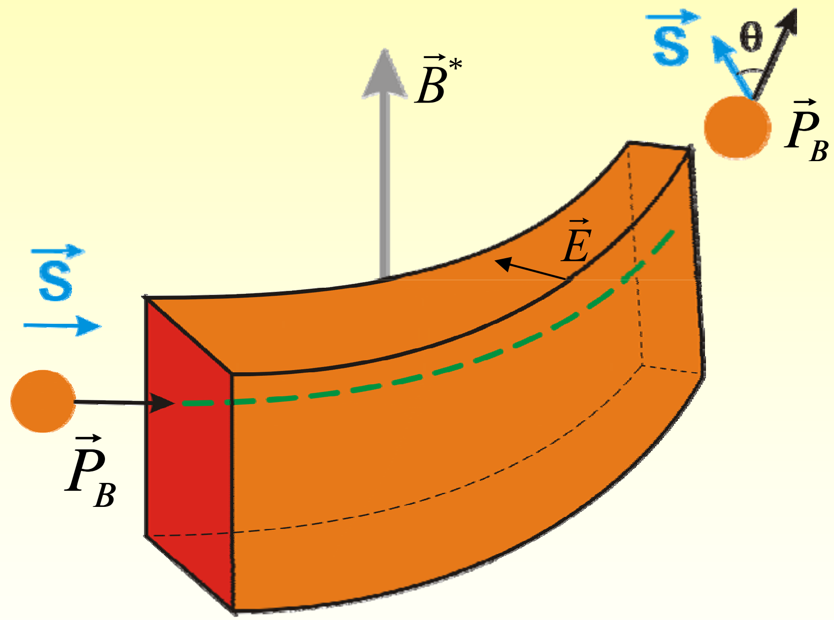
In particle rest frame

$$B^* \rightarrow \gamma E$$

$$\omega' = \frac{2\mu' B^*}{\hbar} = \frac{2\mu' \gamma E}{\hbar}$$

In laboratory frame

$$\omega = \frac{\omega'}{\gamma} = \frac{2\mu' E}{\hbar}$$

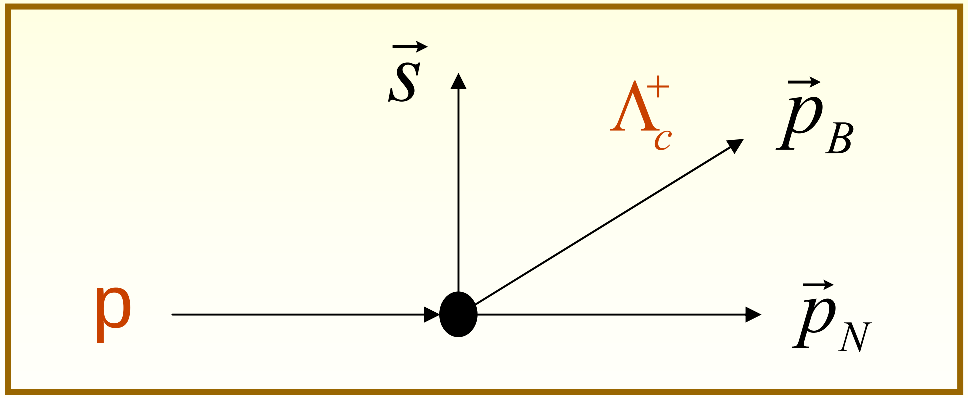


Polarization of Charm and Beauty baryons

Polarized particles are required for magnetic moment measurement.

Amplitude of reaction: $$f = f_0 + \vec{s}\,[\vec{p}_N \times \vec{p}_B]$$

Particles in reactions are born polarized.

