Взаимодействие ускорительных нейтрино с ядрами ^{127}I и влияние зарядово-обменной силовой функции на сечение захвата

Ю.С. Лютостанский[1], А.Н. Фазлиахметов[1,2], Г.А. Коротеев[1,2], А.П. Осипенко[1], В.Н. Тихонов[1]

1 Национальный исследовательский центр “Курчатовский институт”
2 Институт ядерных исследований Российской Академии наук

Сессия-конференция секции ядерной физики ОФН РАН, посвященная 70-летию В.А. Рубакова

Экспериментальные сечения захвата нейтрино

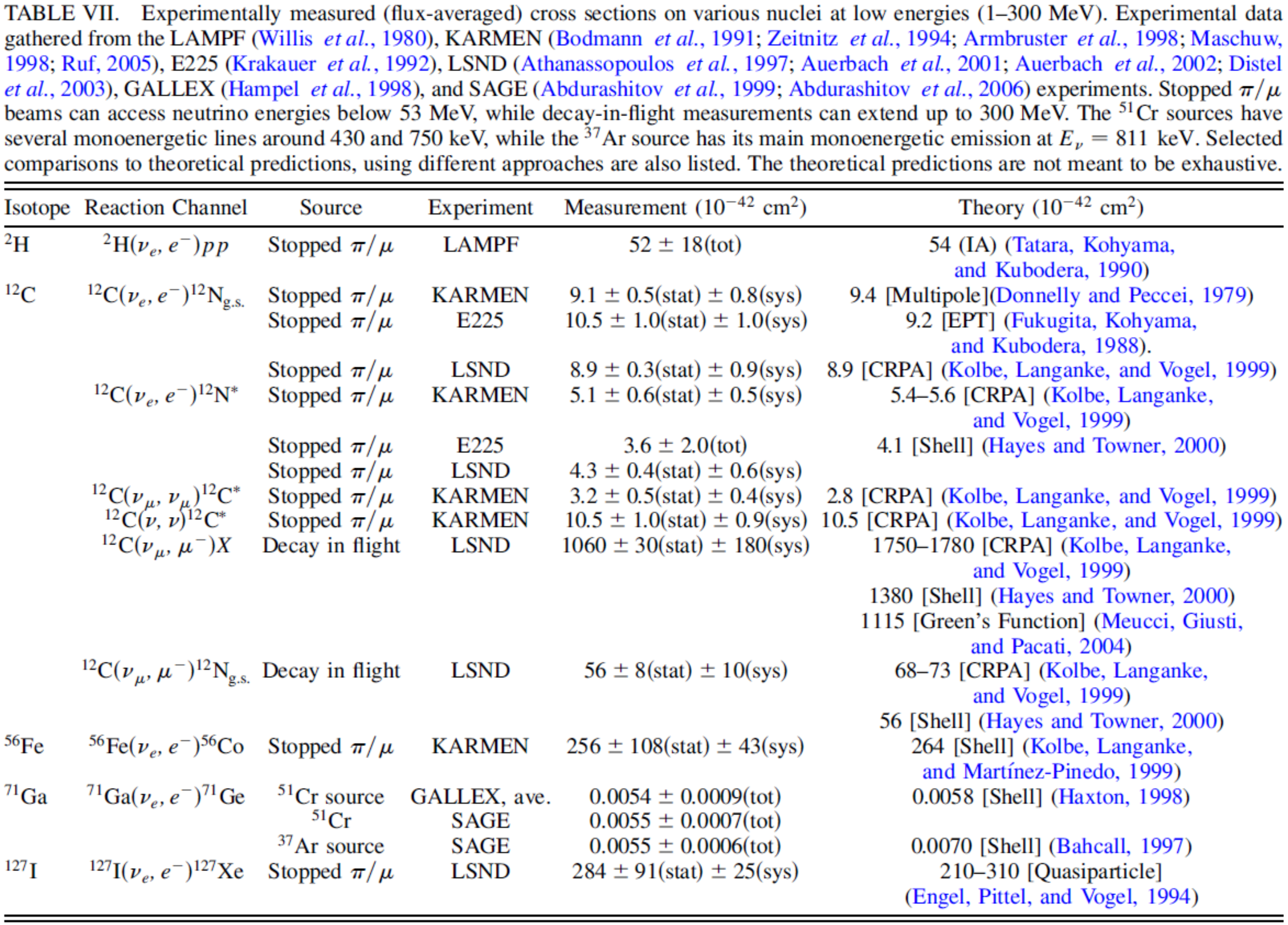
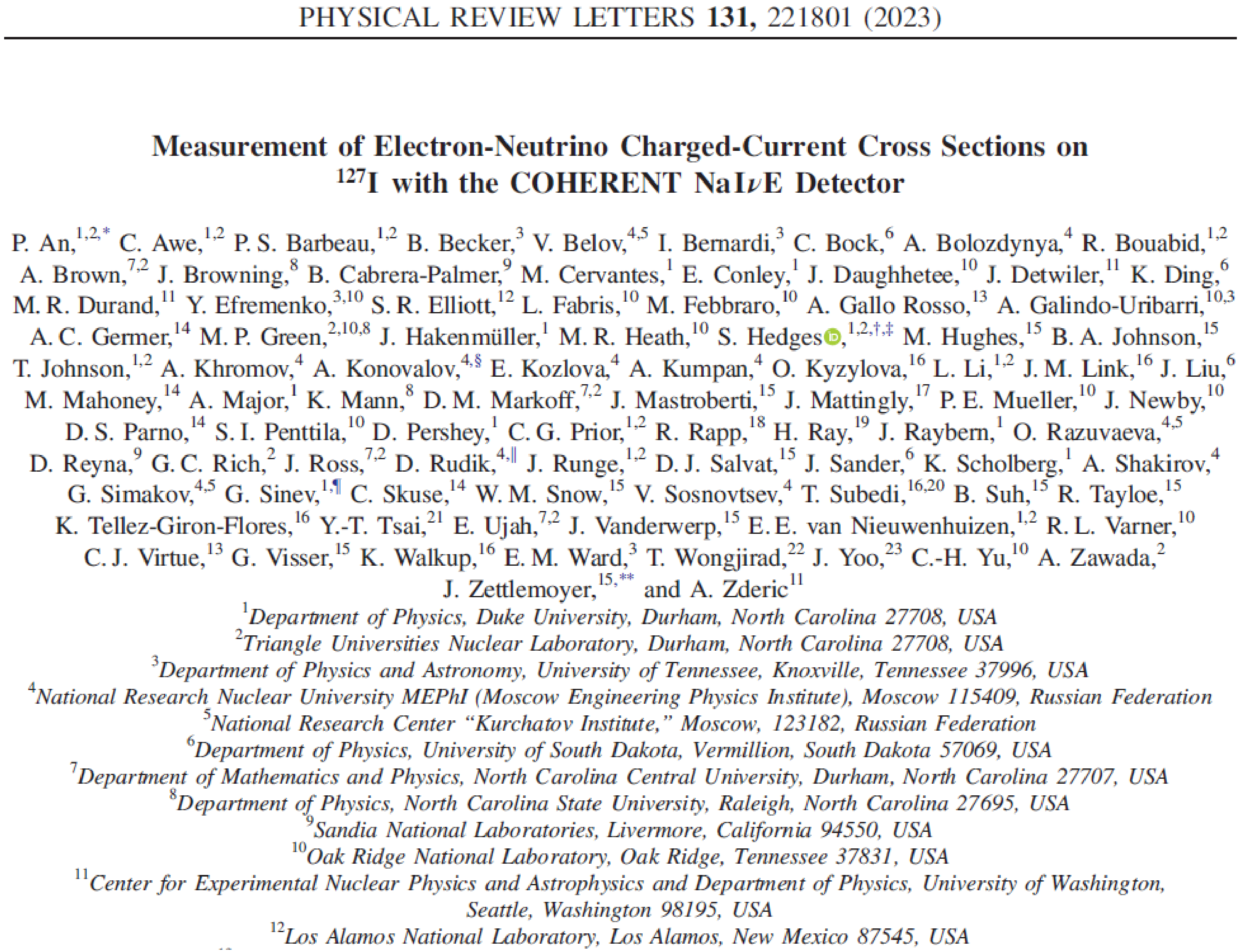


TABLE VII. Experimentally measured (flux-averaged) cross sections on various nuclei at low energies (1–300 MeV). Experimental data gathered from the LAMPF (Willis et al., 1980), KARMEN (Bodmann et al., 1991; Zeitnitz et al., 1994; Armbruster et al., 1998; Maschuw, 1998; Ruf, 2005), E225 (Krakauer et al., 1992), LSND (Athanassopoulos et al., 1997; Auerbach et al., 2001; Auerbach et al., 2002; Distel et al., 2003), GALLEX (Hampel et al., 1998), and SAGE (Abdurashitov et al., 1999; Abdurashitov et al., 2006) experiments. Stopped π/μ beams can access neutrino energies below 53 MeV, while decay-in-flight measurements can extend up to 300 MeV. The ^{51}Cr sources have several monoenergetic lines around 430 and 750 keV, while the ^{37}Ar source has its main monoenergetic emission at $E_\nu = 811$ keV. Selected comparisons to theoretical predictions, using different approaches are also listed. The theoretical predictions are not meant to be exhaustive.

