INER-F0982 **INER-F0982**

出國報告（出國類別：其他）

赴日本參加2015年創新醫療器材與健康照顧國際研討會暨參訪國家量測標準研究所出國報告

服務機關：核能研究所
姓名職稱：李國威　助理研究員
派赴國家：日本
出國期間：104年9月8日~104年9月13日
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摘要

國際學術組織(KES International)於日本京都舉行創新醫療器材與健康照顧國際研討會(Innovation in Medicine and Healthcare, INMED-15)，該會議彙集多學科領域專業人員與會，包括學生、研究人員、工程師、管理人員與醫界從業人員；共同探討內科、外科、醫療保健與人口老齡化所衍伸之醫療問題，以跨領域、創新之概念，提出智能醫療方式以解決當前醫療體系所面臨議題。李員藉由參加INMED 研討會，了解國際醫療器材開發趨勢，有助於提升國內自主開發醫療器材專業能力，對日後工作之推展與問題解決有所助益。

日本產業技術綜合研究院-國家量測標準研究所(National Metrology Institute of Japan, NMIJ)對於輻射劑量評估與量測技術已發展多年，在國際間具技術領導地位；科長 原野英樹(Hideki Harano)邀請本組李員赴日，參訪該中心於筑波市之輻射劑量量測系統，並針對放射診斷劑量量測與模擬技術進行交流討論。藉由參訪該中心，獲取寶貴的實務經驗。

關鍵字：醫療器材、輻射量測、國家標準實驗室

目次

一、目的

(一) 國際學術組織(KES International)於 2015 年假日本京都舉行創新醫療器材與健康照顧國際研討會(Innovation in Medicine and Healthcare, INMED-15)，該會議彙集多學科領域專業人員與會，包括學生、研究人員、工程師、管理人員與醫界從業人員；共同探討內科、外科、醫療保健與人口老齡化所衍伸之醫療問題，以跨領域、創新之概念，提出智能醫療方式以解決當前醫療體系所面臨議題。藉由參加 2015 年創新醫療器材與健康照顧國際研討會，蒐集業界最新醫療器材發展現況，獲得核醫藥物開發、醫學造影儀器開發、輻射劑量評估系統開發等領域資訊。

(二) 日本產業技術綜合研究所(National Institute of Advanced Industrial Science and Technology , AIST)量測標準研究部門(National Metrology Institute of Japan, NMIJ)為日本國家級法定計量技術機構。該機構科長 原野英樹(Hideki Harano)邀請本組李員赴日，參訪該中心於筑波市之輻射劑量量測系統、中子校正系統，並針對放射診斷劑量量測與模擬技術、蒙地卡羅體內劑量評估、擬人化假體驗證等議題進行經驗交流，期能提升國內自主開發醫療器材專業能力與高能中子校正能力，並對日後工作之推展與問題解決有所助益。

二、過程

李員本次赴日本之行程如表 2.1 所示，先參訪日本國家標準實驗室(NMIJ)，後轉赴京都參加 2015 年創新醫療器材與健康照顧國際研討會(INMED-15)，為期 6 天。分別說明 NMIJ 與 INMED-15 行程摘要如下。

表 2.1 出訪行程表

行程				公差地點	工作內容
月	日	地點		地名	
		出發	抵達		
9	8	桃園	日本	筑波市	去程
9	9			筑波市	參訪日本國家標準實驗室(NMIJ)
9	10	筑波市	京都	京都	移動與資料整理
9	11~12			京都	參加創新醫療器材與健康照顧國際研討會(INMED-15)
9	13	京都	桃園		回程

(一) 參訪 NMIJ/AIST

李員於 9/9 赴日本筑波市之 NMIJ 拜訪原野英樹科長，並參訪其轄下之中子校正實驗室、活度校正實驗室，與該實驗室之增田明彥研究員、松本哲郎研究員、柚木樟研究員等人進行技術交流。本次主要交流議題在於：高能中子場之中子偵檢儀器校正方法，以及目前日本

在高能中子輻射場度量之實務經驗。鑒於國內同步輻射中心 3 GeV 加速器以及長庚醫院質子治療中心均已順利完成軟硬體建構，商業運轉在即，高能加速器所可能誘發之高能中子量測技術遂成為國內輻射防護領域必須填補的一環。過去核研所受經濟部委託辦理之國家標準實驗室均採用平均能量 2 MeV 之 Cf-252 自發分裂中子源作為校正射源，其應用在高能中子場校正時將可能引入一定程度之誤差。回顧國際上其他國家的做法發現，各大型加速器實驗室均針對各自輻射場特性進行一定程度的校正結果修正。美國史丹福直線加速器中心的研究結果發現，若比較高能電子加速器遮罩設施外之中子周圍等效劑量(ambient dose equivalent)與有效劑量(effective dose)，可發現當高能中子場內能量大於 20 MeV 中子所占比例逐漸提高時，採用 Cf-252、AmBe 射源校正之 AB remmeter 將造成約 70%的低估情形；實務上史丹福直線加速器中心將 AB remmeter 之劑量讀值乘以 2 倍，來彌補由於校正射源並非高能中子源所造成的誤差。由 Klett 等作者在 2007 年在歐洲核子研究組織(CERN)的研究亦發現，對於能量達到數百 MeV 之中子輻射場，傳統中子劑量監測系統將達到約 30%~40%的劑量低估情形，必須藉由外加重金屬(如鉛)來進行修正；Naismith 與 Tanner 等作者，則搜集了一系列 20MeV 以下之輻射場能譜，提出以不同校正射源校正之區域監測器以及個人劑量計，在不同待測能譜硬度下之量測結果差異分析與歸納；Roberto 作者在 2011 年的回顧文章中更明確指出，若待測工作場所之中子能譜與校正室中子能譜差異明顯，則必須隨著待測輻射場變化而有相對應之劑量修正因數。

核能研究所國家標準實驗室作為國內唯一之中子儀器校正場所，近年來戮力發展高能中子場之校正方法。由李員於 2014 年所發表之國際期刊論文指出，可結合蒙地卡羅評估與現有 Cf-252 儀器校

正結果，做出適當的修正，即可獲得足夠保守且十分簡便之高能輻射場校正因子推估，李員即藉由本次參訪日本 NMIJ 機會，與日方專家進行本方法之深入討論，以吸取同儕之專業意見。經討論，日方對於本所所發展之修正方式深表認同，認為該方式可提供未知高能輻射場的校正依據，與日方在 2006 年所開發的技術略有雷同，但本所所提出的修正方式可更全面涵蓋能量至 10 GeV 高能中子，比日方當年所發展至 20 MeV 的修正方式大幅精進，日方對本所技術多所推崇。

李員進行完分享後，由日方進行現在日本一些高能場的量測實務分享。日方在高能中子場投入的經費與研究時程均較國內領先許多，光是 20 MeV 以上之高能場便有東京大學的 INS(最高能量 50 MeV)、東北大學的 CYRIC(最高能量 90 MeV)、理化學研究所的 RIKEN(最高能量 206 MeV)、日本原子力開發研究機構的 TIARA(最高能量 90 MeV)與大阪大學的 RCNP(最高能量 390 MeV)。日本 NMIJ 團隊均有機會前往前述之輻射場進行量測實驗，並發表為數頗豐之期刊論文，為國際相關領域之領先群。討論過程中日方展示了在各高能場的實際實驗方法，多採用與本所相同具備之波那球系統作為量測工具，較為不同的是，因應高能場的高中子通量，普遍採用金箔或熱發光劑量計作為量測工具，或採用比例計數器但搭配無感時間修正電子模組，來進行能譜量測實驗。

較為可惜的是，李員原期望能前往 NMIJ 鄰近之 TIARA 加速器進行參觀，但卻因其隸屬於日本原子力開發研究機構(JAEA)，相關的申請費時且不容易獲得核可，故無法於本次成行。但透過本次與日方進行技術交流後，日方同意協助本所進行單能中子校正實驗，故李員於返台後，即透過日商將本所習用之波那球系統送往 NMIJ 進行不同能量之中子校正實驗，並將其結果與蒙地卡羅評估結果進行驗證，同時