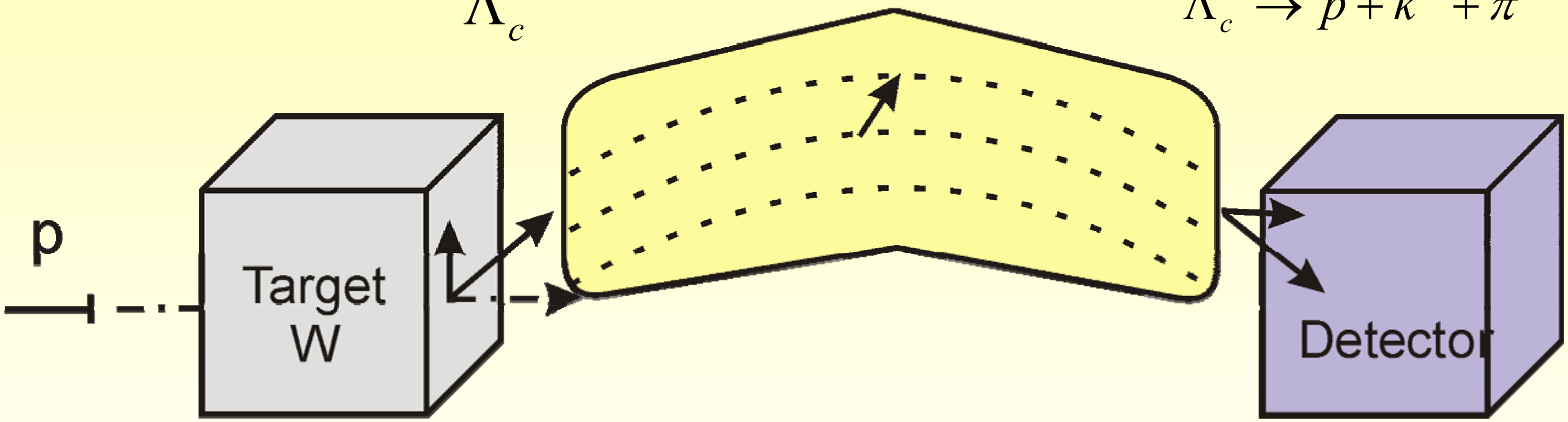


Production plane formed by $\vec{p}_N$ and $\vec{p}_B$

How to measure orientation?

As a result of parity violation in weak decays asymmetry relative to baryon production plane exists. The momentum direction of decay products follows the spin direction.

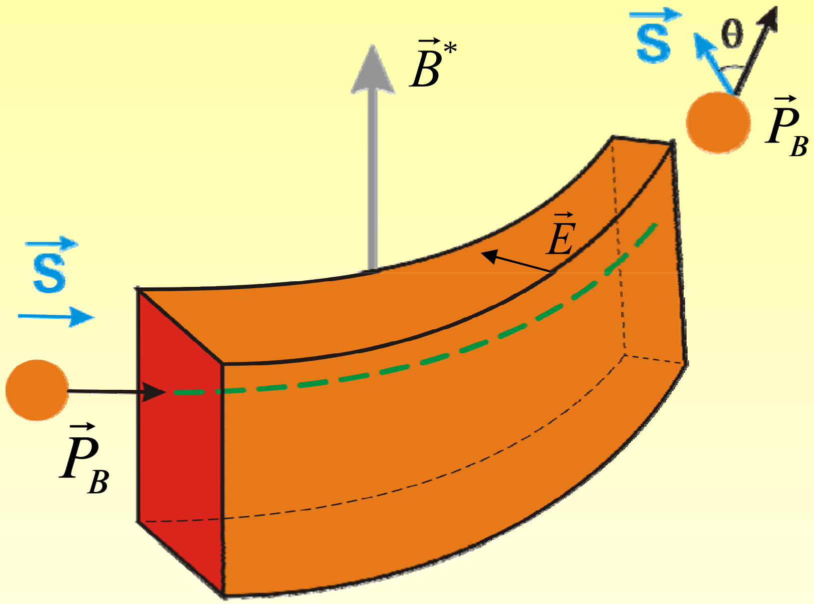
Λ_c^+ $\quad$ $\Lambda_c^+ \to p + k^- + \pi^+$



$$\Lambda_c^+ \to p + k^- + \pi^+ \to k^0 + p + \pi^+ + \pi^- \to \Lambda^0 + \pi^+ + \pi^+ + \pi^-$$

$$\Lambda_c^+ \to \Lambda^+ + \pi^+$$

First experiment to measure (g-2) rotation



E761 Collaboration, FERMILAB

”First observation of spin precession of polarized Σ^+ hyperons channeled in bent crystals”, LNPI Research Reports (1990-1991) 129.

Energy of Σ^+ : 200 – 300 GeV

D. Chen

”First Observation of Magnetic Moment Precession of Channeled Particles in Bent Crystals”, Phys. Rev. Lett. 69 (1992) 3286.

A.V. Khanzadeev, V.M. Samsonov, R.A. Carrigan, D. Chen

”Experiment to observe the spin precession of channeled relativistic Σ^+ hyperons” NIM 119 (1996) 266.

Polarized particles spin rotation

Rotation angle for L=1 cm :

$$\vartheta_{s1} = \frac{g-2}{2}\frac{\gamma}{R}$$

R is the bending radius

and

$$\vartheta_{s1}^{\max} = \frac{g-2}{2}\frac{U'_{\max}}{mc^2}$$

where U is the channel potential energy.

Does not depend on energy!

