Astrophysics and Photoreaction Data

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The present status of photoreaction studies at AIST and the prospect of the future at SPring-8 are presented. The Konan University and the Universite Libre de Bruxelles launch a 5-year project, starting in 2004, of constructing an extended NACRE compilation in which photonuclear reactions will be included.

1. Introduction

There are three major real-photon sources that have been used in nuclear physics: radioactive isotopes, bremsstrahlung, and positron annihilation in flight [1,2]. Recently, a new generation of γ-ray sources has emerged at synchrotron radiation facilities that are devoted to material science. The idea of producing γ rays in the laboratory by interactions between laser photons and relativistic electrons was born in 1963 [3,4]. The idea was first put into reality for practical purposes at Frascati in 1980's [5]. However, its use for astronuclear physics had been ignored until recently.

Photonuclear data of astrophysical relevance concern (γ,γ), (γ,n), (γ,p), and (γ,α) reactions near particle thresholds without/with Coulomb barrier effects in exit channels. As shown in the literature [6], photoneutron reaction rates are determined by the product of a Planck spectrum of black-body radiation and photoneutron cross sections. As a result, (γ,n) cross sections just above thresholds are of astrophysical significance. Although a nuclear physics database for electric giant dipole resonance was constructed after major contributions from the Lawrence Livermore National Laboratory and Saclay [7], the data near thresholds lack sufficient accuracy for astrophysical use. Coulomb barrier effects make (γ,p), and (γ,α) reactions difficult to measure and (γ,γ) cross sections below particle thresholds should never be forgotten for photoreactions on nuclei with thermally equilibrated excited states [8].

2. The present status at AIST

Real photon beams in the MeV region have been developed at the National Institute of Advanced Industrial Science and Technology (AIST) in *head-on* collisions of laser photons with relativistic electrons stored in the accumulator ring TERAS [9]. The laser Compton scattering (LCS) plays a role of *photon accelerator*, producing quasi-monochromatic γ beams in the energy range of 1 - 40 MeV. They are bremsstrahlung-free unlike the positron annihilation in flight, and 100% linearly (circularly) polarized. Because of the monochromaticy, the AIST-LCS beam is best suited to excitation function measurements of photoreaction cross sections with enriched target materials. In addition, photo-activation of natural foils by the AIST-LCS beam can be done for nuclei whose isotopic abundance is sufficiently large.

The AIST-LCS γ-beam with a rather limited intensity (10^{4-5} photons/sec) was so far used to measure cross sections of $^{9}Be(\gamma,n)\alpha\alpha$ for supernovae nucleosynthesis [10,11], $^{181}Ta(\gamma,n)^{180}Ta$ [12] for the p-process nucleosynthesis, and $D(\gamma,n)p$ [13] for big bang nucleosynthesis. The latest photoneutron cross section measurements include ^{186}W, ^{187}Re, and ^{188}Os for the s-process nucleosynthesis and cosmochronometry, and ^{93}Nb and ^{139}La for the p-process nucleosynthesis. Measurements for many more nuclei will follow over the next 5 years.

Large differences were found in electromagnetic quantities ($B(E1)\downarrow$ and $\Gamma_{\gamma}(M1)$) for ^{9}Be between the present real-photon measurement and the electron scattering (virtual-photon) measurement. The present experimental data are analyzed with the help of a microscopic model of the ^{9}Be nucleus [14-16]. The reaction rate of $\alpha\alpha(n,\gamma)^{9}Be$ was evaluated from the photoneutron cross section [11] and compared with those of the CF88 [17] and the NACRE [18] compilations. A factor of two difference was found with respect to CF88 over the temperature range $T = (0.1 - 10) \times 10^{9}$ K, while reasonable agreement with NACRE was obtained, putting aside details in the treatment of individual states in ^{9}Be.

Figure 1 shows photonuclear data for ^{181}Ta [12]. Their interpretation has necessitated a microscopic understanding of threshold behavior of photoneutron cross sections, showing the advantage of a QRPA calculation over a conventional Lorentzian- or hybrid-model analysis. From these nuclear data, it appears that ^{180}Ta, the nature's rarest isotope and the only naturally occurring isomer, can be a p-process nuclide. Nuclear challenges remain in order to reliably evaluate the ^{180}Ta p-process yield from various stellar locations reviewed in [8]. They include ^{180}Ta photo-destruction rate and ^{181}Ta photo-neutron branching to the ^{180}Ta. These would help constraining reaction models.