比對與國內 Cf-252 中子源之校正差異，同時參考該校正結果作為長庚醫院第 5 間實驗室設計參考。由本次交流可知，未來若需與日本 NMIJ 進行中子量測實驗比對，透過日商辦理儀器進出口即可達成；但若需要在 TIARA 高能場進行量測實驗(45 MeV 類單能中子)，則必須先與 NMIJ 有實質的合作計畫，並支付合作計畫費用，待取得正式的 NMIJ 訪問研究員身分後，方可透過 NMIJ 向 JAEA 申請 TIARA 之使用許可。以過往之經驗看來，該合作案之申請需時 1.5 年以上。圖 2.1~圖 2.6 為 TIARA、CYRIC 與 RCNP 加速器示意圖以及該設施之能譜量測結果；圖 2.7~圖 2.8 為李員與日方研究人員討論情形；圖 2.9~圖 2.15 為日本 NMIJ 部分實驗設備照片。

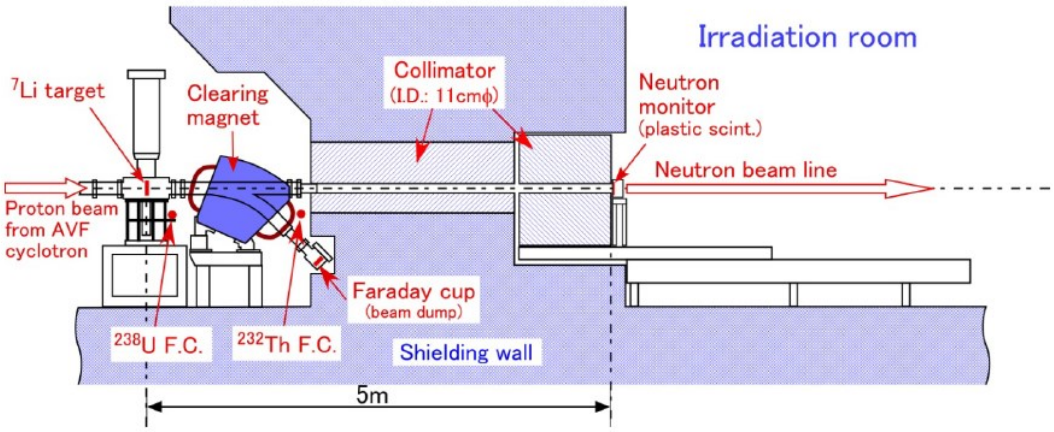

圖 2.1 日本原子力開發研究機構的 TIARA 加速器示意圖

TIARA 加速器隸屬於 JAEA，可產生 40~90 MeV 之類單能中子，主體為相位角調變迴旋加速器(azimuthal varying field cyclotron，AVF cyclotron)，質子束產生後撞擊 Li 靶，並於 Li 靶後設置偏轉磁鐵，將帶電粒子收集於法拉第盃；此外，並設置 U-238 與 Th-232 分裂游離腔作為 beam monitor 之用。照射室尺寸為 19 公尺長、11 公尺寬、與 6 公尺高，並可在 Li 靶後方 5~18 公尺進行量測。圖 2.2 為利用 TOF

方式進行之能譜量測結果，分別為 50 MeV、65 MeV、80 MeV。

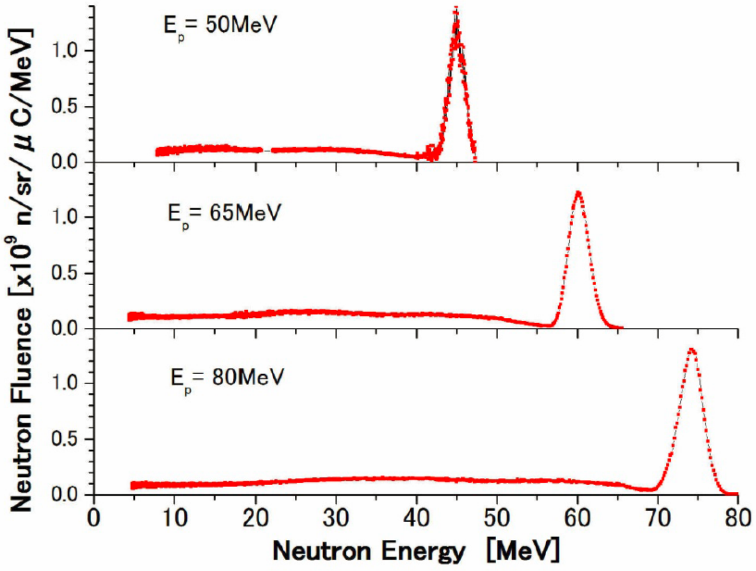

圖 2.2 日本原子力開發研究機構 TIARA 加速器能譜量測結果

CYRIC 加速器隸屬於日本東北大學，加速器亦為 AVF cyclotron，質子加速後撞擊 Li 靶，並以水冷方式冷卻靶材。質子束穿過 Li 靶後，透過偏轉磁鐵將帶電粒子旋轉 25 度。標準之中子源生成強度為 10^{10} sr^{-1}-s^{-1}-μA^{-1}，能量誤差 5%，位置誤差±2%。CYRIC 設計之中子準質儀為厚度 59.5 公分之鋼材(steel)，熱中子通量為 $2x10^4$ cm^{-2}-s^{-1}，透過金箔活化方式進行。圖 2.4 為利用 70 MeV 質子束撞擊 Li 靶後產生之 65 MeV 類單能中子能譜結果，Li 靶的厚度為 0.91 公分，量測位置距離 Li 靶 7.37 公尺。65 MeV 中子能峰通量佔全體通量之 40%，快中子能譜則是利用有機閃爍偵檢器 NE-213 進行量測，並連結 CAMAC 資料擷取系統(DAQ)。照射室長 10 公尺，寬 1.8 公尺，高 5 公尺。

