IOP PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **35** (2008) 014020 (6pp) doi:10.1088/0954-3899/35/1/014020

The measurement of the ^{206}Pb(n, γ) cross section and stellar implications

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Received 29 June 2007
Published 13 December 2007
Online at stacks.iop.org/JPhysG/35/014020

Abstract

The neutron capture cross section of ^{206}Pb has been measured at the CERN n_TOF spectrometer using a setup of two C_6D_6 detectors. In the energy interval from 1 eV to 600 keV the cross section is dominated by resonances, which were analyzed via the *R*-matrix analysis code SAMMY. In the relevant energy ranges for stellar nucleosynthesis, i.e., at thermal energies of $kT = 8$ keV and $kT = 23$ keV, the present Maxwellian average cross section differs by 20% and 9% from the recommended values of Bao *et al* respectively. From the new cross section the s-abundance of ^{206}Pb could be reliably determined as 70(4)%. This result is of importance in order to test and constrain r-process abundance calculations in the actinide region, because the r-process portion of ^{206}Pb is dominated by α-back decays of short-lived transbismuth isotopes.

1. Introduction

The heaviest stable isotopes, lead and bismuth, are synthesized via the slow (s-) and the rapid (r-) neutron capture processes [1, 2]. The s-process abundances (N_s) can be well determined [3], provided that their neutron capture cross sections are measured accurately. Combining N_s with the isotopic abundances observed in the solar system, $N_\odot$, the r-process portion is reliably constrained as

$$N_r \approx N_\odot - N_s. \qquad (1)$$

A characteristic quality of the r-process abundances in the Pb/Bi region is the fact that most of the contribution comes from the decay of short-lived transbismuth isotopes [4]. Although the production of ^{206}Pb is dominated by the s-process, the r-process still produces a substantial portion of it. The latter can be used to examine the performance of r-process models in the actinide region and to estimate the uncertainties involved in those calculations. This becomes relevant when the r-process models are applied to observed actinide abundances in metal-poor stars in order to estimate their ages.

Additionally ^{206}Pb contains a radiogenic asset from the decay of ^{238}U ($t_{1/2} = 4.468$ Gy). However, as will be illustrated in this paper, this radiogenic component is far too small, and hence uncertain, to be used for dating purposes.

2. Measurement

The capture cross section of ^{206}Pb has been measured in the past at ORNL [5–7] and RPI [8]. These measurements show discrepancies, whose source is difficult to assess. Therefore, new measurements have been made recently at IRMM [9] and at the CERN n_TOF time-of-flight facility [10]. In this paper we report about the latter experiment.

At n_TOF neutrons are produced by a 20 GeV proton beam in a lead target. The spallation source is surrounded by a water layer, which serves both as coolant and moderator. The beam is based on intense pulses of (3–7) $\times$ 10^{12} protons, a width of 6 ns and a repetition rate of less than 0.5 Hz. This low duty cycle allows one to cover an energy range between 1 eV and 1 MeV in a single run with favorable background conditions. The experimental capture setup at n_TOF has been designed in order to minimize all known sources of systematic uncertainty. The two C_6D_6 γ-ray detectors used for these measurements have been particularly developed in order to achieve the lowest possible sensitivity to sample-scattered neutrons [11]. Additionally, the detectors were placed at $\sim$125° in order to reduce deviations in the yield due to the angular distribution of the prompt capture γ-rays.

Since typically only one of the capture γ-rays is registered by the C_6D_6 detectors, the pulse height weighting technique (PHWT) needs to be applied [12]. The accuracy of the weighting function (WF) is particularly relevant in this case, since the de-excitation spectra of ^{207}Pb are rather hard compared to the spectrum of the 4.9 eV resonance in ^{197}Au, used as a reference for yield normalization. Therefore, an effort was made in order to determine the WFs for the gold and the lead samples accurately, following the prescription given previously [13].

The neutron intensity at the sample position was monitored at n_TOF using a thin ^{6}Li foil centered in the beam. The outgoing α and ^{3}H particles were detected via four Si-detectors, placed outside the beam and covering a large solid angle. The dependence of the neutron flux on neutron energy is known with an accuracy of 2% from dedicated measurements made at n_TOF [14].

In the energy region of interest, between 1 keV and 1 MeV, the background was dominated by in-beam γ-rays scattered in the sample [10]. For the analysis of the capture yield, this background level was best determined from the measurement of a ^{208}Pb sample.

3. Results

About 61 resonances were observed between 3 keV and 600 keV with good statistics to perform an R-matrix analysis via the SAMMY code [16]. In the analysis we started with initial resonance parameters from [17]. The resonance parameters determined in our R-matrix analysis were used to calculate the Maxwellian averaged capture cross section (MACS) needed for stellar nucleosynthesis (see figure 1). The result shows statistical errors between 1.8% and 2.3% and total systematic uncertainties between 3% and 5%. The MACS was corrected by 6% at 25 keV in order to account for resonances at higher energies, which were not observed

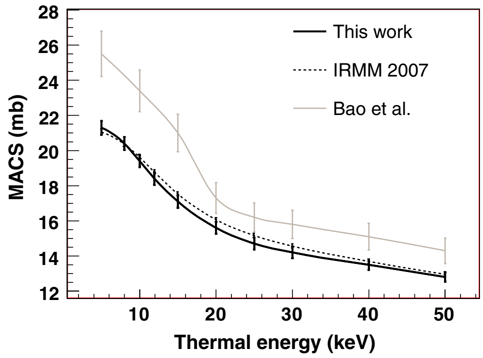

Figure 1. MACS from n_TOF (bold), IRMM (dashed) and Bao *et al* [15] (light).

with enough statistics. However, this correction becomes negligible (less than 0.5%) at 8 keV, where most ^{206}Pb is synthesized (see the following section).