Figure 2 shows photonuclear data for deuterium [13]. The filled circles are from this work. The photodisintegration data for deuterium were converted to cross sections of the $p(n,\gamma)D$ capture reaction. A least-squares fit to the present cross section combined with the existing capture data [19,20] was obtained. It has to be pointed out that the capture cross section was evaluated only theoretically for more than 30 years since the compilation [21].

Furthermore, details of the latest evaluation by Hale compiled in ENDF/B-VI [22] can no longer be traced. The present work has provided an experimental confirmation of the theoretical evaluation, offering the foundation for recent discussions of the baryon density based on observations of primeval deuterium-to-hydrogen ratios in metal-poor hydrogen clouds at high redshifts toward quasars [23-25]. One may be entering a new era of Big Bang nucleosynthesis through an independent confirmation of the baryon density by the observation of temperature anisotropies of the cosmic microwave background (CMB) radiation by the Wilkinson Microwave Anisotropy Probe (WMAP) satellite [26].

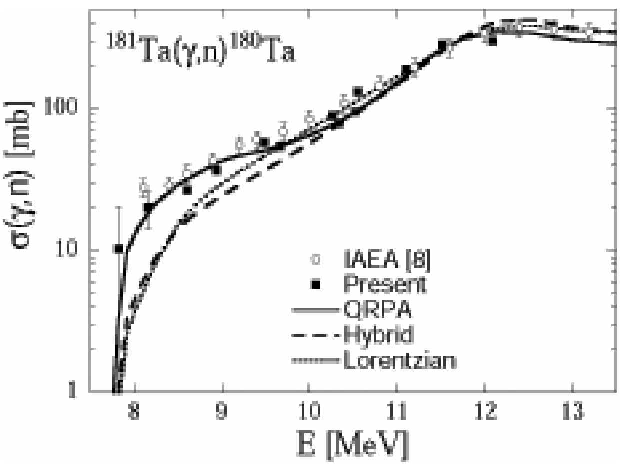

Figure 1. Photodisintegration cross sections for $^{181}Ta(\gamma,n)^{180}Ta$.

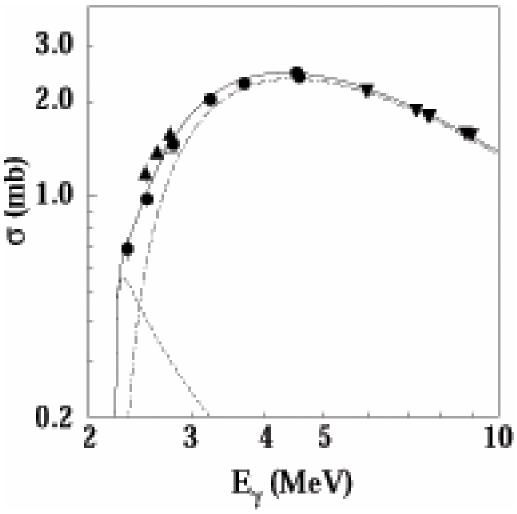

Figure 2. Photodisintegration cross sections for $D(\gamma,n)p$.

3. The future prospect at AIST

Currently two γ-sources are under development at the 8 GeV Super-Photon ring (SPring-8) in Japan: one γ-source is based on inverse Compton scattering of far-infrared laser photons with $\lambda = 118.8$ μm from 8-GeV electrons, the other one being a high-energy radiation from a 10 tesla superconducting wiggler (SCW) [27]. The former is rather white with maximum energy ~ 10 MeV, while the latter is characterized by exponential tails extending to several MeV. It is expected that their intensities are 10^{7-8} photons/sec/MeV near neutron thresholds, ~ 8 MeV.

Figure 3 shows energy spectra of the SCW radiations calculated following the prescription of [28,29]. It is remarkable that the exponential tails of the radiation are equivalent to temperatures of a few to several billions of Kelvin (T_9). In other words, the SCW radiation *mimics* the Planck spectrum of black-body radiation generated in particular during supernova explosions. In a promising astrophysical site for the p-process, the O/Ne layers of massive stars during their pre-supernova phase [30-32] or during their explosions as type-II supernovae [33,34,31,32], temperatures of the blackbody radiation lie in the T_9 = 1.7 - 3.3 range. These temperatures can be accessed by the SCW at lower magnetic fields. The intensity of the high-energy tail of the SCW radiation strongly depends on the magnetic field. Under this condition, the SCW radiation can be used to directly determine photonuclear reaction rates by the activation technique without manipulations such as superposition of several Bremsstrahlung spectra with different end-point energies [35].