最後，日方 NMIJ 人員亦提出，由於 CYRIC 加速器空間較小，導致控制室的人員輻射劑量頗高，此部分亦為國內在進行加速器設計時之重要考量。

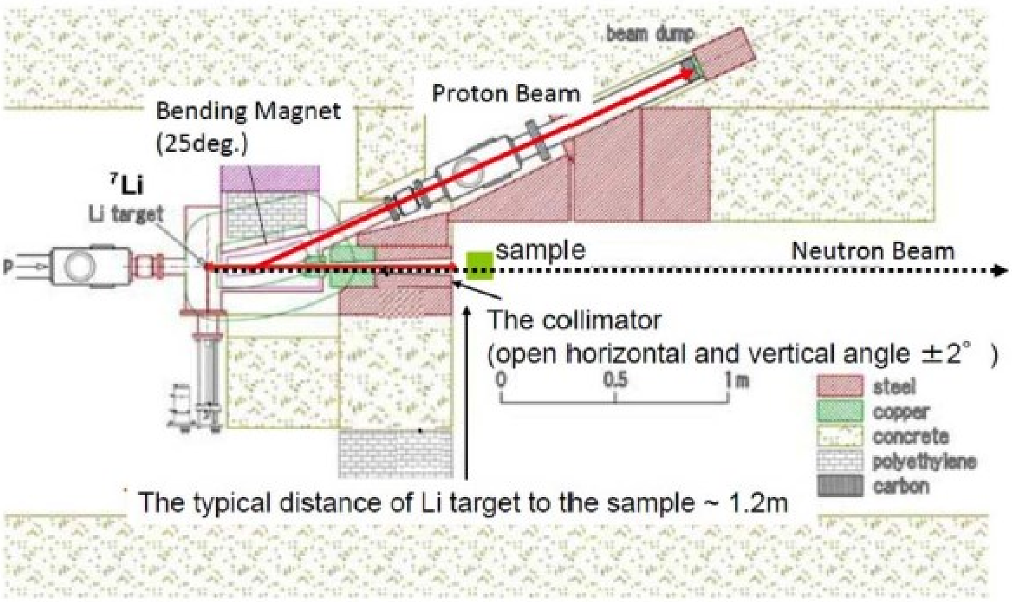

圖 2.3 東北大學的 CYRIC 加速器示意圖

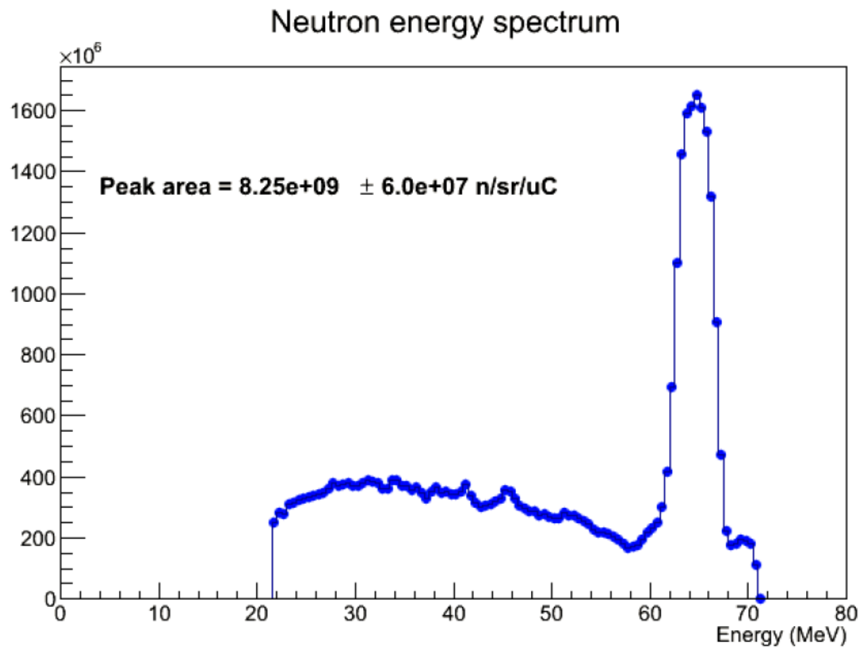

圖 2.4 東北大學的 CYRIC 加速器能譜量測結果

大阪大學的 RCNP 加速器提供能量 100 MeV 至 400 MeV 之高能類單能中子束。在 RCNP 的設計中，先將中子透過 AVF 迴旋加速器加速至 65 MeV，再透過增能環加速至 400 MeV。Li 靶的厚度為 1.0 公分，置於真空中；實驗通道長度為 100 公尺，提供了 TOF 實驗相當良好的條件。圖 2.6 分別是 90 MeV、137 MeV、200 MeV、246 MeV、352 MeV 與 389 MeV 中子束能譜量測結果。

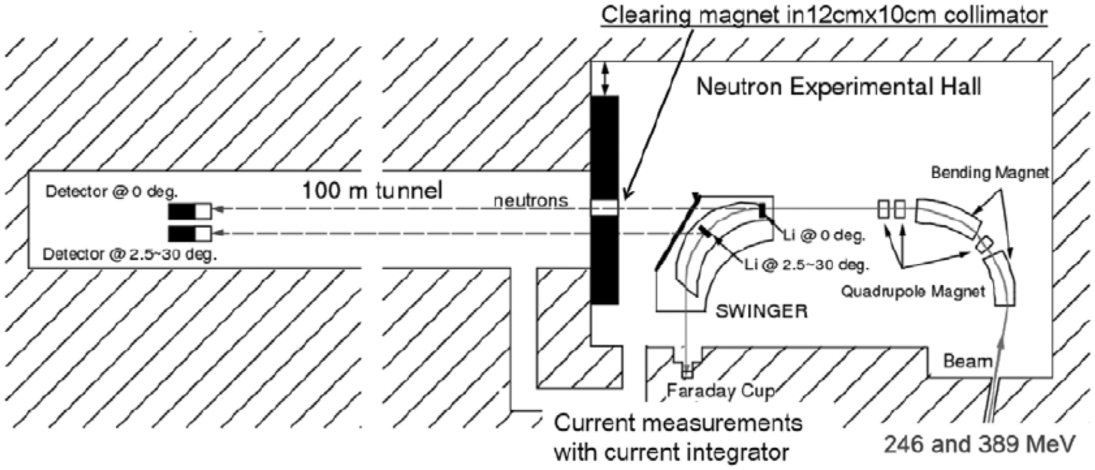

圖 2.5 大阪大學的 RCNP 加速器示意圖

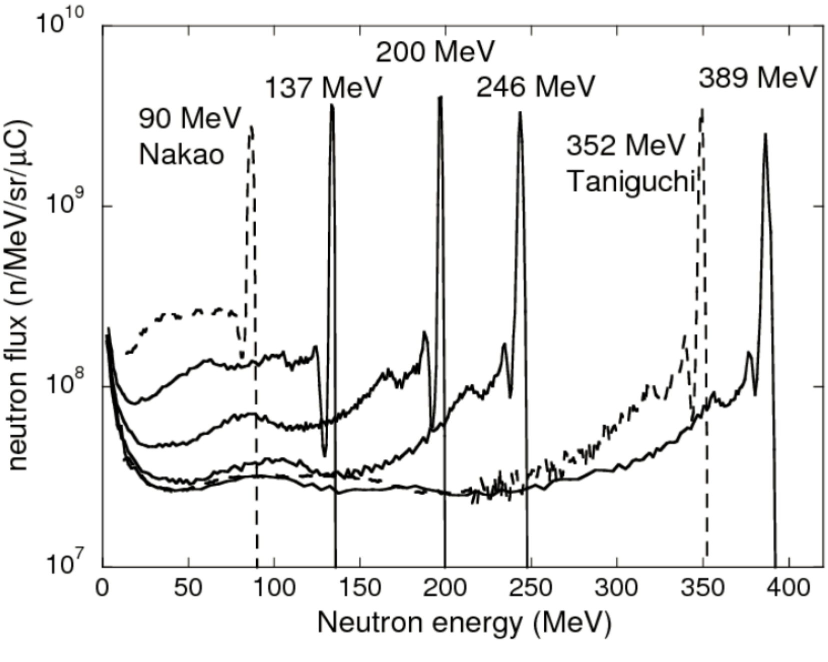

圖 2.6 大阪大學的 RCNP 加速器能譜量測結果

圖 2.7 為李員與日本 NMIJ 松本哲郎研究員於 AIST 加速器討論情形。AIST 共有兩組不同加速器可供實驗，目前最高能量可達 14.1 MeV；松本哲郎研究員之專長在於加速器維護與操作，該加速器於 311 地震中嚴重損壞，松本哲郎研究員經過 2 年多努力，已於 2013 年完成修復，目前已可正常操作運轉。圖 2.7 中，即為松本哲郎研究員再進行例行的加速器維護保養過程，李員有幸參與其中過程，並與松本哲郎研究員仔細討論加速器維護等相關事宜。

核能研究所物理組亦於過去有一台相仿之加速器，惟該加速器亦於 921 地震中遭受嚴重損壞，經成本評估後決定不予維修，因此國內目前相關單能中子場尚付之闕如。

圖 2.7 與日本 NMIJ 松本哲郎研究員討論加速器內部結構

圖 2.8 為李員與日方增田明彥研究員進行討論照片。增田明彥研究員多次參與日本高能加速場中子能譜量測實驗，包括 RCNP、TIARA、CYRIC 場。該團隊並於 2015 年完成於 TIARA 加速器建置

45 MeV 單能中子場，提供日本國內與國際將合作團隊高能中子校正服務。增田明彥研究員本身亦負責波那球中子能譜量測系統之研製與開發，與李員針對波那球系統進行諸多意見交流，並實地帶李員於 NMIJ 校正室內進行量測實驗。

圖 2.8 與日本 NMIJ 增田明彥研究員討論高能中子校正方法

圖 2.9 日本 NMIJ 之波那球中子量測系統

圖 2.10 為 NMIJ 之硫酸錳浴中子原級校正設備。核能研究所過去亦曾經建立相關之技術能力，後因考慮人力與實際使用頻率後予以終止。日方之硫酸錳浴中子原級校正設備現階段亦處於停止運作之狀態，惟該團隊將於 2016 年引進新一代之硫酸錳浴校正設備，可大幅降低操作複雜程度，並節省運維人力。

此外，亦參觀了 NMIJ 的長計數器(long counter)。長計數器由於其平坦的中子響應而被廣泛用作中子通量監測使用。但是，為了達到平坦的中子響應，需要有笨重的中子緩速體包圍偵檢器，其最大的缺點即在於攜帶不便，以及產生了不必要的散射中子源。然而，一旦減少了緩速體的尺寸，將造成中子響應平原的減少，此種情形在高能中子輻射場中特別顯著。為此，NMIJ 開發了一種新型的中子偵檢器，在維持相同平坦的中子響應平原前提下，減少緩速體的尺寸，稱此種偵檢器為緊湊型平坦反應度中子偵檢器(Compact Flat-Response Neutron Detector)。偵檢器由兩個球型 He-3 比例計數器組成，並將球

型計數器放置在圓柱形聚乙烯緩速體中的適當位置。藉由調整兩個偵檢器間的靈敏度比例，來提供一個平坦的總中子響應輸出。實驗後發現，新型中子偵檢器在 20MeV 能量以下，具有和長計數器相當一致且平坦的中子響應平原；且新型偵檢器之重量只有傳統長計數器的五分之一。另一方面，新型偵檢器的「有效中心」位置乃是一中子能量函數，NMIJ 據此提出利用有效中心進行中子能量量測的方法；因此，新型偵檢器將同時具有中子通量以及能量的量測能力，此特徵使得該偵檢器在許多應用場合中將具有明顯的優勢。

