Parity non-conservation in nuclear excitation by circularly polarized photon beam

A.I. Titov$^{1,2}$, M. Fujiwara$^{1,3}$ and K. Kawase$^3$

$^1$ Kansai Photon Science Institute, Japan Atomic Energy Agency, Kizu, Kyoto 619-0215, Japan

$^2$ Bogoliubov Laboratory of Theoretical Physics, JINR, Dubna 141980, Russia

$^3$ Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan

Abstract

We show that the asymmetries in the nuclear resonance fluorescence processes with a circular polarized photon beam may be used as a tool for studying the parity non-conservation (PNC) in nuclei. The PNC asymmetry measurements both in exciting the parity doublet states and in exciting the discrete states near the ground states with parity mixing are discussed. We derived the formulae needed for measuring the PNC asymmetries.

PACS: 24.70.+s; 24.80.+y; 25.20.Dc; 27.20.+n; 27.30.+t

Key words: Parity non-conservation, nuclear resonance fluorescence, parity doublet nuclear state.

Parity non-conservation (PNC) is well known after the discovery of the mirror symmetry violation in $\beta$-decays by Wu [1], following the suggestion by Lee and Yang [2]. The origin of this mirror-asymmetry is now clearly understood.
as a manifestation of the exchange processes of weak bosons, \( W^{\pm} \), which are mediators of \( \beta \)-decay.

Observations of the PNC effect in the nucleon-nucleon interaction are not new. The trial to observe the PNC effect began with the first report by Tanner in 1957 [3], followed by the famous work of Feynman and Gell-Mann [4] for the universal current-current theory of weak interaction. Wilkinson [5] also triggered the enthusiastic long studies of finding the tiny PNC effect in nuclear excitation processes.

The process contributing to the PNC effect is due to the non-trivial quark interactions with weak \( Z^0 \) and \( W^{\pm} \) bosons in the effective nucleon-nucleon-meson vertices. The details of the PNC studies were reviewed in Refs. [6,7]. However, the current problem is essentially focused on the fact that the weak meson-nucleon coupling constants (and in particular, the pion-nucleon coupling constant) deduced from various experiments are not consistent. It is concluded by Haxton et al., [8] that the experimental PNC studies are still not satisfactory, and more experimental as well as theoretical studies are needed.

One of experimental PNC studies is to measure the parity mixing between the parity-doublet states. On the basis of the first order perturbation theory, the wave functions of two closely-located states, \( |\phi_{\pi}\rangle \) and \( |\phi_{-\pi}\rangle \) are mixed by the PNC interaction \( V_{PNC} \) as

\[
|\tilde{\phi}_{\pi}\rangle = |\phi_{\pi}\rangle + \frac{\langle \phi_{-\pi}|V_{PNC}|\phi_{\pi}\rangle}{E_{\pi} - E_{-\pi}} |\phi_{-\pi}\rangle,
\]

where \( \phi_{\pi} \) and \( E_{\pi} \) are the wave function and the excitation energy of the levels with the same spin and opposite parity \( (\pi = \pm) \), respectively. In the traditional experiment, one of the doublet levels is excited in a nuclear reaction.
Then, the PNC effect appears in the asymmetry of emitted circularly polarized photons [6].

\[ P_\gamma \sim \frac{2R}{E_\pi - E_{-\pi}} \langle \phi_{-\pi} | V_{\text{PNC}} | \phi_\pi \rangle , \]  

(2)

where \( R \gg 1 \) is the ratio of the nuclear electromagnetic transitions with opposite parities. Thus, for example, in the case of \(^{21}\text{Ne}\), the level distance between the two excited \( 1/2^- \) and \( 1/2^+ \) states at 2789 keV and 2795 keV is only 5.7 keV, and a mixing of the order of about \( 300 \times 10^{-4} \) is expected. One experiment for \(^{21}\text{Ne}\) was performed by the Seattle group [9] and the asymmetry of \( (0.8 \pm 1.4) \times 10^{-3} \) was reported. Even though the nuclear amplifier factor is rather large, the accuracy of the measurement gives only upper bound of the nuclear PNC-effect. Other examples are reported in the E1 and M1 mixing transitions for \(^{19}\text{F}(1/2^-, 109.9 \text{ keV} \rightarrow 1/2^+, \text{g.s.}), \(^{18}\text{F}(0^-, 1.080 \text{ MeV} \rightarrow 1^+, \text{g.s.}), \) and \(^{175}\text{Lu}(9/2^-, 396 \text{ keV} \rightarrow 7/2^+, \text{g.s.}) \) (for details, see Refs. [6,7,10,11]).