Isotope	Reaction Channel	Source	Experiment	Measurement (10^{-42} cm^2)	Theory (10^{-42} cm^2)
^{2}H	^{2}H$(\nu_e, e^-)pp$	Stopped π/μ	LAMPF	52 ± 18(tot)	54 (IA) (Tatara, Kohyama, and Kubodera, 1990)
^{12}C	^{12}C$(\nu_e, e^-)^{12}$N$_{\text{g.s.}}$	Stopped π/μ	KARMEN	9.1 ± 0.5(stat) ± 0.8(sys)	9.4 [Multipole](Donnelly and Peccei, 1979)
		Stopped π/μ	E225	10.5 ± 1.0(stat) ± 1.0(sys)	9.2 [EPT] (Fukugita, Kohyama, and Kubodera, 1988).
		Stopped π/μ	LSND	8.9 ± 0.3(stat) ± 0.9(sys)	8.9 [CRPA] (Kolbe, Langanke, and Vogel, 1999)
	^{12}C$(\nu_e, e^-)^{12}$N*	Stopped π/μ	KARMEN	5.1 ± 0.6(stat) ± 0.5(sys)	5.4–5.6 [CRPA] (Kolbe, Langanke, and Vogel, 1999)
		Stopped π/μ	E225	3.6 ± 2.0(tot)	4.1 [Shell] (Hayes and Towner, 2000)
		Stopped π/μ	LSND	4.3 ± 0.4(stat) ± 0.6(sys)	
	^{12}C$(\nu_\mu, \nu_\mu)^{12}$C*	Stopped π/μ	KARMEN	3.2 ± 0.5(stat) ± 0.4(sys)	2.8 [CRPA] (Kolbe, Langanke, and Vogel, 1999)
	^{12}C$(\nu, \nu)^{12}$C*	Stopped π/μ	KARMEN	10.5 ± 1.0(stat) ± 0.9(sys)	10.5 [CRPA] (Kolbe, Langanke, and Vogel, 1999)
	^{12}C$(\nu_\mu, \mu^-)X$	Decay in flight	LSND	1060 ± 30(stat) ± 180(sys)	1750–1780 [CRPA] (Kolbe, Langanke, and Vogel, 1999) 1380 [Shell] (Hayes and Towner, 2000) 1115 [Green's Function] (Meucci, Giusti, and Pacati, 2004)
	^{12}C$(\nu_\mu, \mu^-)^{12}$N$_{\text{g.s.}}$	Decay in flight	LSND	56 ± 8(stat) ± 10(sys)	68–73 [CRPA] (Kolbe, Langanke, and Vogel, 1999) 56 [Shell] (Hayes and Towner, 2000)
^{56}Fe	^{56}Fe$(\nu_e, e^-)^{56}$Co	Stopped π/μ	KARMEN	256 ± 108(stat) ± 43(sys)	264 [Shell] (Kolbe, Langanke, and Martínez-Pinedo, 1999)
^{71}Ga	^{71}Ga$(\nu_e, e^-)^{71}$Ge	^{51}Cr source	GALLEX, ave.	0.0054 ± 0.0009(tot)	0.0058 [Shell] (Haxton, 1998)
		^{51}Cr	SAGE	0.0055 ± 0.0007(tot)	
		^{37}Ar source	SAGE	0.0055 ± 0.0006(tot)	0.0070 [Shell] (Bahcall, 1997)
^{127}I	^{127}I$(\nu_e, e^-)^{127}$Xe	Stopped π/μ	LSND	284 ± 91(stat) ± 25(sys)	210–310 [Quasiparticle] (Engel, Pittel, and Vogel, 1994)

From eV to EeV: Neutrino cross sections across energy scales // J. A. Formaggio and G. P. Zeller Rev. Mod. Phys. ***84****, 1307 (2012)*



PHYSICAL REVIEW LETTERS **131,** 221801 (2023)

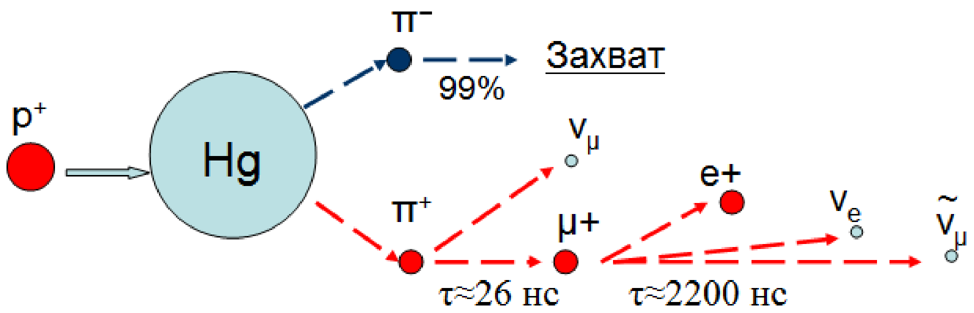
Measurement of Electron-Neutrino Charged-Current Cross Sections on ^{127}I with the COHERENT NaIνE Detector

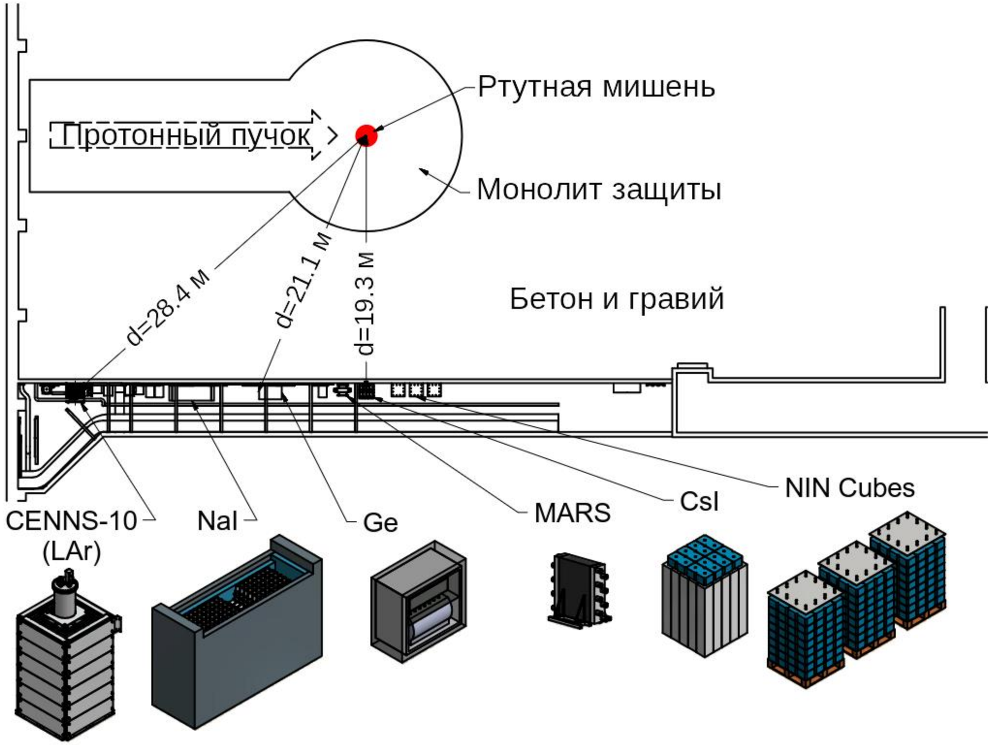
P. An,[1,2,*] C. Awe,[1,2] P. S. Barbeau,[1,2] B. Becker,[3] V. Belov,[4,5] I. Bernardi,[3] C. Bock,[6] A. Bolozdynya,[4] R. Bouabid,[1,2] A. Brown,[7,2] J. Browning,[8] B. Cabrera-Palmer,[9] M. Cervantes,[1] E. Conley,[1] J. Daughhetee,[10] J. Detwiler,[11] K. Ding,[6] M. R. Durand,[11] Y. Efremenko,[3,10] S. R. Elliott,[12] L. Fabris,[10] M. Febbraro,[10] A. Gallo Rosso,[13] A. Galindo-Uribarri,[10,3] A. C. Germer,[14] M. P. Green,[2,10,8] J. Hakenmüller,[1] M. R. Heath,[10] S. Hedges,[1,2,†,‡] M. Hughes,[15] B. A. Johnson,[15] T. Johnson,[1,2] A. Khromov,[4] A. Konovalov,[4,§] E. Kozlova,[4] A. Kumpan,[4] O. Kyzylova,[16] L. Li,[1,2] J. M. Link,[16] J. Liu,[6] M. Mahoney,[14] A. Major,[1] K. Mann,[8] D. M. Markoff,[7,2] J. Mastroberti,[15] J. Mattingly,[17] P. E. Mueller,[10] J. Newby,[10] D. S. Parno,[14] S. I. Penttila,[10] D. Pershey,[1] C. G. Prior,[1,2] R. Rapp,[18] H. Ray,[19] J. Raybern,[1] O. Razuvaeva,[4,5] D. Reyna,[9] G. C. Rich,[2] J. Ross,[7,2] D. Rudik,[4,‖] J. Runge,[1,2] D. J. Salvat,[15] J. Sander,[6] K. Scholberg,[1] A. Shakirov,[4] G. Simakov,[4,5] G. Sinev,[1,¶] C. Skuse,[14] W. M. Snow,[15] V. Sosnovtsev,[4] T. Subedi,[16,20] B. Suh,[15] R. Tayloe,[15] K. Tellez-Giron-Flores,[16] Y.-T. Tsai,[21] E. Ujah,[7,2] J. Vanderwerp,[15] E. E. van Nieuwenhuizen,[1,2] R. L. Varner,[10] C. J. Virtue,[13] G. Visser,[15] K. Walkup,[16] E. M. Ward,[3] T. Wongjirad,[22] J. Yoo,[23] C.-H. Yu,[10] A. Zawada,[2] J. Zettlemoyer,[15,**] and A. Zderic[11]

[1]*Department of Physics, Duke University, Durham, North Carolina 27708, USA*
[2]*Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708, USA*
[3]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[4]*National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow 115409, Russian Federation*
[5]*National Research Center "Kurchatov Institute," Moscow, 123182, Russian Federation*
[6]*Department of Physics, University of South Dakota, Vermillion, South Dakota 57069, USA*
[7]*Department of Mathematics and Physics, North Carolina Central University, Durham, North Carolina 27707, USA*
[8]*Department of Physics, North Carolina State University, Raleigh, North Carolina 27695, USA*
[9]*Sandia National Laboratories, Livermore, California 94550, USA*
[10]*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[11]*Center for Experimental Nuclear Physics and Astrophysics and Department of Physics, University of Washington, Seattle, Washington 98195, USA*
[12]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