圖 2.10 日本 NMIJ 之硫酸錳浴中子原級校正系統

圖 2.11 日本 NMIJ 之石墨管中子原級校正系統

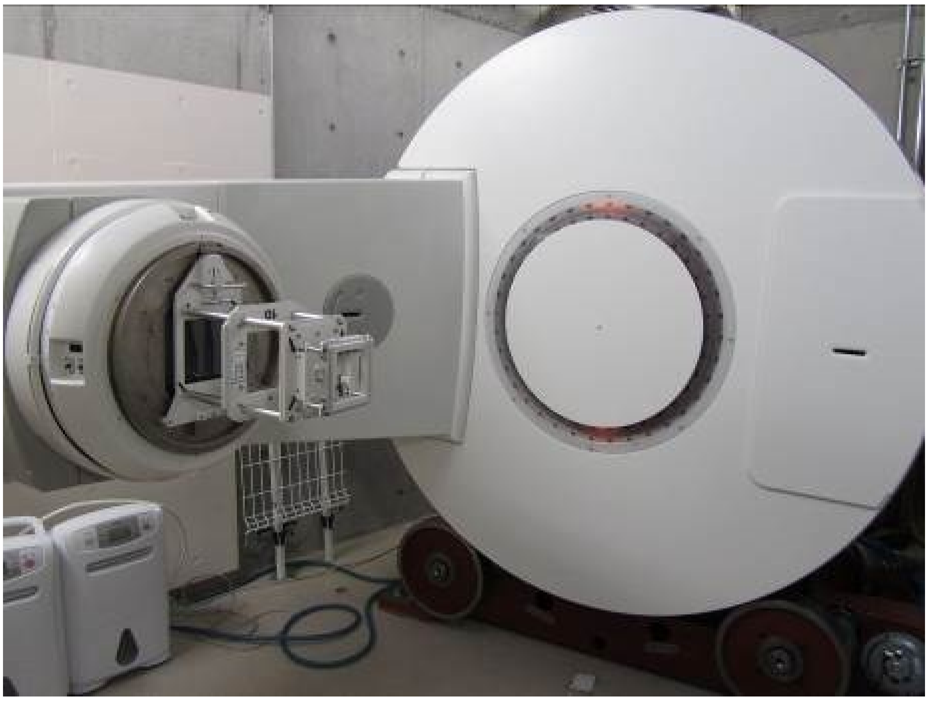

圖 2.12 日本 NMIJ 之直線加速器

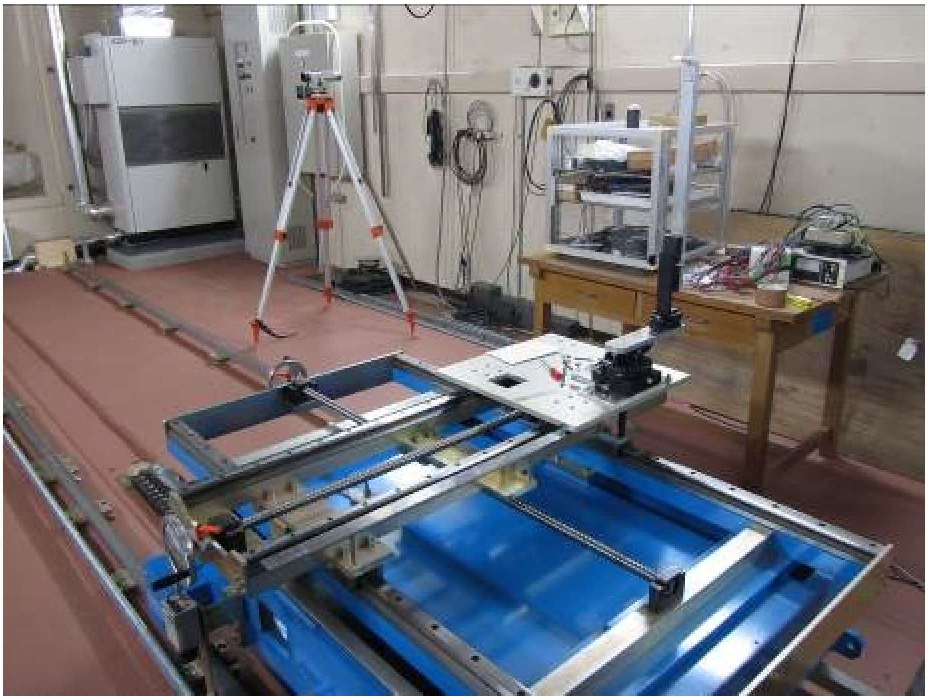

圖 2.13 日本 NMIJ 之量測軌道系統

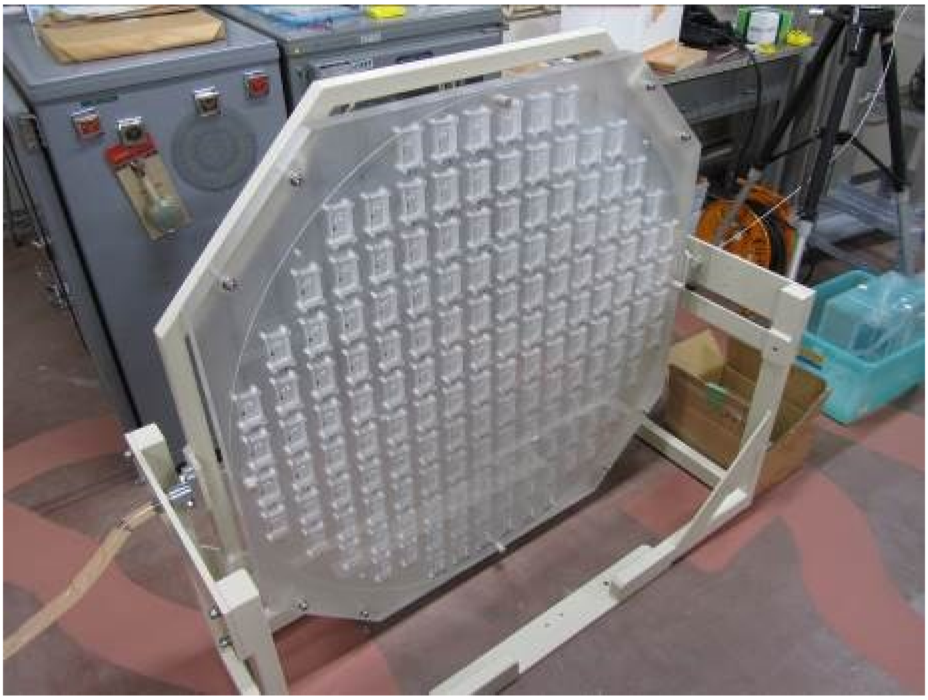

圖 2.14 日本 NMIJ 之熱發光劑量計(TLD)進階校正系統

圖 2.15 日本 NMIJ 之乳房攝影系統

(二) 參加創新醫療器材與健康照顧國際研討會(INMED-15)

本次創新醫療器材與健康照顧國際研討會假京都立命館大學朱雀校區舉辦，為期兩天，由國際知名學者進行最新國際發展趨勢發表，並由廠商發表最新開發產品。彙整會場重要議題如下：

1. 結合穿戴式設備，居家醫護市場逐漸成形

由立命館大學 Tanaka 教授主持的 Advanced ICT for Medical and Healthcare 專題，探討蓬勃發展的穿戴式設備，以及結合手機 APP 系統所形成的雲端醫療服務、電子病歷以及居家醫護市場。事實上，現今已有非常多穿戴式設備，可將使用者之心跳、血壓等個人健康訊息傳送至資料庫內，然而，該數據卻尚需專業人士的判讀與分析方法發揮預防乃至於醫生協助診斷之目的，否則只是儲存了大量的無用訊息，徒增醫療機構之困擾。現已有許多醫療訊息服務商協助民眾進行前述之專業整合與判斷服務，並將彙整後之數據上傳至個人電子病歷中，可於付費後提供給後續需使用的醫療機構。據調查指出，目前美國約有 20%民眾有使用穿戴式設備，且普及率逐年上升中，該長期監控數據尤其可提供如糖尿病、哮喘等慢性病患者做出更健康的生活選擇，並提供醫生作為治療過程之療效評估所用。