In all cases, the prime problems to be solved are insufficient data accuracy and its interpretation for the transition matrix using a model calculation. Obviously, it is still important to obtain different types of reliable experimental results for checking the difficult PNC measurement.

In this paper, we wish to point out a possibility to use a circular polarized high intensive \( \gamma \)-ray beam for the PNC studies via the nuclear resonance fluorescence (NRF) processes. Assuming a circular polarized \( \gamma \)-ray beam is intense, one can excite the parity doublet states and observe the de-excitation of the \( \gamma \)-rays. The parity non-conservation will appear in the difference of the photon absorption with different helicities of the incoming \( \gamma \)-rays.

In fact, the asymmetry of the photon absorption \( A_{RL}^a \)
\[ A_{RL}^a = \frac{\sigma_R^a - \sigma_L^a}{\sigma_R^a + \sigma_L^a}, \]  

where \( \sigma_{R(L)}^a \) stands for the photon absorption cross sections with the right (left)-circularly polarized photons is equal to the asymmetry \( P_\gamma \) in Eq. (2) which was discussed in many papers [6,7,10,11]. The new aspect discussed here is that the asymmetry in reaction \( \gamma_i + A_{gs} \rightarrow A^* \rightarrow \gamma_f + A_{gs} \), \( A_{RL}(\theta) \), is, in general, different from \( A_{RL}^a \). The PNC asymmetry in the NRF process depends on the the angle (\( \theta \)) between the directions of flight of absorbed and emitted photons, and this dependence can enhance or reduce the PNC-effect.

Let us consider electromagnetic excitation and decay of the lowest excited \( \frac{1}{2}^- \) \( (E_x = 109.9 \text{ keV}) \) state in \( ^{19}F \). This example is very transparent and can be easily extended to other parity doublets with higher spins. Therefore, we use it as a starting point of our consideration, leaving discussion of practical utilization of this particular transition, which may be not so easy at once because of the finite life time of the radiative \( ^{19}F \). It is assumed that the ground state with \( J^a = \frac{1}{2}^+ \) and the first excited state with \( \frac{1}{2}^- \) are the parity doublet

\[
\left| \frac{1}{2}^+ \right> \simeq \left| \frac{1}{2}^+ \right> - \alpha \left| \frac{1}{2}^- \right>, \\
\left| \frac{1}{2}^- \right> \simeq \left| \frac{1}{2}^- \right> + \alpha \left| \frac{1}{2}^+ \right>,
\]

with

\[
\alpha = \frac{\langle \frac{1}{2}^- | V_{PNC} | \frac{1}{2}^+ \rangle}{\Delta E},
\]

and \( \Delta E = E_{\frac{1}{2}^-} - E_{\frac{1}{2}^+} \). The amplitude of the process \( \gamma_i + A \rightarrow A^* \rightarrow \gamma_f + A \) \( (A = ^{19}F) \) may be expressed as a product of absorption \( (T^a) \) and decay \( (T^d) \)-amplitudes.
\[ T_{\lambda_i\lambda_f} = T_{m^*;\lambda_i,m_i}^a \cdot T_{\lambda_f,m_f;m^*}^d, \]  

(6)

where \( m_i, m^*, m_f \), and \( \lambda_i, \lambda_f \) are the spin projections of the nucleus \( A \) in the initial, excited, and the final states, and the photon helicities in the initial and the final states, respectively. Here, we assume that the spin projection of the excited state is conserved during its short decay lifetime.