Measurement of Electron-Neutrino Charged-Current Cross Sections on 127I with the COHERENT NaIvE Detector // P. An et al. Phys. Rev. Lett. ***131****, 221801 – Published 29 November 2023*

Ускоритель Spallation Neutron Source и эксперимент COHERENT



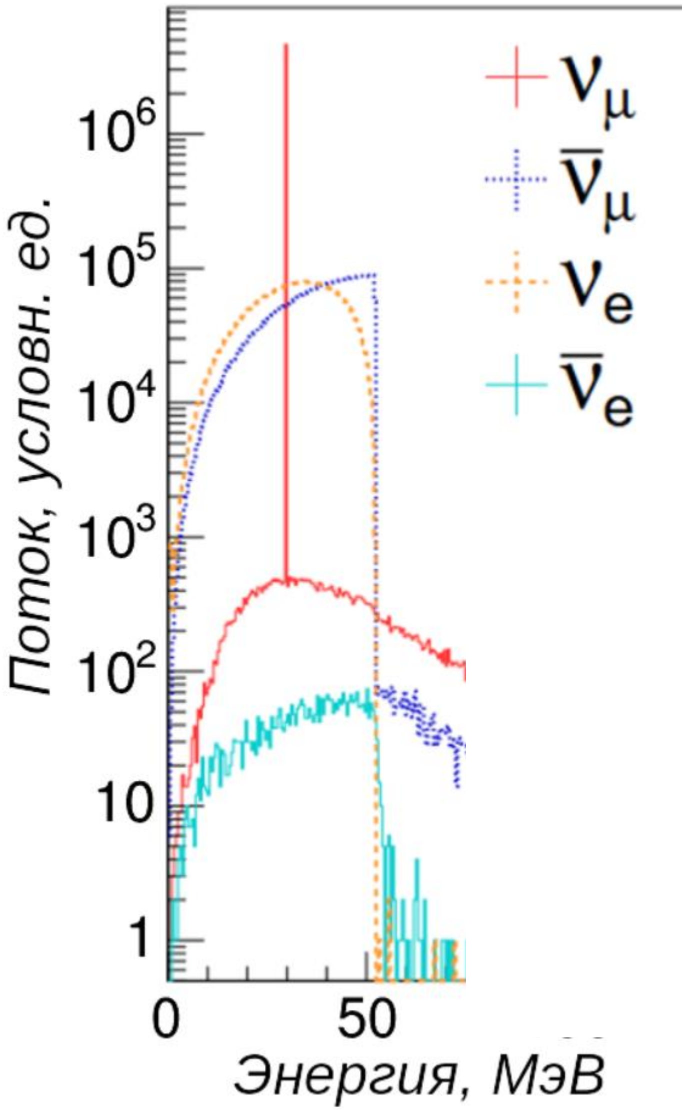


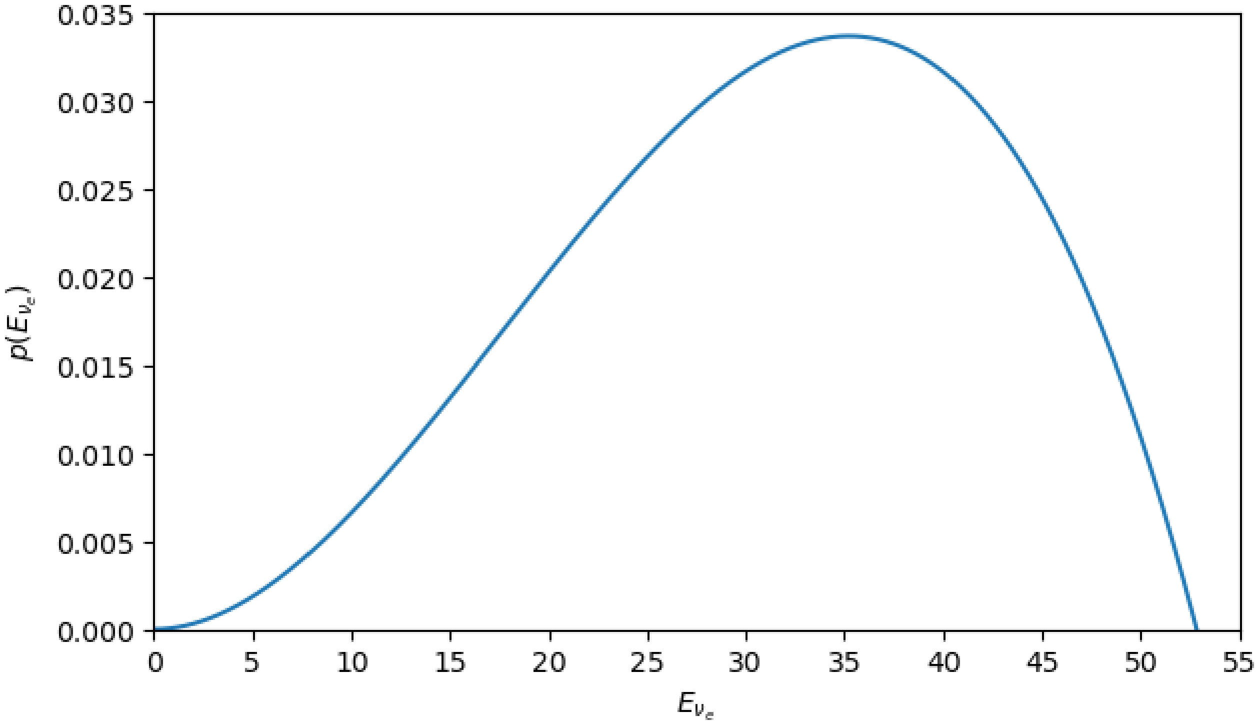
Спектр ускорительных нейтрино от источника SNS

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \quad \text{and} \quad \mu^+ \longrightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

$$p(E_{\nu_e}) = 96\frac{E_{\nu_e}^2}{m_\mu^4}(m_\mu - 2E_{\nu_e}),$$

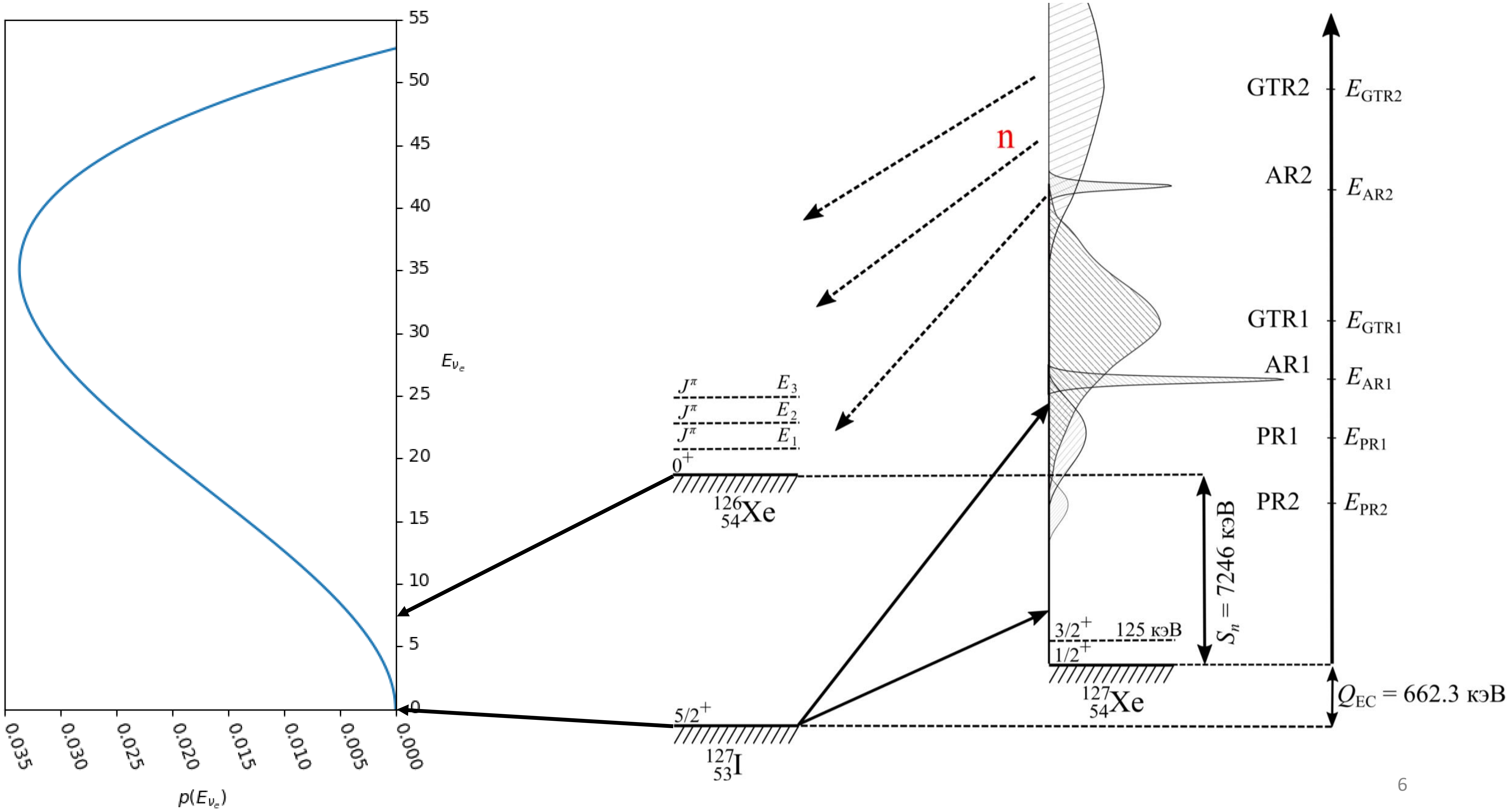
where m_μ is the muon mass and $E_{\nu_e} \in [0, m_\mu/2]$