Polarized particles spin rotation

According to Biryukov* for Si $U' = 5 GeV / cm$

Hence, using the evaluation of g-factor for Λ_c^+ $g \simeq 1{,}36 - 2{,}45$

For $L = 10 cm, \quad \vartheta_s \simeq 1\ rad$

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* Biryukov V.M.,Chesnokov Yu.A,Kotov V.I., Crystal channeling and its application at high-energy accelerators, Springer, Berlin, 1997

Polarized particles spin rotation

With the growth of energy $\vartheta_L \sim \frac{1}{\sqrt{\gamma}}$ everything complicates,

but during the particle production $\delta\vartheta \sim \frac{1}{\gamma}$

Therefore trapped particles part is increasing: $\frac{\vartheta_L}{\delta\vartheta} \sim \sqrt{\gamma}$

With the growth of energy production cross section σ_r increases, but how?

According to J. Appel and J. Russ

$$\sigma_r \sim \gamma$$

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*J. Appel, in: Proc. of the CHARM 2000 Workshop, FERMILAB-CONF-94/190, Fermilab, June 7–9, 1994, Batavia, IL, p. 4.
J. Russ, in: Proc. of the CHARM 2000 Workshop, FERMILAB-CONF-94/190, Fermilab, June 7–9, 1994, Batavia, IL, p. 111.*

Polarized particles spin rotation

But the latest experiments with Λ_c^+ at 7 TeV had shown that the increase is weaker.

LHCb Collaboration, R. Aaij, et al., J. High Energy Phys. 12 (2013) 090.
LHCb Collaboration, R. Aaij, et al., LANL e-print, arXiv:1302.2864v1 [hep-ex].
LHCb Collaboration, R. Aaij, et al., Nucl. Phys. B 871 (2013) 1.

Therefore let us assume $\sigma_r \sim \alpha(\gamma)\gamma;$ with $\alpha(\gamma) < 1.$

As a result, the number of particles N that experienced channeling is

$$N \sim \alpha(\gamma)\gamma^{\frac{3}{2}}$$

The running time

$$T \sim \frac{1}{\sqrt{N}} = \frac{1}{\sqrt{\alpha(\gamma)}\gamma^{\frac{3}{4}}}$$

Running time

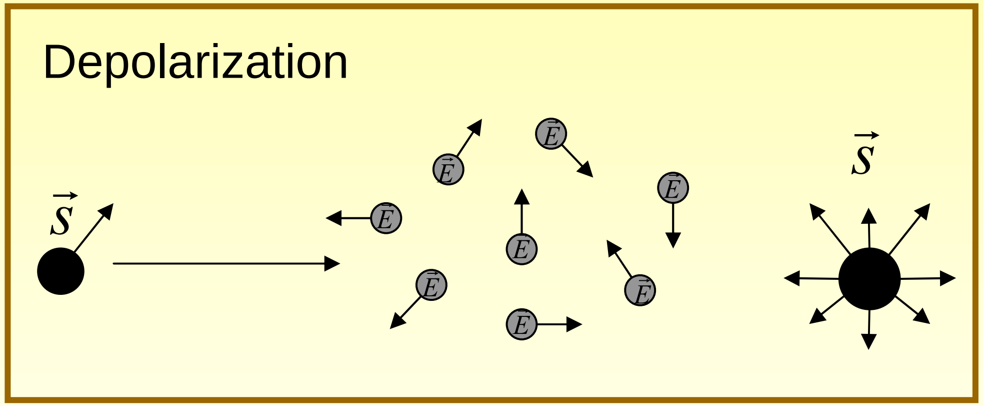
For 7Tev LHC energies the running time required for measuring the magnetic moment of short lived particles is 2-16 hours.

* Baryshevsky V.G., The possibility to measure the magnetic moments of short lived particles (charm and beauty baryons) at LHC and FCC energies using the phenomenon of spin rotation in crystals, Physics Letters B, V. 757, 2016, pp 426–429.

This works well for positively charged particles, but what should be done with negatively charged ones?

Spin depolarization in amorphous target

In amorphous target electric fields possess various values and directions.



The degree of depolarization is small : less than 1% on nuclear absorption length.

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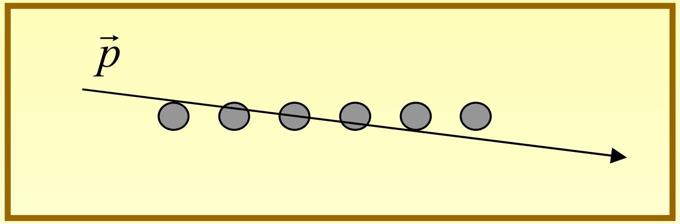
* Lyubosihtz, V.L., (1980b). Depolarization of fast particles travelling through matter, *Sov. J. Nucl. Phys.* **32**, 3, pp. 362–365.