Fig. 1. Reaction scheme of \( \gamma_i + ^{19}F \left( \frac{1}{2}^+ \right) \rightarrow ^{19}F^* \left( \frac{1}{2}^- \right) \rightarrow \gamma_f + ^{19}F \left( \frac{1}{2}^+ \right) \)

First, consider the absorption of the circularly polarized photon. The general form of the nuclear electromagnetic transition amplitude in the obvious standard notations reads [13]

\[ T_{J_i,m_i;J_f,m_f} = -\sum_{L \geq 1} i^L \sqrt{2\pi(2L+1)} \frac{\langle J_i m_i L \lambda | J_f m_f \rangle}{\sqrt{2J_f + 1}} [F_{EL} + \lambda F_{ML}], \]  

(7)

where \( J_{i,f} \) and \( m_{i,f} \) are the spin and spin projection of the initial and the final states, \( \lambda \) is the photon helicity, \( F_{E/M L} = \langle f || T_{E/M}^L || i \rangle \) is the reduced matrix element of the multipole operators. In the case of \( J_i = J_f = \frac{1}{2} \), we have

\[ T_{m_f;\lambda,m_i} = i(\lambda E1 + M1)\delta_{m_f,\frac{\lambda}{2}} \delta_{m_i,-\frac{\lambda}{2}}, \]  

(8)

where we denote \( E1 \equiv \sqrt{2\pi}F_{E1} \) and \( M1 \equiv \sqrt{2\pi}F_{M1} \). The amplitude of the electromagnetic transition in the parity doublet of Eq. (4) reads

\[ T_{m^*;\lambda_i,m_i}(z) = i (\lambda_i E1 + \alpha \mu) \delta_{m_i,\frac{\lambda_i}{2}} \delta_{m_i,-\frac{\lambda_i}{2}}, \]  

(9)

where \( E1 \) is the dipole electric transition, and \( \mu \) is the difference of magnetic moments of the ground \( (\mu^+) \) and excited \( (\mu^-) \) states, respectively: \( \mu = \mu^+ - \mu^- \),
with

$$\mu^\pm = \sqrt{2\pi}\langle \frac{1}{2} | T_M^1 | \frac{1}{2} \rangle. \quad (10)$$

In Eq. 8 we stress the dependence of the transition amplitude on the quantization axis \( z \), explicitly. In our convention for the transition amplitude, the quantization axis coincides with the direction of the incident photon momentum.

Let us turn to the decay of the excited state \(^{19}\text{F}^* \rightarrow \gamma_f + ^{19}\text{F}\). The corresponding amplitude reads

$$T_{\lambda_f, m_f; \lambda f} (z') = -i (\lambda_f E1 + \alpha \mu)^* \delta_{m^* \lambda_f} \delta_{m_f - \lambda_f}. \quad (11)$$

The main difference between absorption and decay amplitudes comes from the difference in the quantization axis. Now it is fixed along the direction of flight of the outgoing photon. The spin polarizations of the excited state in the two frames are related to each other as

$$| \frac{1}{2}, m' \rangle = d^i_{mm'}(\theta) | \frac{1}{2}, m \rangle, \quad (12)$$

where \( d^i_{mm'}(\theta) \) is the Wigner function, and \( \theta \) is the angle between the beam direction and the direction of flight of the emitted photon. This relation leads to

$$T_{\lambda_f, m_f; \lambda f} = -i (\lambda_f E1^* + \alpha (\mu)^*) d^i_{\lambda_f \lambda f}(\theta) \delta_{m_f - \lambda_f}. \quad (13)$$

Taking into account

$$\sum_{\lambda_f} (d^i_{\lambda_f \lambda f}(\theta))^2 = 1,$$

$$\sum_{\lambda_f} \lambda_f (d^i_{\lambda_f \lambda f}(\theta))^2 = \lambda_i \cos \theta, \quad (14)$$
and neglecting the terms proportional to $\alpha^2$, we get the PNC-asymmetry in the following form

$$A_{RL}(\theta) = (1 + \cos \theta) < A_{RL} > ,$$

with

$$< A_{RL} > = 2\alpha \text{Re} \left( \frac{\mu}{E1} \right) ,$$

One can see that the PNC-asymmetry in the reaction $\gamma_i + {}^{19}\text{F} (\frac{1}{2}^+) \rightarrow {}^{19}\text{F}(\frac{1}{2}^-) \rightarrow \gamma_i + {}^{19}\text{F} (\frac{1}{2}^+)$ has “1 + cos $\theta$”-dependence. It is enhanced (suppressed) at $\theta \sim 0$ ($\theta \sim \pi$).

This idea can be extended to the other nuclei. In case of $^{18}\text{F}$, there are parity doublet states with $J^E = 0^+$ and $0^-$ at the energies $E_x = 1.042$ and 1.081 MeV, respectively. Although the $1^+$ ground state of $^{18}\text{F}$ is unstable and thus the experimental feasibility is very low, we show the result of corresponding calculation as a prediction for any $1^+ \rightarrow 0^-(0)$ transitions.