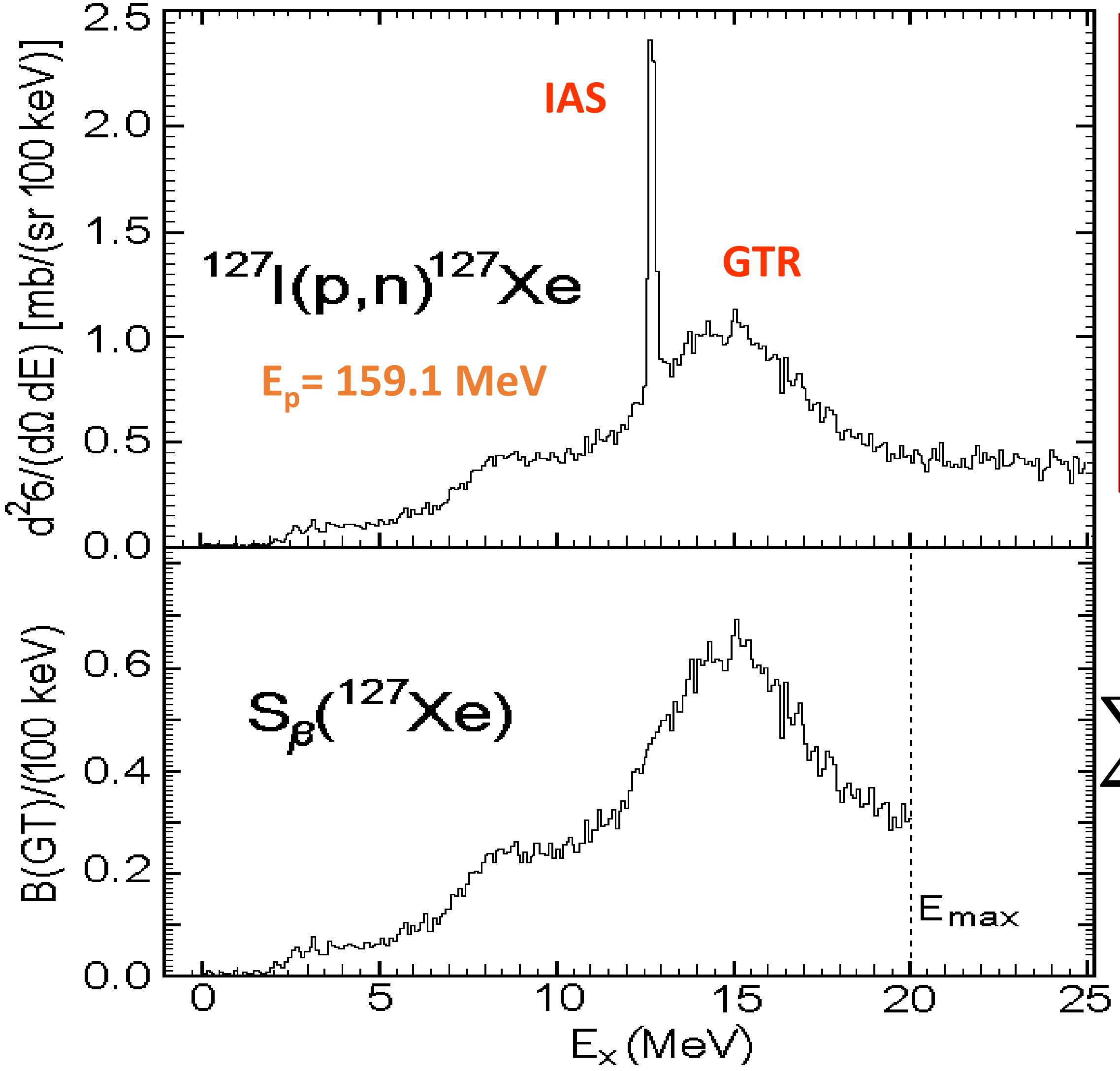


PHYSICAL REVIEW D 106, 032003 (2022) D. Akimov, P. An, C. Awe, P. S. Barbeau, et all. "Simulating the neutrino flux from the Spallation Neutron Source for the COHERENT experiment."

Зарядово-обменные резонансы в реакции $^{127}I(\nu_e, e^-)^{127}Xe$



Зарядово-обменная силовая функция реакции $^{127}I(p,n)^{127}Xe$



Первые расчеты:
Yu. S. Lutostansky, N. B. Shulgina. Phys. Rev. Lett. 67, 430 (1991)
были сделаны задолго до эксперимента и продемонстрировали хорошую точность предсказаний.

$$\sum B(GT) = 53.54 \pm 0.22\ stat.\ {}^{+3.32}_{-19.47} syst.$$

Гистограмма – эксперимент: M. Palarczyk, *et. al*. Phys. Rev. 1999. V. 59. P. 500;

Результаты эксперимента

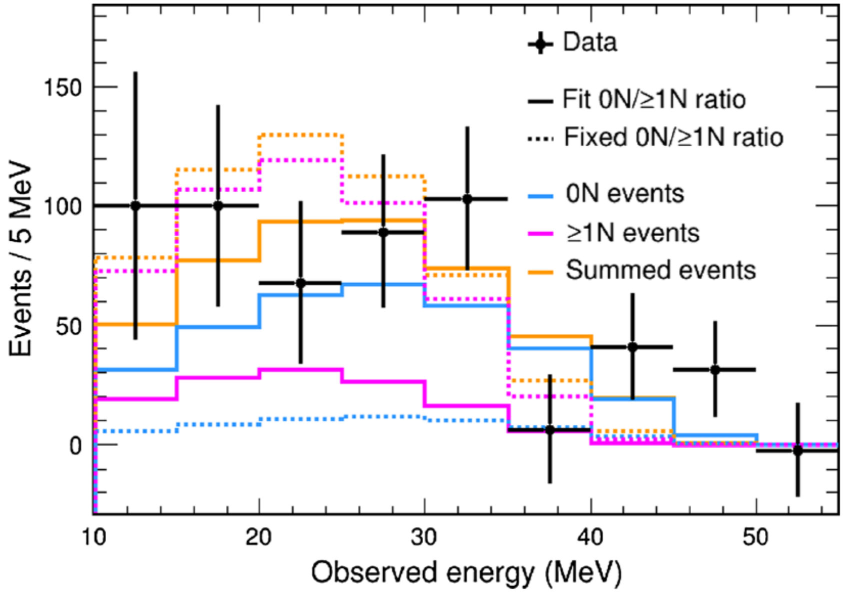


FIG. 4. The visible energy spectrum of CC events between 10 and 55 MeV is shown in black, along with the best-fit spectrum from MARLEY (orange) allowing the $\geq 1n$ and $0n$ amplitudes to float.

Conclusion.—COHERENT has measured the inclusive ν_eCC-^{127}I cross section on ^{127}I between 10 and 55 MeV to be $(9.2^{+2.1}_{-1.8}) \times 10^{-40}$ cm^2. This measurement is roughly 41% of the nominal cross section from MARLEY and to date is the heaviest CC neutrino-nucleus cross section measured in this energy regime.

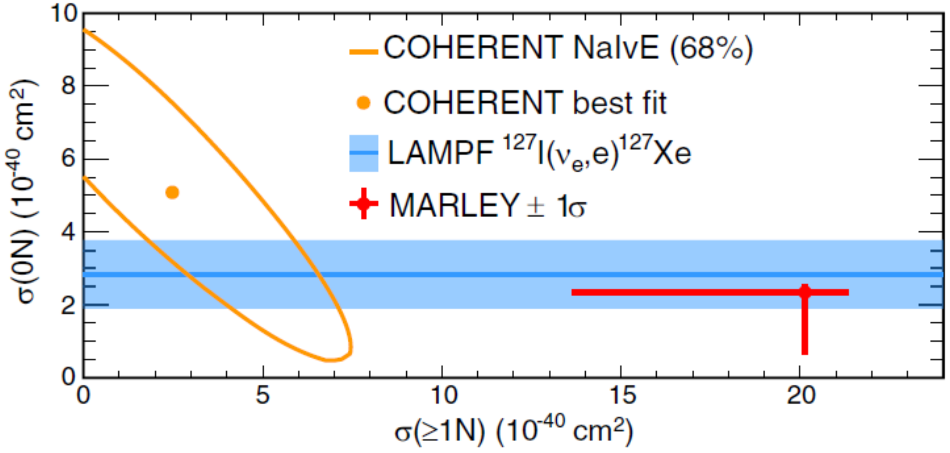


FIG. 5. Measurement (1σ) of the ν_eCC-^{127}I cross section separated into $0n$ and $\geq 1n$ channels compared to the MARLEY prediction and Ref. [12], measuring the $0n$ cross section.

From the 2D fit, we derive measurements of the cross sections to the exclusive $0n$ and $\geq 1n$ channels simultaneously. Our measurement is shown in Fig. 5. At 1σ, the NaIνE data imply $\sigma(0n) = (5.2^{+3.4}_{-3.1}) \times 10^{-40}$ cm^2 after profiling $\sigma(\geq 1n)$, consistent with Ref. [12] and MARLEY's prediction [18], though uncertainties are large due to the $\geq 1n$ events present in NaIνE. The determined 1σ range for $\sigma(\geq 1n)$ is $2.2^{+3.5}_{-2.2} \times 10^{-40}$ cm^2 is roughly 10× lower than the MARLEY model, suggesting the suppression in the total rate relative to MARLEY is due to the modeling of the $\geq 1n$ channel. Profiles for the exclusive cross-section fits can be found in Supplemental Material [18], which includes Refs. [29–37].