此外，根據 Transparency Market Research 公司於 2013 年發布的調查報告指出，全球居家醫護市場將由 2013 年的 1,761 億美金，以年複合增長率 10%以上的速度增長，至 2020 年將達到 3,036 億美金。該市場除前述透過穿戴式設備進行之監控行為外，另外發展極為快速的是治療儀器，包括胰島素注射器、呼吸機、治療睡眠呼吸中止症的正壓呼吸輔助器(CPAP)、靜脈注射器等；此外，復健、遠距離醫療與非技術性之居家醫護服務亦佔很大部分。

2. 以光療法進行腫瘤治療技術持續發展

光療法在本次創新會議中亦為一討論亮點，事實上，利用光療法治療腫瘤已發展一段時間，但由於過去僅能治療淺部腫瘤而導致其發展受到限制。而華盛頓大學的 Achilefu 教授於 2015 年在 Nature Nano technology 雜誌(IF=34.05)上發表的創新方法，則已經發展出可治療身體深部之腫瘤，且透過搭配化療藥物，以二元治療的理念增加療效。在研究中指出，光療法透過刺激感光材料，釋放出足以殺死腫瘤細胞的自由基，但只能應用在有光以及有氧氣的環境下，成為光療法發展的最大阻礙。Achilefu 教授提出的方式，乃是結合光療法與核醫正子檢查過程所使用的 FDG 藥物，藉由 FDG 藥物可聚集於腫瘤位置之特性，作為傳統示蹤劑功能；並根據放射性 F-18 核種衰變過程產生的正子，於人體內自然形成的薛倫可夫輻射光(Cherenkov radiation)，作為可見光光源。薛倫可夫輻射是由於帶電粒子在介質中以超過光的速度行進時所自然發出的藍色輝光，因此即便治療位置位於身體深處，亦可透過吸收 FDG 藥物而將光源帶至腫瘤位置。

在有了光源之後，研究團隊另外的工作即在於選擇良好的感光材料。經大量篩選後，發現 TiO_2 奈米粒子可在無氧情形下受光激發產生殺死癌細胞的自由基，若結合化療藥物環戊二烯鈦與 FDG 藥物作為光源，可達到最佳的療效。也正由於光療法的協助，化療藥物環戊二烯鈦所需劑量將可大幅降低，減輕人體所需承受之副作用。前述藥物已在動物實驗中獲得顯著的成效，研究團隊正在規劃小規模人體試驗的進行。

3. 美國 FDA 批准新型減肥醫療器材

會場上另外一個討論的議題，在於美國 FDA 於 2015 年批准了新型態的減肥醫療器材(並非藥物)，這是自 2007 年來的首例。與藥物控制方式不同，名為 Maestro 的醫療器材透過手術的方式植入人體，透過間歇性的放電刺激人體的迷走神經，藉此影響大腦與胃部的神經活動，來產生飽足感並抑制飢餓感。目前，該醫療器材僅適用於無法用常規方使控制體重或是極度肥胖的患者(BMI 大於 35 以上)，並已在 233 名臨床試驗患者中，達到 12 個月內減重 10%～20%目標，且在 18 個月後依然具有持續減重的效果。

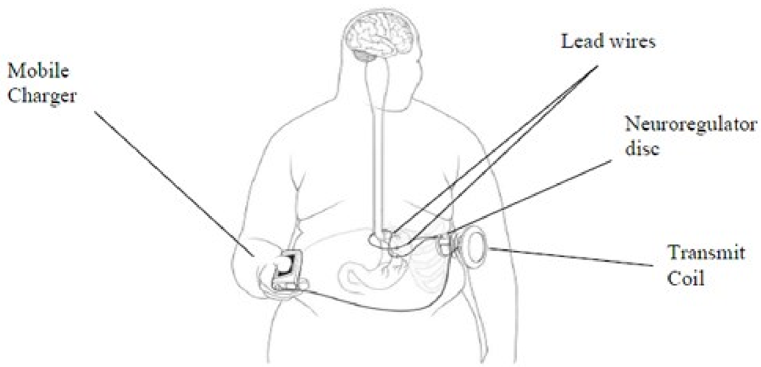

圖 2.14 美國 FDA 官方網站提供的示意圖

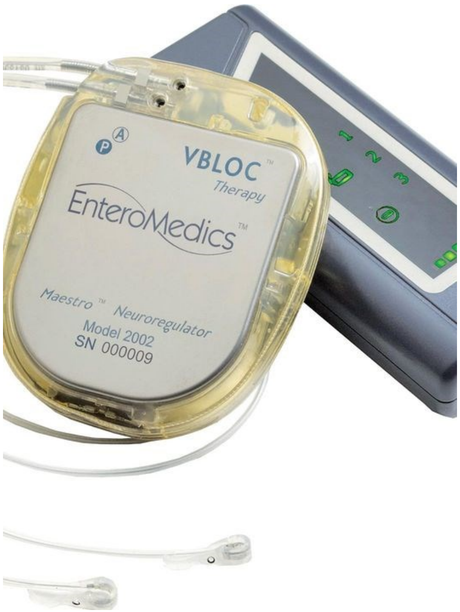

圖 2.15 減肥醫療器材 Maestro 實體照片

4. 個人化醫療與 3D 列印相結合

3D 列印的議題在近幾年來蓬勃發展，尤其材料的選擇日趨多樣化，以至於可為諸多現存之醫療技術提供新的解決方法。其中，為各別患者提供個人化醫療器材之應用，存在著最多的想像空間。本次研討會中討論到 3D 列印的應用，主要由於聚乳酸(Polylactic Acid，PLA)與聚己內酯(Polycaprolactone，PCL)兩種與人體組織相類似之化合物，此二材質可讓 3D 列印成品具備高孔隙率、高仿生度，並可依據各別患者生理特徵做出適度調整。主要之應用層面包括(1)義肢、(2)可吸收植入物；(3)個人化藥物給予。

對於目前之商業義肢而言，義肢的功能在於提供患者輔助性功能，並不能讓患者恢復原有功能，其單價較高，且無法具備個人化特徵。據研究統計，美國一年有約 185,000 名患者需進行截肢手術，但每位患者需要截肢的部位差異非常大，因此，美國的 GRASP 公司已開始透過 3D 列印方式提供輕巧、便宜、但個人化的義肢。患者將可透過提供截肢部位的照片 ，進行專屬義肢訂做。

對於醫療用植入物來說，目前普遍使用有機物質甲基丙烯酸甲酯（methyl methacrylate，MMA）作為基材，但該有機物不具生物可分解性，需於一段時間後透過手術取出。然而，會議中提到，美國的 South Windsor 公司，以利用 3D 列印方式生產獲得美國 FDA 核可之頭骨以及面部矯正儀器，可在植入一定時間後自動分解，無須額外透過手術取出。美國 FDA 另於 2014 年 10 月舉辦名為醫療器材 3D 列印研討會，就醫療器材在 3D 列印的應用面、法規面進行探討。期望在未來有更多 3D 列印商品應用於實際醫療行為中，且有更嚴謹的法規予以規範。

至於在個人化藥物給予部分，名為 organicNANO 的新創公司與路

易斯安那理工大學合作，開發出個人化藥物輸送設備，可將抗生素、化療藥物附著於可自動溶解的傳導絲上，並輸送至患部位置，以物理控制的方式進行靶向治療。前述之傳導裝置完全由 3D 列印完成，並可自行決定藥物釋放時間點以及釋放劑量。目前前述裝置尚未通過美國 FDA 認可，規劃於未來 1~2 年達成產品上市目標。

目前，由 3D 列印為出發點的醫療器材技術革命尚在萌芽之初，不同的材料、不同的應用正急速發展；除了應用面的發展外，法規管制面的腳步亦需要加速跟上，以期提供給患者更好的醫療選擇。

5. 以計算機程式輔助判斷急性腦中風病症

基於計算機程式的快速發展，許多輔助醫生進行臨床診斷的「專家系統」蓬勃發展，台灣核醫界已與廠家協助開發腦神經診斷藥物 TRODAT 專家系統，透過正常人、患者之資料庫建立與類神經網路之自我學習模式，已可快速提供臨床醫師進行診斷依據；除此之外，核能研究所放射影像技術團隊亦針對 X 光機影像，提出協助診斷之專家系統，藉由計算機程式自行判斷患者是否骨折等病症，協助醫師大幅減少判讀影像所需時間。