In case of the transition $\gamma + (1^+) \rightarrow (0^-)[1081 \text{ keV}] \rightarrow \gamma + (1^+)$ in $^{18}\text{F}$, the asymmetry is isotropic, because the excited state with $J = 0$ loses information about the spin-helicity in the initial state

$$A_{RL}(\theta) = < A_{RL} > = 2 \frac{< 0^-|V_{\text{PNC}}|0^+ >}{E_{0^+} - E_{0^-}} \text{Re} \left( \frac{M1}{E1} \right) .$$

Here $E1$ and $M1$ are the amplitudes of the $1^+ \rightarrow 0^-$ and $1^+ \rightarrow 0^+$ transitions, respectively.

The PNC asymmetry for the transition $\gamma + (\frac{3}{2}^+) \rightarrow (\frac{1}{2}^-)[2789 \text{ keV}] \rightarrow \gamma + (\frac{3}{2}^+)$ in $^{21}\text{Ne}$ has the following form
\[ A_{RL}(\theta) \simeq (1 + \frac{1}{4}\cos \theta) < A_{RL} >, \quad (18) \]

where

\[ < A_{RL} > = -2\frac{(\frac{1}{2} | V_{PNC} | \frac{1}{2}^*)}{E_{\frac{1}{2}^+} - E_{\frac{1}{2}^-}} \text{Re} \left( \frac{M_1}{E_1} \right), \quad (19) \]

where \( E_1 \) and \( M_1 \) are the amplitudes of the \( \frac{3}{2}^+ \rightarrow \frac{1}{2}^- \) and \( \frac{3}{2}^+ \rightarrow \frac{1}{2}^+ \) transitions, respectively, and the terms proportional to \( M_2/E_1 \) and \( E_2/M_1 \) are neglected. The factor \( \frac{1}{4} \) in Eq. (18) reflects the fact that the spin projection \( m_i \) of the ground state at the fixed photon helicity \( \lambda_i \) may be \( -\frac{1}{2}\lambda_i \) or \( -\frac{3}{2}\lambda_i \).

Instead of the reactions with polarized photons and unpolarized target, one can analyze the reactions with polarized target and unpolarized beam. The spin asymmetry is defined as

\[ A_S = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}, \quad (20) \]

where \( \sigma_\pm \) stands for the cross section with the target polarization \( M_i/J_i = \pm 1 \), and the quantization axis is along the beam direction. The corresponding asymmetries are related to the photon asymmetries \( A_{RL} \) as following:

\[ ^{19}F \]

\[ A_S(\theta) = -A_{RL}(\theta) = -(1 + \cos \theta) < A_{RL} >; \quad (21) \]

\[ ^{18}F \]

\[ A_S(\theta) = -A_{RL}(\theta) = - < A_{RL} >; \quad (22) \]

and \( ^{21}\text{Ne} \)

\[ A_S(\theta) = -(1 + \frac{1}{2}\cos \theta) < A_{RL} >. \quad (23) \]
In Table 1, we show other possible examples for studying the PNC-transitions in light nuclei by NRF. For completeness, we also show the corresponding angular correlations for the photon asymmetries for transitions with the spin in initial and final states are $J_i$ and $J_f$, respectively.

Transitions $0 \to 1$

$$A_{RL}(\theta) = \left(1 + \frac{\cos \theta}{1 + \cos^2 \theta}\right) < A_{RL} >.$$  
(24)

Transitions $0 \to 2$

$$A_{RL}(\theta) = \left(1 + \frac{2 \cos \theta (2 \cos^2 \theta - 1)}{1 - 3 \cos^2 \theta + 4 \cos^4 \theta}\right) < A_{RL} >.$$  
(25)

Transitions $1 \to 1$

$$A_{RL}(\theta) = \left(1 + \frac{2 \cos \theta}{5 + \cos^2 \theta}\right) < A_{RL} >.$$  
(26)

Transitions $1 \to 2$

$$A_{RL}(\theta) = \left(1 + \frac{90 \cos \theta}{73 + 21 \cos^2 \theta}\right) < A_{RL} >.$$  
(27)