Система уравнений для эффективного поля (λ – представление)

Для расчетов зарядово-обменных возбуждений ядер использовалась теория конечных ферми-систем А.Б. Мигдала, в которой параметры изобарических состояний находятся из решения системы уравнений для эффективного поля гамов-теллеровского типа:

$$\left.\begin{aligned}
&V_{\lambda\lambda'} = V^{\omega}_{\lambda\lambda'} + \sum_{\lambda_1\lambda_2} \Gamma^{\omega}_{\lambda\lambda'\lambda_1\lambda_2} A_{\lambda_1\lambda_2} V_{\lambda_2\lambda_1} + \sum_{\nu_1\nu_2} \Gamma^{\omega}_{\lambda\lambda'\nu_1\nu_2} A_{\nu_1\nu_2} V_{\nu_2\nu_1};\\
&V_{\nu\nu'} = \sum_{\lambda_1\lambda_2} \Gamma^{\omega}_{\nu\nu'\lambda_1\lambda_2} A_{\lambda_1\lambda_2} V_{\lambda_2\lambda_1} + \sum_{\nu_1\nu_2} \Gamma^{\omega}_{\nu\nu'\nu_1\nu_2} A_{\nu_1\nu_2} V_{\nu_2\nu_1};\\
&V^{\omega} = e_q \boldsymbol{\sigma\tau}^{+}; \quad A^{(p\bar{n})}_{\lambda\lambda'} = \frac{n^{n}_{\lambda}(1-n^{p}_{\lambda'})}{\varepsilon^{n}_{\lambda} - \varepsilon^{p}_{\lambda'} + \omega}; \quad A^{(n\bar{p})}_{\lambda\lambda'} = \frac{n^{p}_{\lambda}(1-n^{n}_{\lambda'})}{\varepsilon^{p}_{\lambda} - \varepsilon^{n}_{\lambda'} - \omega}.
\end{aligned}\right\}$$

Г-Т ПРАВИЛА
ОТБОРА: Δ *j* =0;±1
Δ *j* =+1: *j=l+1/2 → j =l–1/2*
Δ *j* =0: *j=l±1/2 → j=l±1/2*
Δ *j* = –1: *j=l–1/2 → j=l+1/2*
j =l–1/2→ j =l–1/2

Использовалось локальное взаимодействие F^{ω} (Ландау-Мигдал):

$$F^{\omega} = C_0 (f_0' + g_0' \sigma_1\sigma_2)\, \tau_1\tau_2\, \delta(r_1 - r_2)$$

где константы: f_0' спин-спинового и g_0' спин-изоспинового взаимодействия квазичастиц, являются феноменологическими параметрами. $f_0' = 1.35$, $g_0' = 1.22$.

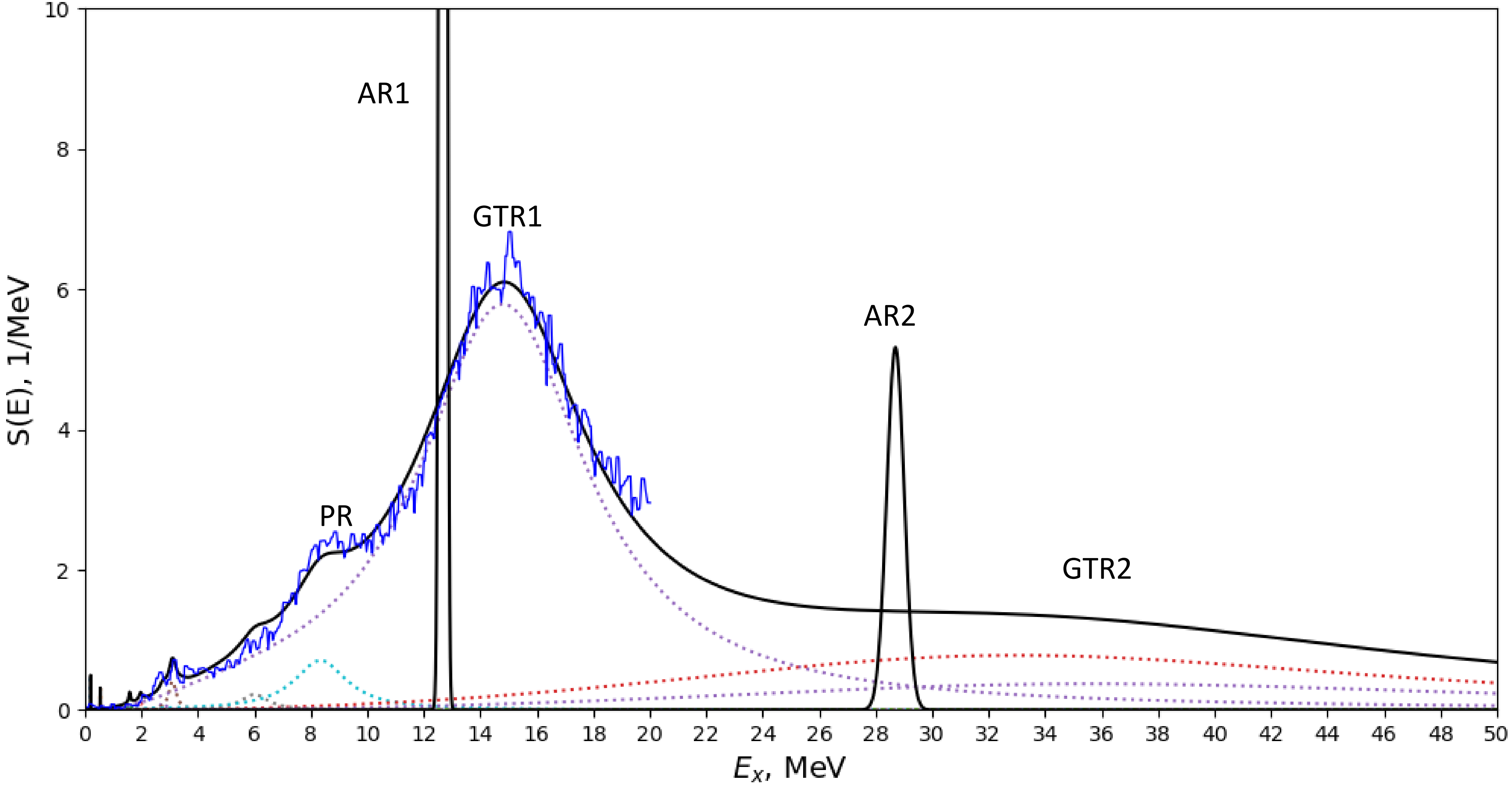
Матричный элемент M_{GT} : $$M^{2}_{GT} = \sum_{\lambda_1\lambda_2} \chi_{\lambda_1\lambda_2} A_{\lambda_1\lambda_2} V^{\varpi}_{\lambda_1\lambda_2}$$

Для парциальных силовых функций получаем: $$S^{i}_{\beta}(E) = M^{2}_{i} \cdot \frac{\Gamma_i(1 - \exp(-(E/\Gamma_i)^2))}{(E - w_i)^2 + \Gamma_i^2}$$

Ширина Γ_i согласно Мигдалу определяется соотношением: $\Gamma = \alpha \text{ x } \varepsilon|\, \varepsilon\, | + \beta\, \varepsilon^3 + \gamma\, \varepsilon^2|\, \varepsilon\, | + O(\varepsilon^4)\ldots,$

$\Gamma_{\mathrm{i}}(\omega_{\mathrm{i}}) = 0{,}018\ \omega_{\mathrm{i}}^2$ МэВ

Зарядово-обменная силовая функция ядра ^{127}I



Сечение захвата нейтрино ядром ^{127}I

$$\sigma(E_\nu) = \frac{g_A^2}{\pi}\int G^2 p_e E_e F(Z,E_e) S(E) dE$$

Ферми-функция – поправочный множитель, учитывающий кулоновское взаимодействие $F(Z,E_e) = \frac{|\psi_e(0)|_Z^2}{|\psi_e(0)|_{Z=0}^2}$

E. Fermi, “An attempt of a theory of beta radiation. 1.”, Z. Phys.88, 161–177(1934)

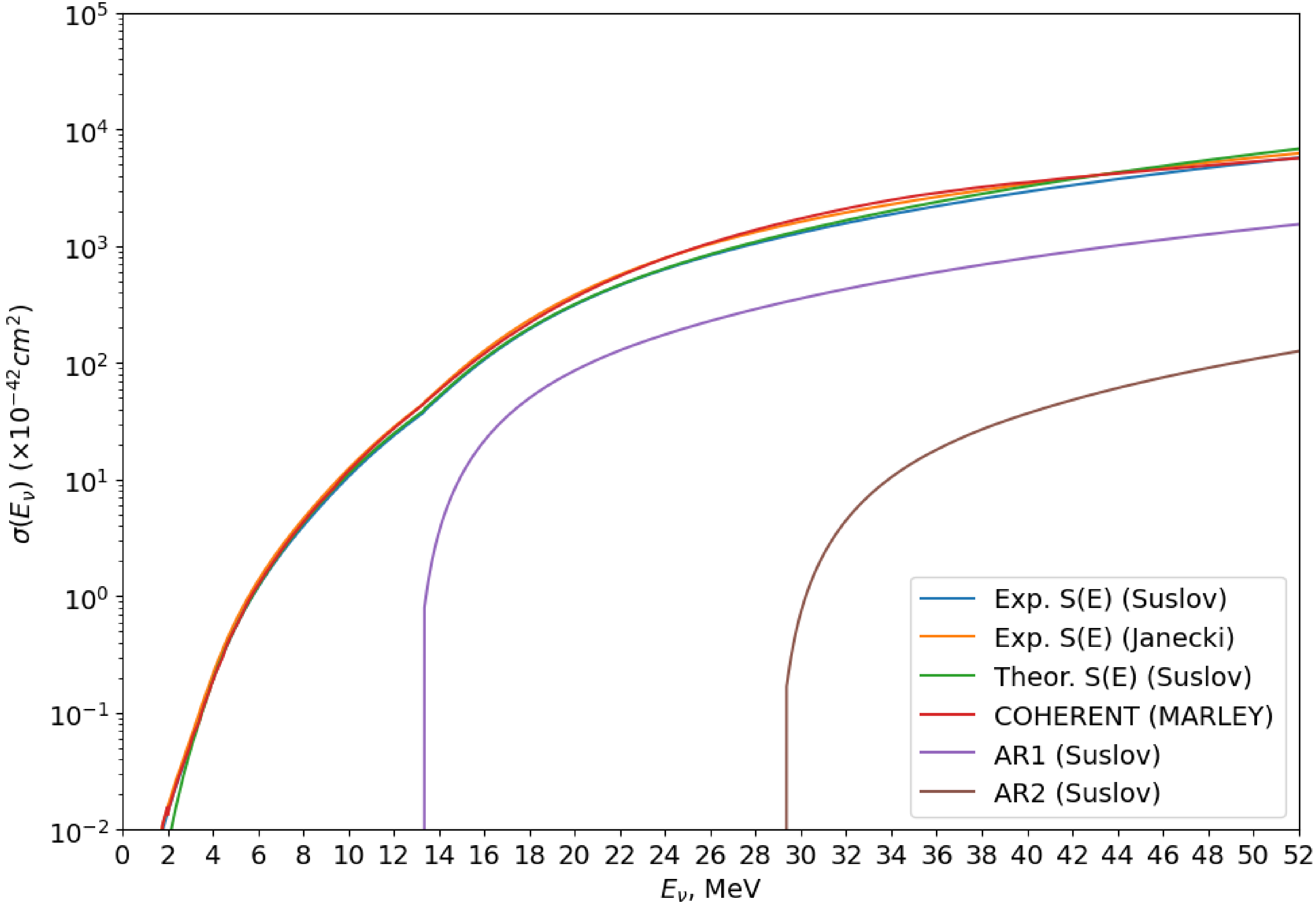
$$F_0(Z,A,W) = 4(2pR)^{2(\gamma-1)}\frac{|\Gamma(\gamma+iy)|^2}{(\Gamma(1+2\gamma))^2}e^{\pi y}, \gamma = \sqrt{1-(\alpha Z)^2}, y = \pm\alpha ZW/p$$