本次研討會中，所討論的內容與前述應用十分類似，為香港理工大學透過專家系統協助醫師進行急性腦中風診斷。該系統透過讀入 80~100 張患者 CT 影像，將診斷時間由過去的 15 分鐘降到 1~3 分鐘以內，且準確率高達 90%以上，與醫師判讀差異小於 10%。該專家系統所關注的，即在於提供急性中風患者快速診斷結果；由於急性中風患者隻黃金搶救時間小於 3 小時，但專科醫師並無法時刻駐診，因此透過此專家系統將可提供即時的診斷，讓醫療人員縮短等待診斷時間，提供患者即時、必須的搶救程序。此專家系統之核心演算法，在

於選定 ROI 後，自動判斷 CT number 與正常人之差異。由於中風患者之腦血液含量不足，專家系統透過類神經網路比對正常人資料庫，藉此將懷疑異常之區域自動標示出來，提供給第一線醫護人員參考。除此之外，該系統亦可透過與正常人資料庫差異比較提供早期預防功能，諸如皮髓質病變、血塊、腫瘤等。

專家系統已在很多領域中發揮重要的功用，尤其針對需要時效性的診斷，更可快速提供第一線醫護人員診斷結果，據此做為後續治療依據，本所具備該影像分析、影像重建技術能量，透過與醫界之 unmet need 相結合，可創造出非常廣泛的應用與產業規模。

三、心得

由本次於京都大學舉辦之創新醫療器材與健康照顧國際研討會可發現，醫療器材之發展已走進多領域整合階段，結合手持裝置、3D列印、計算機程式輔助診斷乃至於光療法等，均為未來的醫療市場開創無限的可能性。值此快速演進之發展階段，法規面的配合在各國間均顯得跟不上腳步。近年來在歐美國家均已進行相關審理程序的加速與適度鬆綁，以期能在安全無虞的大前提下，提供給民眾更佳的醫療選擇。

日本 NMIJ 的中子度量團隊成員僅 3 員，但每次前往參觀均有驚豔之感。除了高學歷(3 員均為輻射相關領域博士)外，該研究團隊對於精進標準技術的心態以及國家經費的穩定挹注，營造了良好的研究環境；兼之日本具備完整的輻射相關產業鏈，研發經費的來源廣泛，各實驗室間的競合關係造就了科研技術的領先，相關經驗值得國內參考。

四、建議事項

(一)創新醫療器材如何快速通過國家法律核可進入市場，已成為醫療器材商最關切的議題；建請本所持續關注我方衛福部與國際間簽署之相關合作協議，俾利本所科研成果技術加速商品化推展。

(二)3D 列印技術開創了非常廣大的應用市場，惟國內在該領域之開發因原料專利問題導致諸多限制，建請本所同仁可持續關注該領域技術發展，並就本所之技術專長思考利基點，即早對該領域做出技術與專利佈局。

(三)國際間針對高能中子的發展與應用十分蓬勃，包括用過核子燃料再處理、基本粒子組成探討等領域，均需世紀明燈：高能中子的挹注來協助探索。本所目前與日本 NMIJ 國家實驗室、英國 NPL 國家實驗室、德國 PTB 實驗室均有相互合作基礎，期能在未來藉由多方之密切合作，持續提升國內相關技術發展。

附錄-日方提供之參考文獻

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ARTICLE

Characterization of quasi-monoenergetic neutron source using 137, 200, 246 and 389 MeV ^{7}Li(p,n) reactions

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The authors measured the neutron energy spectra of a quasi-monoenergetic ^{7}Li(p,n) neutron source with 137, 200, 246 and 389 MeV protons set at seven angles (0°, 5°, 10°, 15°, 20°, 25° and 30°), using a time-of-flight (TOF) method employing organic scintillators NE213 at the Research Center for Nuclear Physics (RCNP) of Osaka University. The energy spectra of the source neutrons were precisely deduced down to 2 MeV at 0° and 10 MeV at other angles. Neutron energy spectra below 100 MeV at all angles were comparable, but the shapes of the continuum above 150 MeV changed considerably with the angle. In order to consider the correction required to derive the response in the peak region from the measured total response for high-energy neutron monitors, the authors showed the subtractions of H*(10) obtained at larger angles from the 0° data in the continuum part. It was found that subtracting the dose equivalent at larger angles (21° for 389 MeV, 25° for 246 MeV and 26° for 200 MeV) from the 0° data almost eliminates the continuum component. This method has potential to eliminate problems associated with continuum correction for high-energy neutron monitors.

***Keywords:** quasi-monoenergetic neutron; lithium; neutron energy spectrum; continuum correction; RCNP*

1. Introduction

Radiation fields behind accelerator shielding and flight altitudes are characterized by a large contribution of neutrons with energies above 20 MeV. When investigating neutron fields in such places, integrating detectors such as Bonner spheres, ionization chambers and dosimeters have been used with newly developed methods. Determining the reliability of detector response matrices requires calculations using Monte Carlo codes and calibration measurements. Quasi-monoenergetic neutron reference beams are of special importance for calibrating the detectors.

Facilities such as the iThemba [1] have quasi-monoenergetic neutron fields with energies up to 200 MeV using ^{7}Li(p,n$_{0,1}$)^{7}Be (g.s. + 0.429 MeV, Q = -1.64 and -2.08 MeV). On the other hand, the Research Center for Nuclear Physics (RCNP) cyclotron facility has neutron fields in energy regions up to 400 MeV, and neutron energy spectra at 0° for 352 MeV protons have been measured [2]. These neutron energy spectra at 0° have not only peak neutrons but also low-energy continua caused by breakup and spallation reactions. The fraction of the peak component in the neutron spectrum is around 50 %, but data correction for the contribution of continuum neutrons disturbs to derive the response in the peak region from the measured total response. Nolte et al. reported an interesting method to reduce the contribution experimentally at iThemba using the 100 MeV ^{7}Li(p,n) reaction [3]. They concluded that subtracting the data obtained at 16° from the 0° data provides a true monoenergetic spectrum because the spectrum of the continuum component is almost the same at 0° and at 16°. Although this method has the potential to eliminate problems associated with continuum correction, the neutron energy spectrum at larger angles for 100 - 400 MeV proton incident reactions has never been measured and the continuum correction has never been investigated.

This paper considers the measurement of neutron energy spectra at seven angles (0°, 5°, 10°, 15°, 20°, 25° and 30°) for the 140, 200, 246 and 389 MeV ^{7}Li(p,n) reactions at RCNP, and the characterization of peak and

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Development and Evaluation of Activation Neutron Detectors for Spectrum Measurements of Quasi-Monoenergetic High-Energy Neutron Fields

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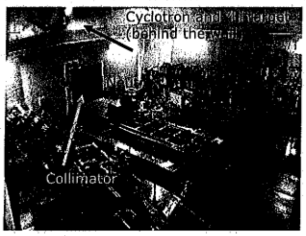
MEXT 科研費 KAKENHI

Introduction

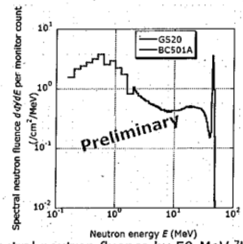
- High-energy neutron standard fields have been developed for calibrating radiation protection devices used in accelerator facilities and high-altitude environments, and testing of semiconductor devices.
- High-energy neutron fields above 20 MeV are produced by the ^{7}Li(p,n) reaction using cyclotrons.
- The quasi-monoenergetic neutron field consists of a high-energy peak and a continuum down to the low-energy region.
- Information of the continuum is necessary to subtract the effect of the continuum in the calibration and testing.

Time-of-flight measurement of quasi-monoenergetic high-energy neutron fields

- The lower limit energy of the TOF measurement was removed using a new beam-chopping system of the AVF cyclotron facility in the TIARA/JAEA.
- TOF measurements down to the keV region were achieved with scintillation detectors. (keV region: ^{6}Li-glass scintillator GS20; MeV region: Organic liquid scintillator BC501A)



Neutron irradiation room of TIARA/JAEA



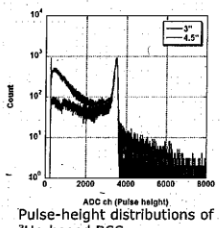
Spectral neutron fluence by 50-MeV ^{7}Li(p,n) reaction measured by the TOF method

- Derived result consists of a high-energy peak and a continuum, as expected.
- No significant count remains below ~150 keV after eliminating time-independent component.

- Energies of neutrons which directly come from the target are above ~150 keV.
- Neutrons below ~150 keV are time-independent.
- Bonner sphere spectrometer (BSS) is effective to evaluate the time-independent low-energy neutrons below ~150 keV.