In the equations described above, the average value of the asymmetry is defined as a the product of the PNC-matrix element and the nuclear amplifier factor

$$| < A_{RL}^i > | = 2 \left| \frac{P_N}{\Delta E_i} \langle |V_{PNC}| \rangle_i \right|.$$  
(28)

In summary, we have discussed the possibilities for studying the PNC asymmetries in the nuclear resonance fluorescence processes. This measurement is inverse compared to the widely discussed processes for the measurements of circular polarized $\gamma$-rays from the radioactive sources. In the previous experiments for the circular polarization measurement of emitted $\gamma$-rays, one of the
Table 1

Possible candidates for studying the PNC asymmetry in the light nuclei. The energy levels and the amplifier factors $|R_N/\Delta E|$ are given in keV and MeV$^{-1}$, respectively.

| $^AZ$ | $^{\text{transition}}\left(J^+_i;I_i\right)\rightarrow\left(J^+_f;I_f\right)$ | $[E_f]$ | $^{\text{admixture}}\left(J^-_f;I'_f\right)\rightarrow\left[J^-_f;I'_f\right]$ | $|R_N/\Delta E|$ |
|-------|---------------------------------|--------|---------------------------------|----------------|
| $^{14}$C | $(0^+, 1) \rightarrow (2^-, 1)$ | [7340] | $7010$ | $31 \pm 6$ |
| $^{14}$N | $(1^+, 0) \rightarrow (1^+, 0)$ | [6203] | $5691$ | $7.0 \pm 2.0$ |
| | $(1^+, 0) \rightarrow (0^+, 1)$ | [8624] | $8776$ | $40 \pm 5$ |
| | $(1^+, 0) \rightarrow (2^-, 1)$ | [9509] | $9172$ | $45 \pm 5$ |
| $^{15}$O | $(1^-, \frac{1}{2}; \frac{1}{2}) \rightarrow (1^-, \frac{1}{2}; \frac{1}{2})$ | [11025] | $10938$ | $37 \pm 7$ |
| $^{16}$O | $(0^+, 0) \rightarrow (2^-, 0)$ | [8872] | $6917$ | $18 \pm 2$ |
| | | | | $[11520]$ | $9.5 \pm 0.7$ |
| $^{18}$F | $(1^+, 0) \rightarrow (1^-, 0 + 1)$ | [5605] | $5603$ | $590 \pm 110$ |
| $^{20}$Ne | $(0^+, 0) \rightarrow (1^-, 0)$ | [11270] | $11262$ | $670 \pm 7000$ |

Parity doublet levels was excited via a nuclear reaction, and the admixture of the configuration of the opposite parity was manifested as the asymmetry $A_\gamma$ of $\gamma$-rays emitted from the excited states with a polarization, or as the circular polarization $P_\gamma$ of $\gamma$-rays emitted from unpolarized excited states. The isospin-structure of the corresponding transitions in each of these cases are different. This results in different structure of the transition matrix elements, and therefore it is possible to get independent information on the elementary parity-violated meson-nucleon coupling constants.
At present, there is no data available to measure the PNC effect with circular polarized photons although there are theoretical estimations for the PNC effect in the deuteron photodisintegration [14,15] for which the $A_{RL}$ asymmetry are expected to be very small as the $10^{-7}$ level.

In case of the PNC measurement for the transition from the $1/2^+$ ground state to the 109.9 keV $1/2^-$ state in $^{19}$F, for example, a high intensity photon source from the synchrotron radiation facilities at SPring-8 is useful. The intensity of photons from a elliptical multipole wiggler system at SPring-8 [16] reaches at around $10^{13}$ photons/second even at $E_\gamma=109.9$ keV with an energy width ($\Delta E$) of 100 eV. The expected yield rate $R$ of the $\gamma A \rightarrow A^* \rightarrow \gamma A$ reaction reads [17]

$$R = \pi^2 \lambda^2 \frac{\Gamma}{\Delta E} I_i \rho d N_A/A_t,$$

(29)

where $\Gamma = 7.7 \times 10^{-7}$ eV is the resonance width [18], $\lambda = \hbar c/E_\gamma \approx 1.79 \times 10^{-10}$ cm, $d$ and $\rho$ are the target thickness and the density, respectively, $N_A$ is the Avogadro constant, $A_t$ is the molecular weight of the target. Assuming implementation of a LiF target ($\rho \approx 2.64$ g/cm$^3$) with a thickness $d$ of 0.5 cm, $A_t \approx 26$, and $I_i \approx 10^{13}$, the expected yield ratio amounts to $7.4 \times 10^8$/second for exciting the 109.9 keV $1/2^-$ level in $^{19}$F.