H. Behrens and J. Janecke,*Numerical Tables for Beta-Decay and Electron Capture, Landolt-Boernstein - Group I Elementary Particles,Nuclei and Atoms (Springer, 1969).*

Джелепов Б. С., Зырянова Л. Н., Суслов Ю. П. *Бета-процессы. Функции для анализа бета-спектров и электронного захвата. — Л.: Наука (1972).*

Jonathan Engel, *Approximate treatment of lepton distortion in charged-current neutrino scattering from nuclei, Phys. Rev. C V. 57, #4 (1998)*

Сечение захвата нейтрино ядром ^{127}I



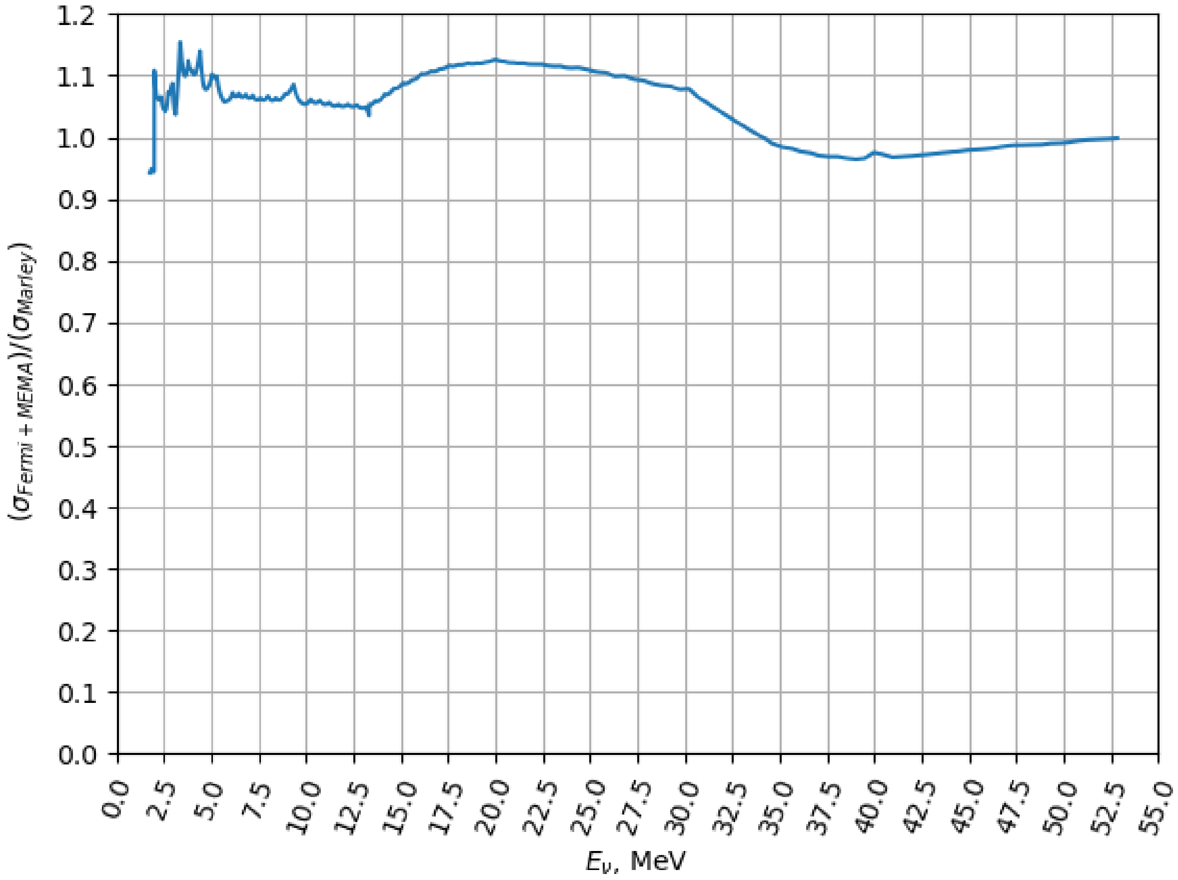
Результаты расчетов сечения захвата ускорительных нейтрино ядром ^{127}I

	$\sigma(0n) \times 10^{-40} cm^2$	$\sigma(\geq 1n) \times 10^{-40} cm^2$
Теор. расч. COHERENT (код MARLEY)	$2.3^{+0.2}_{-1.7}$	$\sigma(1n) = 18.9^{\pm 1.0}_{-5.3}$ $\sigma(2n) = 0.8^{\pm 0.1}_{-0.4}$
Эксп. результат COHERENT	$5.2^{\pm 3.4}_{-3.1}$	$\sigma(\geq 1n) = 2.2^{\pm 3.5}_{-2.2}$
Расчет (эксп. *S(E),* ферми функ. Суслова)	1.7	18.9
Расчет (теор. *S(E),* ферми функ. Суслова)	1.9	21.1

Выводы

- В работе представлена зарядово-обменная силовая функция *S(E)* ядра ^{127}I
- Впервые выполнены расчеты теоретической силовой функции ядра ^{127}I, рассчитанной в ТКФС, с учетом пигми, гигантского Гамов-Теллеровского и более высоколежащих ГТ состояний
- Выполнены расчеты сечения захвата ускорительных нейтрино ядром ^{127}I с использованием экспериментальной и теоретической силовой функции, рассчитанной в ТКФС
- Для $\sigma(0n)$ результаты расчетов находятся в хорошем согласии с результатами коллаборации COHERENT, для $\sigma(\geq 1n)$ расхождения все еще остаются
- Требуются дальнейшие исследования

Спасибо за внимание!