Design of activation Bonner sphere spectrometer

- BSS using ^{3}He proportional counter has problem at the high-energy neutron fields.



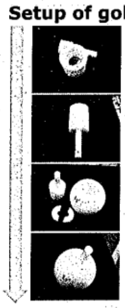
Pulse-height distributions of ^{3}He-based BSS

Signals attributed to high-energy particles disturb precise counting of ^{3}He(n,p) signals.

BSS based on activation detector

- Gold activation method is suit for measurements in the high-energy neutron experiments.
- (n,γ) reaction can be isolated from other reactions.

Setup of gold-foil BSS



Gold foils (20 mm dia, 1 mm thick) were installed in high-density polyethylene (HDPE) attachments.

Attachments containing gold foils were installed in Bonner spheres.

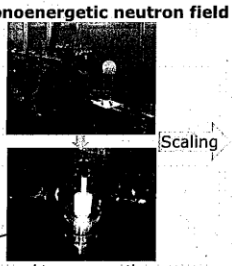
Evaluation of activation BSS

- Response of the gold-foil Bonner sphere is defined as "saturated count rate C_∞ of a specific HPGe detector (AIST HPGe) for neutron fluence rate".
- Response matrix of the gold-foil BSS was evaluated by Monte Carlo calculation using MCNPX and measurements at the 565-keV monoenergetic neutron standard field of AIST.
- The activation BSS are demonstrated in the quasi-monoenergetic high-energy neutron field of TIARA.

Measurements for monoenergetic neutron field

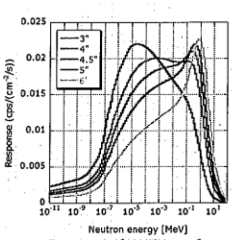
Irradiation in the 565-keV monoenergetic neutron standard field of AIST.

Activity measurement of ^{198}Au with the AIST HPGe.



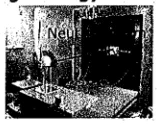
Additional attachment is used to measure the activities on the same geometrical condition.

Calculation by MCNPX



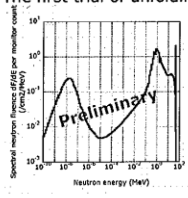
Response functions of the activation BSS

Demonstration in the quasi-monoenergetic high-energy neutron field in TIARA



^{7}Li(p,n) reaction using 50 MeV p$^+$
Neutron peak energy: 45 MeV
Spheres: 3", 4", 4.5", 5", 6"

The first trial of unfolding with the gold-foil BSS



Unfolding code: MAXED in the UMG 3.3 package
Default spectrum: result of the TOF measurement (>150 keV) + extrapolation (<150 keV, Maxwellian distribution and flat connection region)
Requested χ^2 per degree of freedom: 1.0

Conclusions

- The low-energy continuum is studied for the precise application of the quasi-monoenergetic high-energy neutron field.
- TOF measurements revealed energies of neutrons which directly come from the target were above ~150 keV. Neutrons below ~150 keV were time-independent and the BSS unfolding method is considered to be effective.
- The unfolding method using activation BSS was proposed to avoid difficulties of ^{3}He-based BSS in the high-energy neutron field.
- The activation BSS was developed and demonstrated in the quasi-monoenergetic high-energy neutron field.
- Future tasks: Improvement of reliability and accuracy of the proposed method by experiments and calculations.

A part of this work is the result of "Study on a progressive calibration method for neutron dosimeters using white neutrons" carried out under the Strategic Promotion Program for Basic Nuclear Research by the Ministry of Education, Culture, Sports, Science and Technology of Japan, and was financially supported by Japan Society for the Promotion of Science KAKENHI Grant Number 25871197.

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Quasi-monoenergetic high-energy neutron standards above 20 MeV

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Abstract

This paper provides an overview of high-energy quasi-monoenergetic neutron sources and facilities above 20 MeV around the world. Various technical matters are discussed which are required in characterizing the neutron fields by spectrometry, fluence and beam profile measurements. Important topics regarding the calibration of neutron detectors are also introduced with emphasis on beam monitoring, tail correction, background subtraction and fluence-to-dose conversion. Efforts to standardize the high-energy neutron fluence in Japan and by the German national metrology institute in collaboration with Belgian and South African institutions are also presented.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

High-energy quasi-monoenergetic neutron reference fields above 20 MeV have been developed in cyclotron facilities. Compared with monoenergetic neutron reference fields of energies below 20 MeV, high-energy reference fields are less common but their significance has not been less for various reasons. High-energy neutrons above 20 MeV are present at aircraft altitudes and in space as well as in high-energy accelerator facilities. Dosimetry is important in these high-energy neutron workplaces [1, 2] and various types of dosemeters and detectors have been developed for this purpose. Bonner spheres with enhanced responses for high-energy neutrons are one of the most effective tools for determining the spectral fluence in these workplaces [3–5]. High-energy neutron reference fields have been required for calibrating these neutron detectors as well as for verifying their energy responses [2, 6]. The reference fields have also been extensively used for shielding-benchmark experiments for high-energy accelerator facilities [7] and for cross-section studies for interactions induced by high-energy neutrons [2, 8–17]. Cross-section data for high-energy neutrons are especially required for developing accelerator-driven subcritical fission reactors or transmutation of radioactive waste [18]. Furthermore, quasi-monoenergetic neutron beams have been used for accelerated testing of semiconductor devices to investigate neutron-induced single-event effects [19].

This paper reviews high-energy quasi-monoenergetic neutron sources above 20 MeV and methodologies for characterizing neutron fields and calibrating neutron detectors, which have been used and may have potential use for metrology purposes. Efforts have been made to develop high-energy neutron fluence standards in Japan, and by a collaboration with German, Belgian and South African partners which are also introduced here.

2. Neutron sources

High-energy quasi-monoenergetic neutrons above 20 MeV have been generated at cyclotron facilities with accelerated protons striking thin targets of light elements such as Li and Be. Cyclotrons typically generate proton beams with a pulse duration of 1 ns at a repetition rate of 20 MHz to 30 MHz. The time interval between pulses can be enlarged up to one order of magnitude by employing a beam pulse selector to reduce the beam pulse repetition rate, especially for precision measurements using the time-of-flight (TOF) technique. Beam currents are adjusted between 1 nA and 10 μA depending on experimental requirements.

The targets are most commonly made of metal Li up to 10 mm thick. The protons undergo a ^{7}Li(p, n)^{7}Be reaction ($Q = -1.644$ MeV) in the Li target to forward generate neutrons, which form a main peak in the spectrum. Since the protons lose 1 MeV to 2 MeV in the target, the main peak has a width corresponding to the energy loss. The main

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ARTICLE

Development of the Quasi-monoenergetic Neutron Calibration Fields of Several Tens of MeV at TIARA

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Development of three calibration fields for 45, 60 and 75 MeV neutrons has been in progress at Takasaki Ion Accelerators for Advanced Radiation Application (TIARA) of JAEA-Takasaki. Achievement of the neutron calibration fields requires establishment of both measurement of neutron fluence and its monitoring technique. In order to measure the neutron fluence of main energy peak especially at a reference point on low fluence condition, a proton recoil counter telescope with high efficiency has been developed. The design of relatively large telescope components brought a high detection efficiency at the reference point with wide irradiation area at a long distance. Effective and precise measurement of the neutron fluence could be performed with uncertainties less than 6.5 % (standard deviation). For detecting neutrons without scattering near the target, a transmission type neutron fluence monitor has been newly developed to measure the neutron fluence directly at the collimator exit. Its performance such as counting rates was tested for various beam intensities.

KEYWORDS: neutron calibration field, TIARA, proton recoil counter telescope, fluence monitor

I. Introduction*

High energy proton accelerator facilities such as J-PARC have been developed to pursue frontier research in particle physics, nuclear science and technology. In order to implement the quality of radiation protection in such facilities, neutron calibration fields in a wide energy range are required to evaluate the energy response of neutron monitors and dosimeters.

For the neutron fields above 20 MeV, the standard calibration fields have not been fully established in Japan. For the purpose of the development of such calibration fields, the quasi-monoenergetic neutron irradiation fields of several tens of MeV are available at Takasaki Ion Accelerators for Advanced Radiation Application (TIARA) of Takasaki Advanced Radiation Research Institute (TARRI), Japan Atomic Energy Agency (JAEA).[1)] Therefore, investigation of the characteristics of the neutron fields at TIARA[2,3)] has been furthered in order to contribute to the establishment of the standard fields by the National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology (AIST), in the future. Three neutron fields with 45, 60 and 75 MeV peaks are planned to be established, considering the international intercomparison of the neutron fields at TIARA with those at other facilities in a similar energy range.