Spin depolarization in crystals

Mean-square angle of multiple scattering $\left\langle \vartheta_p^2 \right\rangle_{cr}$ becomes much bigger in crystals



$$\zeta_{\parallel} = \zeta_z(0) e^{-\frac{1}{2}\left\langle \vartheta_{s1}^2 \right\rangle_{cr} l}$$

$$\left\langle \vartheta_{s1}^2 \right\rangle_{cr} = \left(\frac{g-2}{2} \right)^2 \gamma^2 \left\langle \vartheta_{p1}^2 \right\rangle_{cr}$$

$\left\langle \vartheta_{p1}^2 \right\rangle_{cr} \sim \dfrac{1}{\gamma^2}$

$\left\langle \vartheta_{s1}^2 \right\rangle_{cr}$

Mean-square angle of multiple scattering per unit length
Does not depend on γ

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* Baryshevsky V.G., Spin rotation and depolarization of relativistic particles traveling through a crystal, Nucl. Instrum. Methods B, 44, 3 (1990), 266-272.

Spin depolarization in crystals

Depolarization in crystal is increasing up to dozens percent on 1 cm.

$$|g-2| = \sqrt{\frac{8}{\gamma^2 \left\langle \vartheta_p^2(l) \right\rangle_{ch}} \ln \frac{\left\langle \zeta_z(0) \right\rangle}{\left\langle \zeta_z(l) \right\rangle}}$$

Enables measurement of magnetic moment of negative beauty baryons.

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* Baryshevsky V.G., Spin rotation and depolarization of relativistic particles traveling through a crystal, Nucl. Instrum. Methods B, 44, 3 (1990), 266-272.

* Baryshevsky V.G. Spin rotation and depolarization of high-energy particles in crystals at Hadron Collider (LHC) and Future Circular Collider (FCC) energies and the possibility to measure the anomalous magnetic moments of short-lived particles, arXiv:1504.06702 [hep-ph].

Neutral baryons spin depolarization in crystals

The scattering cross section on neutral baryons in crystal can be analyzed using the following expression for differential cross section

$$\frac{d\sigma_{cr}}{d\Omega} = \frac{d\sigma}{d\Omega}\frac{1}{N}\left|\overline{\sum_{n=1}^{N}\exp(i\vec{q}\,\vec{r}_n)}\right|^2$$

$$\frac{d\sigma}{d\Omega} = tr\rho f^{+}(\vec{q})f(\vec{q})$$

$f(\vec{q})$ the amplitude of elastic scattering of the spin $\vec{S}$ particle by the nucleus

ρ spin density matrix of the particle

According to Dyumin, Baryshevsky * for neutrons with energies up to several MeV the cross section σ_{cr} increases by a factor ten compared with σ in amorphous matter.

* A.N. Dyumin, I.Ya. Korenblim, V.A. Ruban, B.B. Tokarev, Electromagnetic (Schwinger) scattering of fast neutrons in crystals, JETP Lett. 31, 7 (1980) 384.

* V.G. Baryshevsky, A.M. Zaitseva, Izv. VUZov, Fizika, 3 (1985) 103–104.

Neutral baryons spin depolarization in crystals

The degree of longitudinal (transverse) depolarization of neutral baryons in crystal :

$$\eta^{cr}_{\|(\perp)}(\vartheta_0) \simeq \frac{\sigma_{cr}(\vartheta_0)}{\sigma}\eta_{\|(\perp)am}$$

$\sigma_{cr}(\vartheta_0)$ the total scattering cross section in crystal due to spin-orbit interaction (Schwinger scattering),

σ the total spin-orbital Schwinger scattering cross section by nucleus in the amorphous medium.

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* V.G. Baryshevsky, Nucl. Instrum. Methods B, 44, 266-272, 1990.

* V.G. Baryshevsky, Depolarization of high-energy neutral particles in crystals and the possibility to measure anomalous magnetic moments of short-lived hyperons, arXiv:1608.06815v1 [hep-ph], 2016.

Neutral baryons spin depolarization in crystals

When energy grows, σ_{cr} grows. As a result the degree of depolarization of hyperons at LHC and FCC energies reaches tens percent at several cm length.

Running time for charm baryons 2-20 hours.

Running time for more heavy bottom baryons – tens of hours (up to 200 hours).

… motion towards the experiment on the above basis

CERN UA9 Collaboration now enters upon a project:

Measurement of Short Living Baryon Magnetic Moment using Bent Crystals at SPS and LHC

Project Manager/Technical Coordinator:
Walter Scandale

CERN-SPSC-2016-030

Conclusion

High-energy particles interaction with crystals provides us with unique opportunities for measuring important spin-dependent characteristics of elementary particles.

* V.G. Baryshevsky, High-Energy Nuclear Optics of Polarized Particles, World Scientific, 2012.

Thank you!