Because of the low multiplicity of the ^{206}Pb capture cascades, some of the registered prompt γ-rays (for resonances with spin $J > 1/2$) may deviate from an isotropic angular distribution. A corresponding systematic error of ~4% was estimated for resonances with $J^{\pi} = 3/2^{-}$ and of ~10% for resonances with spins $3/2^{+}$ and $5/2^{+}$. The impact of these uncertainties on the final Maxwellian averaged cross section is rather small, because the cross section is dominated by $J = 1/2$ and $J^{\pi} = 3/2^{-}$ resonances in the relevant energy range between 5 keV and 30 keV.

The comparison in figure 1 shows that the results from the last two measurements on ^{206}Pb are in excellent agreement and considerably lower than the recommended values of [15]. At stellar temperatures corresponding to $kT = 8$ keV, where most of the ^{206}Pb is produced (see the following section), the new MACS is about 20% lower compared to [15].

4. Nucleosynthesis of ^{206}Pb and cosmochronology

The nucleosynthesis of ^{206}Pb takes place in low-mass asymptotic giant branch (AGB) stars of low metallicity [18]. In this scenario, about 95% of the neutron exposure is provided by the ^{13}C$(\alpha, n)^{16}$O reaction at a thermal energy of $kT \approx 8$ keV. At this stellar temperature, the new MACS is smaller and considerably more accurate than the recommended values [15] (see figure 1), resulting in an improved s-process contribution to ^{206}Pb. A model calculation was carried out for low metallicity ([Fe/H] = −0.3) thermally pulsing AGB stars of masses 1.5 and 3 $M_{\odot}$. The average of these two models can be used [3] as a good estimate for the production of ^{206}Pb during galactic chemical evolution [18, 19]. From this approach, an abundance of $N_s^{206} = 70(4)\%$ of the solar system value, $N_{\odot}^{206}$, was obtained. Using the results from r-process model calculations [4], one can derive a ^{206}Pb radiogenic component of $N_c^{206} = N_{\odot}^{206} - N_s^{206} - N_r^{206} = 3.3\%$. Neglecting all uncertainties, but those on the N_s^{206} value determined here, one finds a ratio $N_c^{206}/N_{\odot}^{238} = 1.1 \pm 1.3$ at the epoch of the early solar system. Combining the latter result with the Fowler model for galactic chemical evolution [20], an r-process age of $\Delta_r = 7.7^{+5.8}_{-9}$ Gyr is obtained (see figure 2). Assuming an age for the universe, $t_U = \Delta_r + 4.6$ Gy, the result obtained here for Δ_r is in perfect agreement with the most accurate determination available of t_U [21]. Obviously, the large uncertainty in this age estimation (shaded region in figure 2) prevents the $N_c^{206}/N_{\odot}^{238}$ ratio to be used

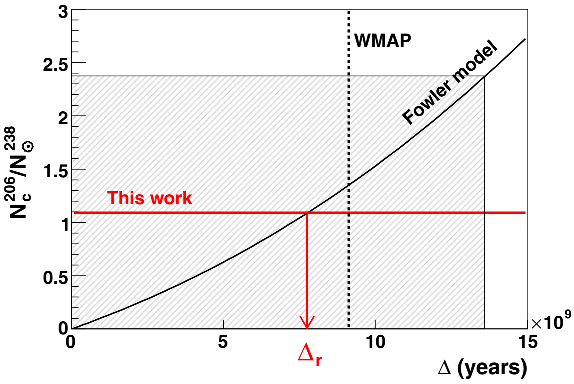

Figure 2. r-process age (Δ_r) determined from the $N_c^{206}/N_\odot^{235}$ ratio and the Fowler model. (This figure is in colour only in the electronic version)

as a cosmochronometer, but it shows that the independently determined s- and r-process abundances are fully consistent. A similar calculation made with more recent r-process model calculations [22, 23] provides also a compatible r-process age. Given the present values of $N_\odot^{206}$ and N_s^{206}, one can estimate that a change of about $\pm 15\%$ on the r-process model calculation still gives compatible age results. Therefore that interval probably provides a realistic estimate of the uncertainty on these r-process models, concerning the production of the eight short-lived parents of ^{206}Pb in the actinide region. Nevertheless, the same test needs to be carried out for the higher mass Pb isotopes and for bismuth, in order to establish a more complete picture of the entire region. Such independent tests are important in order to verify the r-process models for interpreting observed actinide abundances in metal poor stars and for obtaining reliable age estimates from those stars.

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