1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
$(\sigma_{Fermi+MEMA})/(\sigma_{Marley})$
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
22.5
25.0
27.5
30.0
32.5
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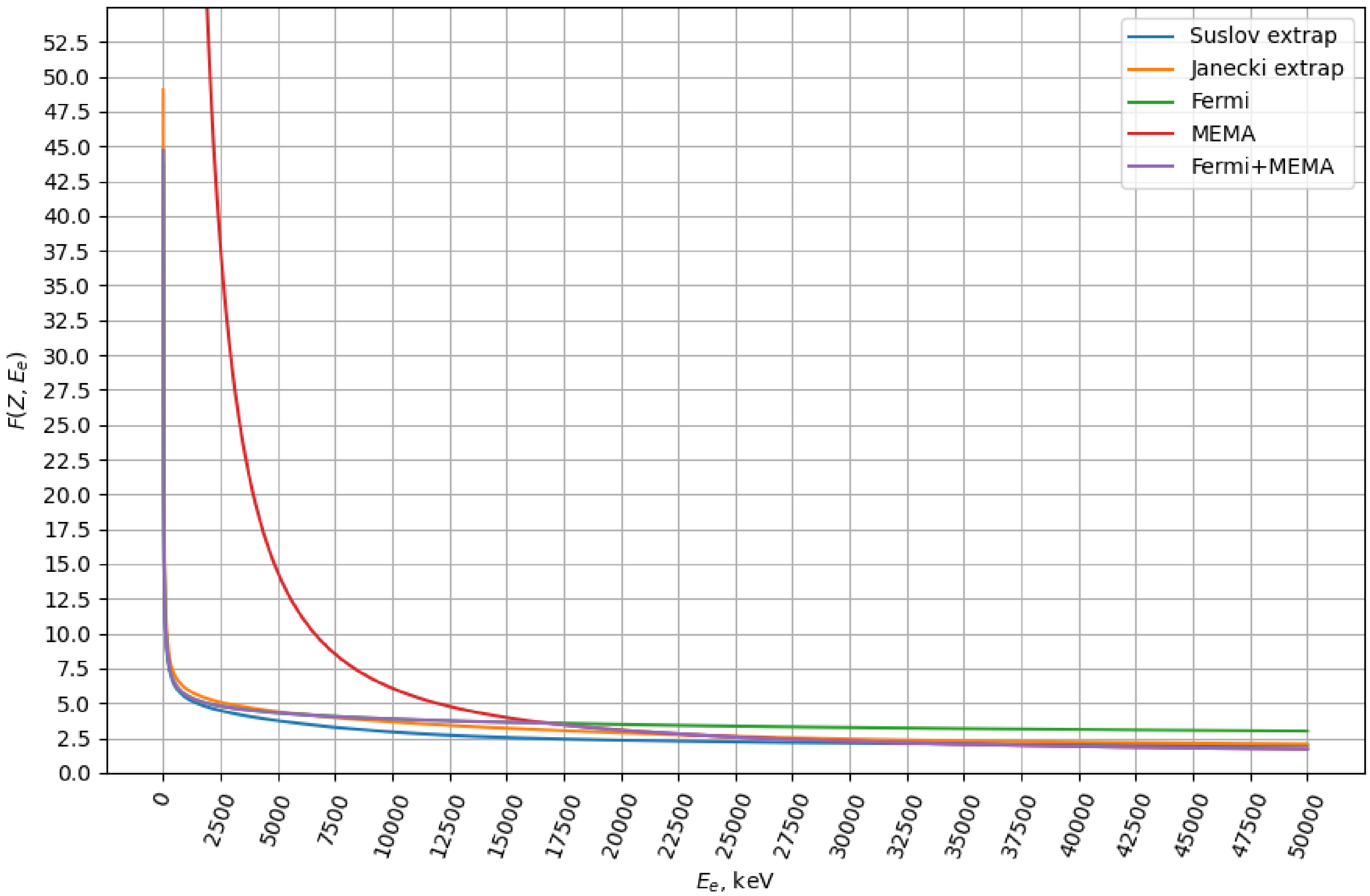
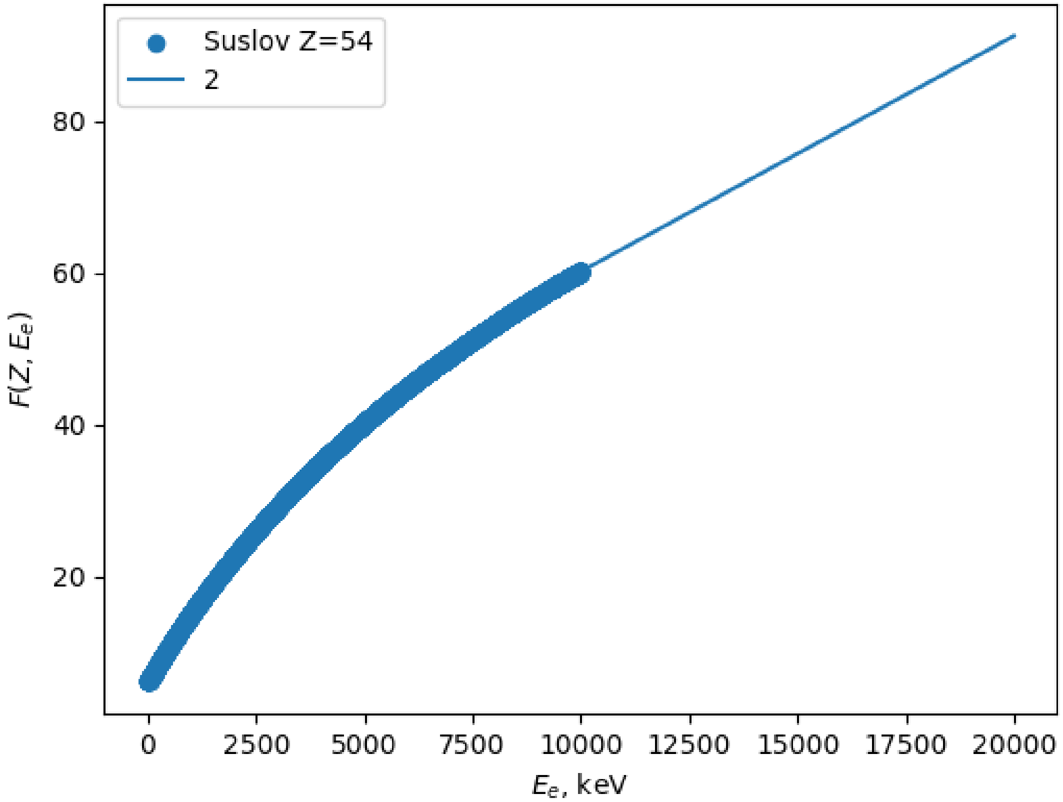
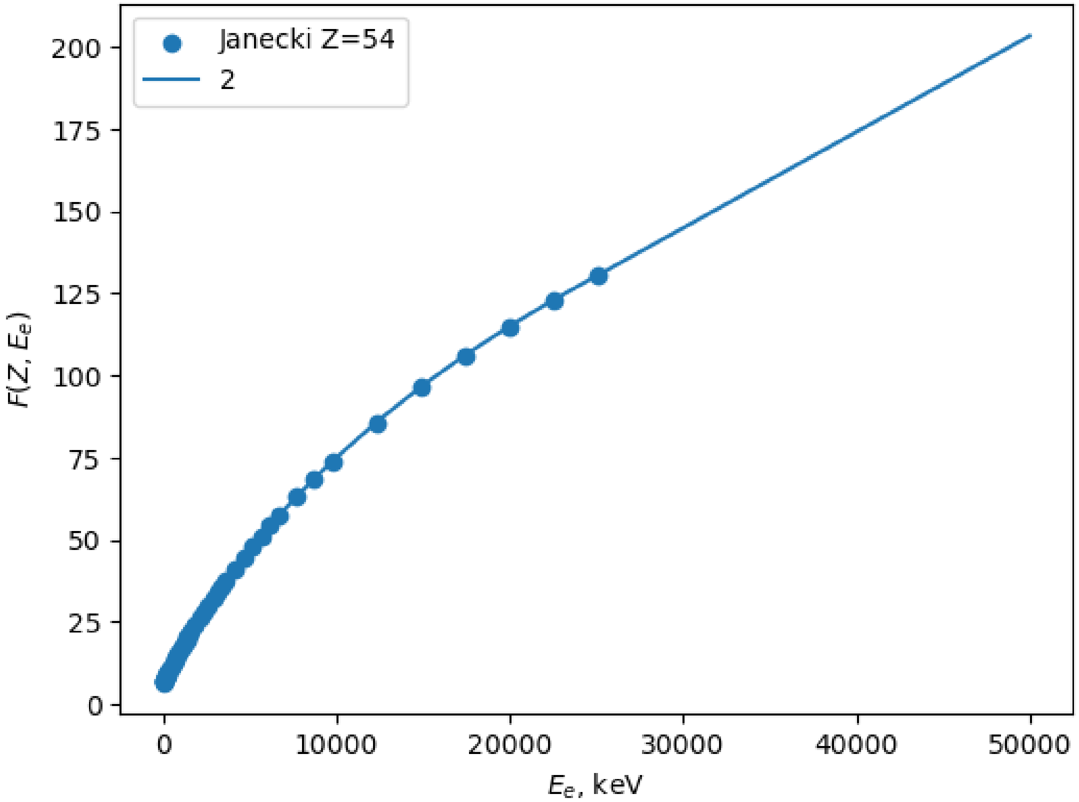
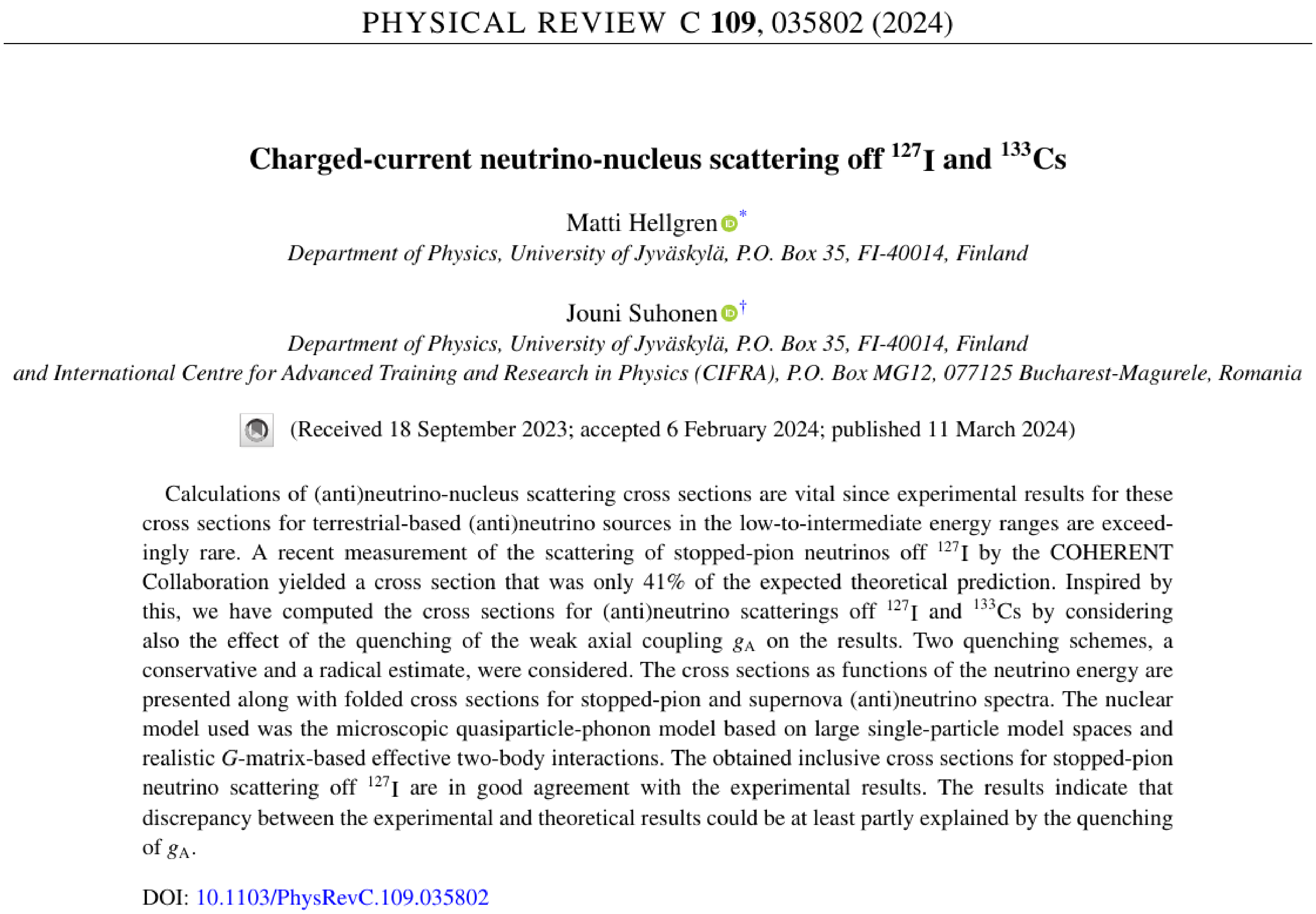
40.0
42.5
45.0
47.5
50.0
52.5
55.0
E_ν, MeV