Experimentally, the higher the intensity the more feasible the measurement. The intensity at the maximum 10 Tesla field is indeed attractive. The threshold behavior of the photoneutron cross section can be parametrized by

$$\sigma(E) = \sigma_0 \, [(E_\gamma - S_n)/S_n]^p,$$

where E_γ is the γ-ray energy and S_n is the neutron separation energy. When a neutron with an orbital angular momentum l is emitted in a photodisintegration, p is given by $l + 1/2$. Generally different values of l contribute, depending on the spin and the parity of the residual nucleus in the photodisintegration. This is in interesting contrast with the fact that s-wave neutrons are preferentially captured at low energies. σ_0 and p are parameters to be determined experimentally. Based on Eq.(1), a few measurements of the photoreaction rate with the SCW radiation at the highest available magnetic fields enable us to determine these experimental parameters. This method is most promising in the p-process study, opening up a variety of applications. We have a long list (not presented here) of photoreactions to be studied by the photoactivation technique.

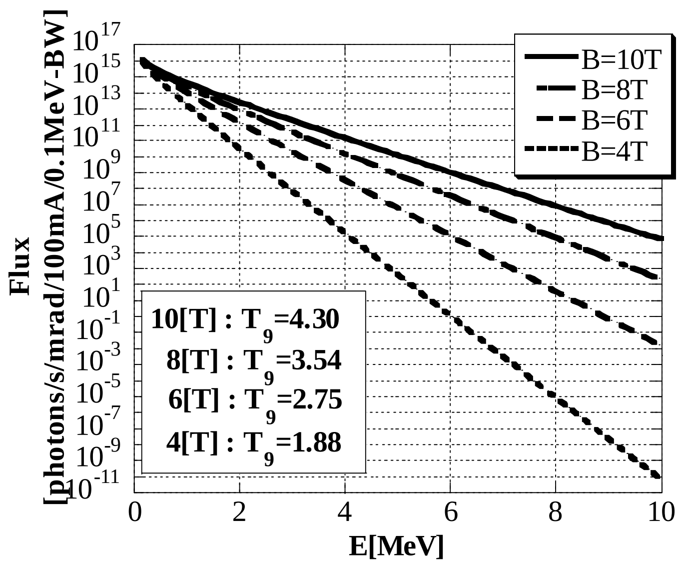

Figure 3. Synchrotron radiation from a 10 Tesla superconducting wiggler at SPring-8 (calculations).

The highest priority would be placed on the photo-destruction of ^{180}Ta among the long list, ^{180}Ta[0.012%](γ,n)^{179}Ta[$T_{1/2}$ =1.82 y]. Preparing enriched ^{180}Ta material for photonuclear reactions is out of question. This reaction can be studied by photoactivation of natural tantalum foils with a high-intensity γ-source at SPring-8 (see [36] for details). On the other hand, a higher luminosity of the order of 10^{11} photons/sec is awaited by another p-process nuclide ^{138}La[0.09%] whose photo-destruction leads to ^{137}La[$T_{1/2}$ =6 × 10^4 y].

4. Konan-Brussels Database

Since the first compilation by W.A. Fowler *et al.* in 1967 [21], the astrophysics community benefited from a series of the CalTech compilations [21,37-39,17]. It was nearly 10 years after the last one that a new compilation NACRE [18], a partial update of the CalTech compilation, was constructed.

The Konan University and the Universite Libre de Bruxelles are launching a 5-year project, starting in April 2004, of constructing an extended NACRE compilation based on a comprehensive convention between the two universities. In the first place this may be a *public service* to the international astrophysics and very low-energy nuclear physics communities. In addition, we intend to stimulate experimental, observational, and theoretical developments in astrophysics.

We are at the start of an unexplored field of photonuclear reaction studies with new g sources available at synchrotron radiation facilities. In addition to reactions induced by neutrons and charged particles, the Konan-ULB database will also include information on photonuclear reactions. To be most successful and continuously updated, our compilation and evaluation effort has clearly to benefit from the input from the international nuclear astrophysics community.

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