Up to now, beam profile, main peak energy of quasi-monoenergetic neutron, and neutron spectra inside and outside the irradiation field were measured and reported.[2,3)] Among remaining issues on neutron fluence for the main energy peak and on corrections for low energy neutrons below the main energy peak region and gamma rays, measurement of neutron fluence and establishment of fluence monitoring technique are important for the development of the calibration fields. This paper reports the results of absolute measurement of neutron fluence by using a proton recoil counter telescope (PRT) with high detection efficiency and the development of a transmission type neutron fluence monitor to monitor neutron beam directly.

II. Quasi-monoenergetic Neutron Fields at TIARA

The quasi-monoenergetic neutron fields by using ^{7}Li(p,n)^{7}Be reaction for 40-90 MeV neutrons have been established at TIARA as the irradiation field for experimental use.[1)] The neutron spectra have the main energy peak in high energy region and continuous distribution below the peak region. **Figure 1** shows the layout of the quasi-monoenergetic neutron source facility at TIARA. A proton beam from an AVF cyclotron is transported to a ^{7}Li target with thickness corresponding to 2 MeV energy loss. Protons passing through the target are bent by a clearing magnet into a Faraday cup shielded by an iron beam dump. Neutrons are guided to the experimental room through about 3 m thick collimator (inner-diameter of 11 cm) consisting of an iron rotary-shutter

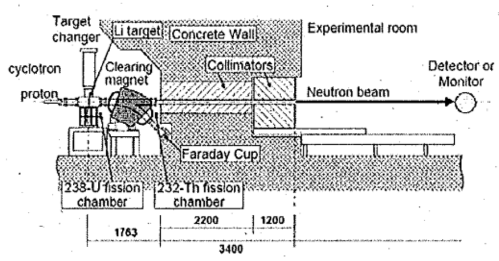

Fig. 1 Schematic view of the quasi-monoenergetic neutron source facility at TIARA.

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Time-of-Flight Measurements for Low-Energy Components of 45-MeV Quasi-Monoenergetic High-Energy Neutron Field from ^{7}Li(p, n) Reaction

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***Abstract*—A quasi-monoenergetic neutron field generated in the ^{7}Li(p, n) reaction consists of a high-energy monoenergetic peak and a continuum to the low-energy region. In this study, the spectral fluence of the continuum was measured with the time-of-flight (TOF) method using a ^{6}Li-glass scintillation detector and an organic liquid scintillation detector for the keV and MeV region, respectively. The neutron spectral fluence was determined down to the keV region by implementing a new beam chopping system and the results showed that the neutrons that came directly from the target had a lower energy limit about 100 keV. Discussions were made also on the effect of the time-independent neutrons which are assumed to be room-scattered neutrons. The obtained information is expected to contribute to understanding the quasi-monoenergetic high-energy neutron field and improvements of calibrating neutron detectors in the field.**

***Index Terms*—High-energy neutrons, neutrons, quasi-monoenergetic neutron fields, spectrometry, time-of-flight method.**

I. INTRODUCTION

QUASI-MONOENERGETIC high-energy neutron fields with energies above 20 MeV are being developed for high-energy neutron standards at cyclotron facilities [1]–[3]. Calibration of the neutron detectors used for scientific experiments and dose controls in high-energy accelerator facilities and high-altitude environments is performed in such fields [4]. The quasi-monoenergetic neutron field is generated by the ^{7}Li(p, n) reaction and consists of a high-energy monoenergetic peak and a continuum to the low-energy region. This continuum disturbs the calibration of neutron detectors for the high-energy monoenergetic peak neutrons so its effect should be properly considered [5]–[7].

Although a time-of-flight (TOF) method with an organic liquid scintillation detector is typically used in spectral measurements of the quasi-monoenergetic high-energy neutron field [8], the repetition rate of the accelerated proton beam and the distance between the neutron source and the detector impose a minimum energy limit. Neutrons with energies below this limit overlap with neutrons in the next pulse. This limit energy has typically been several MeV because of the high-repetition rate of the proton beam accelerated by an AVF cyclotron with a common beam chopper located after it. The spectral information below the TOF threshold energy has been evaluated by the unfolding method using a Bonner sphere spectrometer (BSS) [4], [6]. However, the BSS unfolding method may not be accurate due to the lack of a reliable default spectrum based on TOF measurements below the threshold energy.

At the same time, common neutron detectors using polyethylene moderators generally have a local maximum response at an energy of several MeV and the effect of the unknown continuum has significant influence on the measurement. A two-angle differential measurement method using a target swinger has also been attempted [5][6]; however, it could not directly reveal the spectral structure of the continuum, and the target swingers are only available at a few facilities. Therefore, a TOF measurement method for the low-energy region of the continuum is required.

Recently, a beam chopping system [9] called "P-chopper" became available for neutron experiments [10] at the AVF cyclotron facility at the Takasaki Ion accelerators for Advanced Radiation Application (TIARA) of the Japan Atomic Energy Agency (JAEA). The P-chopper is located in a beam injection line of the cyclotron, and can reduce the beam repetition rate considerably when it is used together with an existing beam chopping system called an "S-chopper." Using the chopping systems, the TOF threshold has, in principle, been removed, and the low-energy region of the continuum is measured using the TOF method with scintillation detectors in this study.

II. EXPERIMENT

The TOF measurement was performed at the LC0 beam line for neutron experiments at the AVF cyclotron facility of TIARA.

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Quasi-monoenergetic neutron energy spectra for 246 and 389 MeV ^{7}Li(p,n) reactions at angles from 0° to 30°

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ABSTRACT

The authors measured the neutron energy spectra of a quasi-monoenergetic ^{7}Li(p,n) neutron source with 246 and 389 MeV protons set at seven angles (0°, 2.5°, 5°, 10°, 15°, 20° and 30°), using a time-of-flight (TOF) method employing organic scintillators NE213 at the Research Center for Nuclear Physics (RCNP) of Osaka University. The energy spectra of the source neutrons were precisely deduced down to 2 MeV at 0° and 10 MeV at other angles. The cross-sections of the peak neutron production reaction at 0° were on the 35–40 mb line of other experimental data, and the peak neutron angular distribution agreed well with the Taddeucci formula. Neutron energy spectra below 100 MeV at all angles were comparable, but the shapes of the continuum above 150 MeV changed considerably with the angle. In order to consider the correction required to derive the response in the peak region from the measured total response for high-energy neutron monitors such as DARWIN and Wendi-2, the authors showed the subtractions of $H^*(10)$ obtained at larger angles (10°, 15°, 20° and 30°) from the 0° data in the continuum part for the 246 and 389 MeV ^{7}Li(p,n) reactions. It was found that subtracting the dose equivalent at about 20° from the 0° data almost eliminates the continuum component. This method has potential to eliminate problems associated with continuum correction for high-energy neutron monitors.

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1. Introduction

Radiation fields behind accelerator shielding and flight altitudes are characterized by a large contribution of neutrons with energies above 20 MeV. When investigating neutron fields in such places, integrating detectors such as Bonner spheres, ionization chambers and dosimeters have been used with newly developed methods. Determining the reliability of detector response matrices requires calculations using Monte Carlo codes and calibration measurements. Quasi-monoenergetic neutron reference beams are of special importance for calibrating the detectors. They are also used efficiently for shielding benchmark experiments and cross-section studies of neutron-induced reactions, taking advantage of the narrow energy distribution at the peak.

Facilities such as the Tri University Meson Facility (TRIUMF) [1], iThemba [2] and RIKEN [3] have quasi-monoenergetic neutron fields with energies up to 200 MeV using ^{7}Li(p,n)^{7}Be (g.s.+0.429 MeV, $Q=-1.64$ and -2.075 MeV). On the other hand, the Research Center for Nuclear Physics (RCNP) cyclotron facility [4–6] has neutron fields in energy regions up to 400 MeV, and neutron energy spectra at 0° for 140–400 MeV protons have been measured [7,8]. These neutron energy spectra at 0° have not only peak neutrons but also low-energy continua caused by breakup and spallation reactions. The fraction of the peak component in the neutron spectrum is around 50%, but data correction for the contribution of continuum neutrons disturbs to derive the response in the peak region from the measured total response. Nolte et al. [9] reported an interesting

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