The accuracy of the measurement depends on the details of the experimental set-up (counting rates, detection solid angles etc.). According to our estimation we expect to achieve the accuracy better than 10-20% for one week measurement, which exceeds considerably the previous experiments in the traditional design. The difficulty for this kind of experimental studies stems from a high counting ratio of the Compton scattered photons as background.
One method to overcome this problem is to use a multi-segmented detector in order to greatly reduce the counting rate of each detector and obtain the necessary total counts of $N \sim 10^{10}$ as the NRF events. The use of newly developed lutetium oxyorthosilicate (Lu$_2$SiO$_5$, LSO) and lutetium-yttrium oxyorthosilicate (Lu$_2$(1-x)Y$_2$SiO$_5$, LYSO) crystals [19,20] with a decay constant of about 40 ns and an energy resolution of 7-10% is also promising for the NRF measurement with a high-counting rate. Another way is to obtain a photon beam with an ultra high resolution of $\Delta E/E \sim 10^{-5} - 10^{-6}$. In this case, the background photons due to Compton scattering are greatly reduced, and the $\gamma$-ray events due to the NRF process are relatively enhanced to get a high counting rate necessary for performing a high-statics PNC measurement.

Acknowledgements

We thank H. Akimune, H. Ejiri, S. Dat’e, M. Itoh, Y. Ohashi, H. Ohkuma, Y. Sakurai, S. Suzuki, K. Tamura, H. Toki, and H. Toyokawa for fruitful discussions. One of the authors (A.I.T.) thanks T. Tajima for his hospitality to stay at SPring-8. This work was strongly stimulated by a new project to produce a high-intensity MeV $\gamma$-rays at SPring-8.

References

[1] Wu C S et al 1957 Phys. Rev. 105 1413

[2] Lee T D and Yang C N 1956 Phys. Rev. 104 254

[3] Tanner N 1957 Phys. Rev. 107 1203
[4] Feynman R P and Gell-Mann M 1958 *Phys. Rev.* **109** 193

[5] Wilkinson D H 1958 *Phys. Rev.* **109** 1603

[6] Adelberger E G and Haxton W C 1985 *Ann. Rev. Nucl. Sci.* **35** 501

[7] Desplanques B 1998 *Phys. Rep.* **297** 1

[8] Haxton W C, Liu C -P and Ramsey-Musolf M J 2002 *Phys. Rev. C* **65** 045502

[9] Earle E D, McDonald A B, Adelberger E G, Snover K A, Swanson H E, von Lintig R, Mak H B and Barnes C A, 1983 *Nucl. Phys. A* **396** 221c

[10] Holstein B.R “Weak Interactions in Nuclei”, (Princeton University Press, 1989)

[11] “Symmetries and Fundamental Interaction in Nuclei”, ed. by W. C. Haxton and E. M. Henley. World Scientific Publishing Co. Pte. Ltd. 1995, p. 17

[12] Adelberger E G, Hindi M M, Hoyle C D, Swanson H E, Von Lintig R D and Haxton W C 1983 *Phys. Rev. C* **27** 2833

[13] De Forest T and Walecka J D 1966 *Adv. Phys.* **15** 1

[14] Fujiwara M and Titov A I 2004 *Phys. Rev. C* **69** 065503

[15] Liu C P, Hyun C H and Desplanques B 2004 *Phys. Rev. C* **69** 065502

[16] Maéchal X.-M, Hara T, Tanabe T, Tanaka T and Kitamura H 1998 *J. Synchrotron Rad.* **5** 431

[17] Skorka S.J. “The electromagnetic interaction in nuclear spectroscopy” ed. by W.D. Hamilton. North-Holland 1975, p. 283

[18] Ajzenberg-Selove F, 1972 *Nucl. Phys. A* **190** 1, and see Table 19.10

[19] Qin L, Pei Yu, Lu S, Li H, Yin Z, and Ren G 2005 *Nucl. Instr. and Meths in Phy. Res. A* **545** 273, and references therein

[20] Chen J, Zhang L and Zhu R 2004 *Nuclear Science Symposium Conference Record IEEE* **1** 117