Suslov extrap
Janecki extrap
Fermi
MEMA
Fermi+MEMA
$F(Z, E_e)$
52.5
50.0
47.5
45.0
42.5
40.0
37.5
35.0
32.5
30.0
27.5
25.0
22.5
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
0
2500
5000
7500
10000
12500
15000
17500
20000
22500
25000
27500
30000
32500
35000
37500
40000
42500
45000
47500
50000
E_e, keV


Suslov Z=54
2
80
60
40
20
0
2500
5000
7500
10000
12500
15000
17500
20000
$F(Z, E_e)$
E_e, keV


Janecki Z=54
2
200
175
150
125
100
75
50
25
0
0
10000
20000
30000
40000
50000
$F(Z, E_e)$
E_e, keV



PHYSICAL REVIEW C **109**, 035802 (2024)

Charged-current neutrino-nucleus scattering off ^{127}I and ^{133}Cs

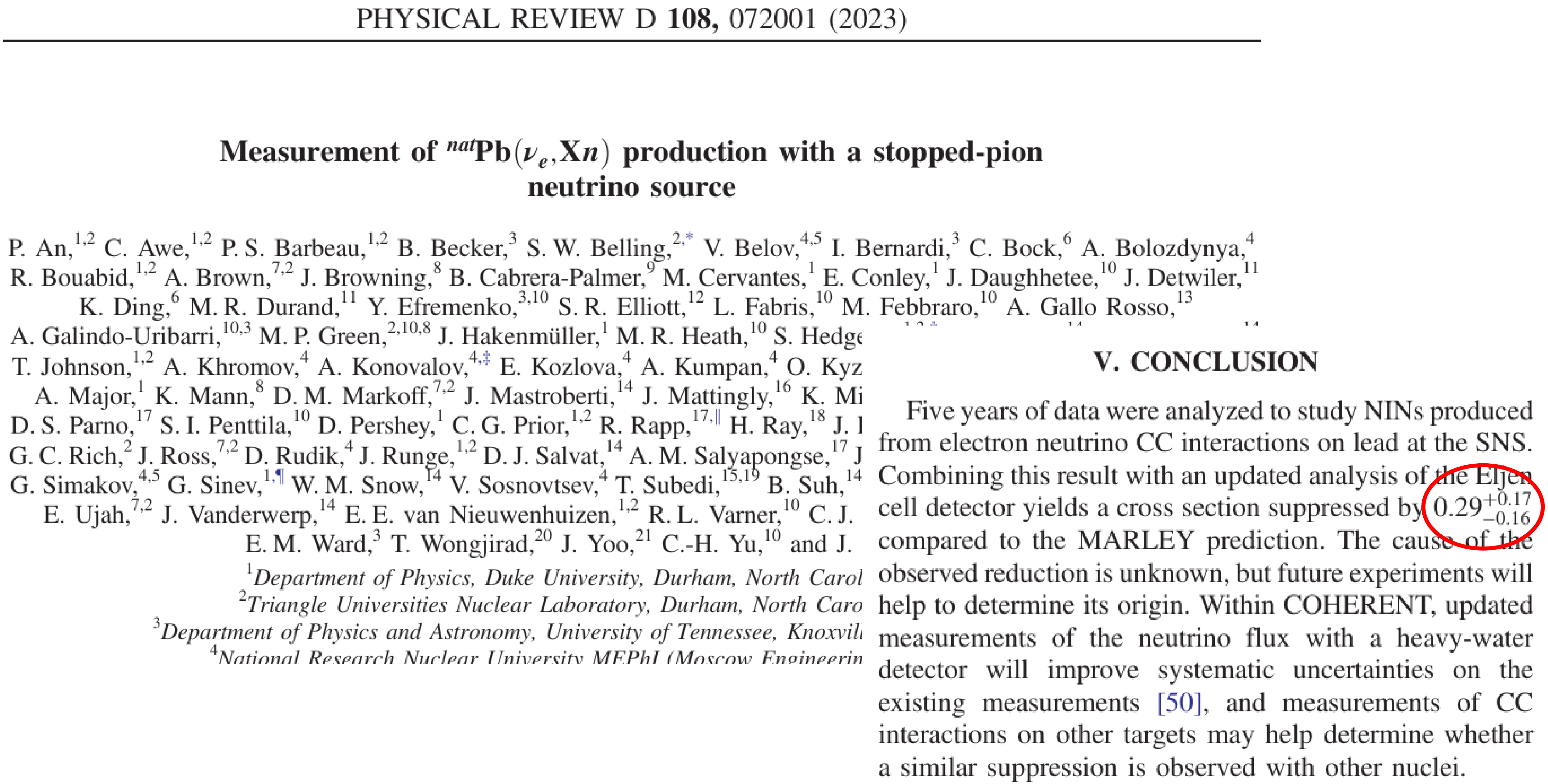
Matti Hellgren[*]
Department of Physics, University of Jyväskylä, P.O. Box 35, FI-40014, Finland

Jouni Suhonen[†]
Department of Physics, University of Jyväskylä, P.O. Box 35, FI-40014, Finland
and International Centre for Advanced Training and Research in Physics (CIFRA), P.O. Box MG12, 077125 Bucharest-Magurele, Romania

(Received 18 September 2023; accepted 6 February 2024; published 11 March 2024)

Calculations of (anti)neutrino-nucleus scattering cross sections are vital since experimental results for these cross sections for terrestrial-based (anti)neutrino sources in the low-to-intermediate energy ranges are exceedingly rare. A recent measurement of the scattering of stopped-pion neutrinos off ^{127}I by the COHERENT Collaboration yielded a cross section that was only 41% of the expected theoretical prediction. Inspired by this, we have computed the cross sections for (anti)neutrino scatterings off ^{127}I and ^{133}Cs by considering also the effect of the quenching of the weak axial coupling g_A on the results. Two quenching schemes, a conservative and a radical estimate, were considered. The cross sections as functions of the neutrino energy are presented along with folded cross sections for stopped-pion and supernova (anti)neutrino spectra. The nuclear model used was the microscopic quasiparticle-phonon model based on large single-particle model spaces and realistic G-matrix-based effective two-body interactions. The obtained inclusive cross sections for stopped-pion neutrino scattering off ^{127}I are in good agreement with the experimental results. The results indicate that discrepancy between the experimental and theoretical results could be at least partly explained by the quenching of g_A.

DOI: 10.1103/PhysRevC.109.035802



PHYSICAL REVIEW D **108,** 072001 (2023)

Measurement of $^{nat}\mathrm{Pb}(\nu_e,\mathrm{X}n)$ production with a stopped-pion neutrino source

P. An,[1,2] C. Awe,[1,2] P. S. Barbeau,[1,2] B. Becker,[3] S. W. Belling,[2,*] V. Belov,[4,5] I. Bernardi,[3] C. Bock,[6] A. Bolozdynya,[4]
R. Bouabid,[1,2] A. Brown,[7,2] J. Browning,[8] B. Cabrera-Palmer,[9] M. Cervantes,[1] E. Conley,[1] J. Daughhetee,[10] J. Detwiler,[11]
K. Ding,[6] M. R. Durand,[11] Y. Efremenko,[3,10] S. R. Elliott,[12] L. Fabris,[10] M. Febbraro,[10] A. Gallo Rosso,[13]
A. Galindo-Uribarri,[10,3] M. P. Green,[2,10,8] J. Hakenmüller,[1] M. R. Heath,[10] S. Hedge
T. Johnson,[1,2] A. Khromov,[4] A. Konovalov,[4,‡] E. Kozlova,[4] A. Kumpan,[4] O. Kyz
A. Major,[1] K. Mann,[8] D. M. Markoff,[7,2] J. Mastroberti,[14] J. Mattingly,[16] K. Mi
D. S. Parno,[17] S. I. Penttila,[10] D. Pershey,[1] C. G. Prior,[1,2] R. Rapp,[17,∥] H. Ray,[18] J.
G. C. Rich,[2] J. Ross,[7,2] D. Rudik,[4] J. Runge,[1,2] D. J. Salvat,[14] A. M. Salyapongse,[17] J
G. Simakov,[4,5] G. Sinev,[1,¶] W. M. Snow,[14] V. Sosnovtsev,[4] T. Subedi,[15,19] B. Suh,[14]
E. Ujah,[7,2] J. Vanderwerp,[14] E. E. van Nieuwenhuizen,[1,2] R. L. Varner,[10] C. J.
E. M. Ward,[3] T. Wongjirad,[20] J. Yoo,[21] C.-H. Yu,[10] and J.

[1]*Department of Physics, Duke University, Durham, North Carol*
[2]*Triangle Universities Nuclear Laboratory, Durham, North Caro*
[3]*Department of Physics and Astronomy, University of Tennessee, Knoxvil*
[4]*National Research Nuclear University MEPhI (Moscow Engineerin*

V. CONCLUSION

Five years of data were analyzed to study NINs produced from electron neutrino CC interactions on lead at the SNS. Combining this result with an updated analysis of the Eljen cell detector yields a cross section suppressed by $0.29^{+0.17}_{-0.16}$ compared to the MARLEY prediction. The cause of the observed reduction is unknown, but future experiments will help to determine its origin. Within COHERENT, updated measurements of the neutrino flux with a heavy-water detector will improve systematic uncertainties on the existing measurements [50], and measurements of CC interactions on other targets may help determine whether a similar suppression is observed with other nuclei.